THE EVOLUTION OF MANAGEMENT PROCEDURES FOR THE SOUTH AFRICAN HAKE RESOURCE IN THE 2000s

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Declaration

I hereby declare that this thesis has not been submitted, either in the same or different form, to this or any other university for a degree and that it represents my own work. Apart from the normal guidance from my supervisors, I have received no assistance except as stated below:

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- Chapter 3 and Glossary: Rademeyer RA, Plagányi ÉE and Butterworth DS. 2007. Tips and Tricks in designing Management Procedures. ICES Journal of Marine Science. 64: 618-625.
- Chapter 4: Rademeyer RA, Butterworth DS and Plagányi ÉE. 2008. Assessment of the South African hake resource taking its two-species nature into account. African Journal of Marine Science. 30(2): 263-290.

- Chapter 5: Rademeyer RA, Butterworth DS and Plagányi ÉE. 2008. A history of recent bases for management and the development of a species-combined Operational Management Procedure for the South African hake resource. African Journal of Marine Science. 30(2): 291-310.

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Abstract

Since the 1990s Operational Management Procedures (OMPs), as recognised under the South African Marine Living Resources Act (MLRA) (Act 18 of 1998), have provided the basis for annual scientific TAC recommendations for the major South African fisheries. South Africa is one of the world leaders in implementing this approach, which satisfies the requirements of the FAO's Precautionary Approach (as required by the MLRA).

The South African hake fishery, which consists of two species, the deep-water *Merluccius paradoxus* and the shallow-water *M. capensis*, has been managed using OMPs since 1990. This thesis summarises the management of the hake resource, focusing on the development of two MPs: OMP-2007, which was the basis for the 2007 to 2010 TAC recommendations, and OMP-2011, which was first used for the 2011 TAC recommendation and which is intended to be used for a further three years.

The biology of the Cape hakes and the current fishery are briefly reviewed. The South African hake trawling fishery was certified in May 2004 (and re-certified in March 2010) by the Marine Stewardship Council (MSC), and the process is described briefly.

An overview of the OMP approach to fisheries management is given and simple guidelines are provided to assist in the construction of Management Procedures (MPs), as well as their evaluation and implementation. Suggestions are provided on how to choose between candidate MPs, on key trade-offs in selecting between empirical and model-based formulations and on dealing with different sources of uncertainty. Some guidelines are given for presenting the results effectively, which is one of the key challenges of a successful implementation process.

Because catch and effort statistics collected from the fishery are not species-disaggregated, previous published quantitative assessment methods have treated the two hake species as one. Furthermore, recent evidence suggests that (although treated as two separate populations in past assessments) the South African South and West coasts components of each species form a single stock. The Operating Models (OMs) on which the simulation testing of OMP-2007 is carried out are based on the first fully species-disaggregated coast wide assessment of the South African hake resource. A Reference Set (RS) of 24 OMs is developed by taking into consideration the primary sources of uncertainties in this assessment, namely the level of natural mortality, the species-split of the catches and the steepness of the stock-recruitment curve. *M. paradoxus* is estimated to be well below its pre-exploitation (or pristine) level *K* in 2006 (<10% for the baseline assessment) whereas *M. capensis* is estimated to be well above its maximum sustainable yield level.

The bases for historical catch limits placed on the hake fishery are reviewed in brief for earlier years and then in some depth over the period from 1991 when the OMP approach was introduced for this fishery. The new OMP implemented from 2007 (OMP-2007) is the first to be based on the use of rigorous species-disaggregated assessments of the resource as OMs. The Reference Set and range of robustness trials, together with the associated OMs, which were used for the simulation testing of OMP-2007 are described. Performance statistics for a number of candidate OMPs are compared, and the two key trade-off decisions in the selection process discussed (substantial *M. paradoxus* and catch per unit effort (CPUE) recovery, and TAC stability constraints). Details of the OMP adopted are provided. Its control rule is derivative based, depending on recent trends in CPUE and survey estimates of abundance, raising and lowering TACs in relation to these recent trends. To ensure necessary *M. paradoxus* recovery, initial TACs are reduced unless the *M. paradoxus* trend in abundance exceeded 2% p.a. OMP-2007, which is tuned to a median 20-year recovery target of 20% of pristine spawning biomass for *M. paradoxus* and a 50% increase in CPUE over the next 10 years, has been adopted for recommending hake TACs over the 2007–2010 period until the next scheduled major review.

The TAC recommendations based on OMP-2007 are described for the period 2007-2010. Anecdotal reports of atypical environmental conditions during the January 2008 West Coast survey were the source of further analyses to determine whether this survey should be deemed "non-comparable" to previous surveys and therefore excluded from the TAC computations. Strong scientific evidence could not be provided and the OMP computations for the 2009 TAC did include the 2008 West Coast survey. Based on OMP-2007 outputs, the South African hake TAC decreased from 150 000t in 2006 to 118 578t in 2009, with a slight increase in 2010 to 119 833t.

Arising from the change in hake assessments from a species-combined to a species-disaggregated form, surprise has been expressed by some at the different statuses estimated for *M. paradoxus* (well below its MSYL) and *M. capensis* (well above its MSYL). The reasons underlying the recent estimates of depletion for the two South African hake species are investigated by identifying which data source(s) is the primary determinant of these current estimates. The relatively high extent of depletion estimated for the *M. paradoxus* population is found to be robustly determined, with all five sources of data contributing to the assessment suggesting that both this depletion and recent fishing mortality are relatively high. However these fives sources lead to appreciably different perceptions for the extent of depletion of the *M. capensis* population. The GLM-standardised CPUE series commencing in 1978 is found to be the most influential of the five in leading to present estimates of both a relatively low extent of depletion and fishing mortality for this population. However if there is a trend in bias over time in this index as a measure of abundance, irrespective (almost) of the direction of this bias, the extent of depletion of the *M. capensis* population would be estimated to be notably higher. Research priorities indicated by this analysis include a focus on ageing and sex-differentiation for *M. paradoxus*, and on the possibility that factors responsible for an increase in catching efficiency may have been omitted from the *M. capensis* CPUE GLM standardisation.

For the development of OMP-2011, the assessment methodology for the hake resource is refined to include gender-disaggregation, and to fit directly to age data with growth curve parameters estimated internally in the likelihood maximisation process. This approach successfully resolves the conflict between fits to catch-at-age and catch-at-length distributions evident in earlier assessments. The 2010 *M. paradoxus* female spawning biomass is estimated to be at 59% of its MSY level, whereas the corresponding *M. capensis* estimate is well above that level.

A Reference Set (RS) of 12 scenarios is selected as the primary basis to be used to simulation test candidates for the revised OMP for hake, OMP-2011. The median (over the RS of OMs) 2010 spawning biomass estimate for *M. paradoxus* is 16% compared to the 8% estimated for 2006 for the OMP-2007 RS. The principal uncertainty axes spanned by the RS are the central year for the switch from a primarily *M. capensis* to a primarily *M. paradoxus* fishery, values for natural mortality at age, and the form of the stock-recruitment relationship. The *M. paradoxus* depletion is particularly sensitive to assumptions about the pre-1977 split of the catch between *M. capensis* and *M. paradoxus*. The previous assessment favoured (in likelihood terms) lower values in the range from 1940 to 1970 for the mid-year of the central year of the shift from a primarily *M. capensis* to a primarily *M. paradoxus* fishery, and this led to lower values for B_{current}/K for *M. paradoxus*. However, the likelihoods for the current assessment no longer favour any choice of central shift year within this 1940-1970 period. Historic information has been examined to throw light on this shift year, but different approaches yielded differing inferences. The *M. paradoxus* B_{current}/K (in terms of spawning biomass) ranges from about 10% to a little over 30% across this range of values for the central shift year. Importantly however, though K estimates for *M. paradoxus* vary depending on the choice for this central shift year for the species dominating the catch, estimates of B_{current} and B_{MSY} are broadly stable across the range considered, with $B_{\text{current}}/B_{MSY}$ consistently in the range of higher 50%s to lower 60%s. Thus the statistic $B_{\text{current}}/B_{MSY}$ appears the more robustly estimated, which suggests using this as the primary measure on which to base reporting of current status and selection of recovery targets for *M. paradoxus* instead of B_{current}/K.

Results for conditioning of the full set of robustness/sensitivity tests are also given. Projections are carried out under a constant catch strategy to select a core set of robustness tests to run in the CMP selection process.

The anticipated performances of a series of illustrative Candidate Management Procedures (CMPs) for the South African hake resource for the Reference Set of trials are presented. The final choice CMP (OMP-2011) to provide TAC recommendations for 2011 to 2014 is detailed, with associated results presented for the RS and a wide range of robustness tests. In making the final choice for OMP-2011 the Demersal Working Group focused on i) trade-offs between future TACs compared to the risk of *M. paradoxus* depletion (together with subsequent recovery) for the Reference Set of trials and for the most difficult of the robustness tests (a decrease in carrying capacity K in the past), and also ii) the extent of inter-annual TAC variability. Details of the OMP formulae are provided; key changes from OMP-2007 were in terms of simplifications, except that the formulae used transformed overtime from derivative- to target-based, and that integration of resource abundance indices into a single representative index took the variability of the different components into account. A set of general guidelines adopted for the process of possible overruling of recommendations from OMPs or bringing forward their reviews within an otherwise intended four-year cycle is detailed.

Future work priorities for the South African hake resource are discussed. These include incorporating a temporal variability in the fishing selectivity, including additional CPUE information and discard information. Possible temporal changes in somatic growth should be investigated and the species-splitting of the catch should be regularly validated. Future assessments should include spatial disaggregation with movement of the fish between areas and take explicit account of the high levels of inter-specific predation and cannibalism. Consideration should be given to including environmental variables when standardizing the survey catch rate data. The possibility of "pseudo species-specific" management (implemented by broadly regulating fishing depths for example) and incorporating socio-economic factors into the OMP selection process should be investigated. Multispecies models should be developed for possible use in fisheries management in an ecosystem approach to fisheries (EAF) context, and models should be developed to investigate the implications of Marine Protected Areas (MPAs) for the resource and the local fisheries. Finally, if some sharing of the hake stocks between Namibia and South Africa can be demonstrated, different scenarios pertaining to the extent of stock sharing should be modelled to investigate the consequences of alternative management arrangements.

Glossary

Definitions of some terms used throughout this thesis are as follows:

AAV: Average annual variation in a TAC from one year to the next (expressed as a proportion of the average annual catch); this performance statistic is often used to measure the attainment of an objective related to minimizing catch variability.

Assessment: A mathematical population model coupled to a statistical estimation process that integrates data from a variety of sources to provide estimates of reference points and past and present abundance, fishing mortality, and productivity of a resource.

CMP: Candidate MP—one of a set of MPs under consideration for implementation to manage a resource.

Conditioning: An OM is "conditioned" on available information by adjusting the parameter values to ensure that it is consistent with this information, and hence reflects assumptions that are plausible—this process is similar (sometimes identical) to an assessment; the conditioning provides the initial conditions for projecting resource dynamics forward.

Error: Differences, reflecting uncertainties, between the actual dynamics of the resource (described by the OM) and perceptions arising from observations and assumptions. Four types of error may be distinguished, and simulation trials may take account of one or more of them:

- Estimation error: differences between the actual values of the parameters of the OM and those provided by the estimator when fitting a model to available data;
- Implementation error: differences between intended limits (as output by an MP) and those actually achieved;
- Observation error (or measurement error): differences between the measured value of some resource index and the corresponding actual value in the OM;
- Process error: natural variations in resource dynamics or systematic errors in outputs from an estimator arising from the use of a parameter value or model structure different from that of the OM.

Estimator: The statistical estimation process within an assessment; in a MP context, the component that provides information on resource status and productivity from past and generated future resource-monitoring data for input to the HCR.

Feedback control: Rules or algorithms based directly or indirectly on trends in observations of resource indices, which adjust the values of management measures such as TACs in directions intended to reverse inferred trends in abundance away from the target level reflecting decision-makers' objectives. FLR: Fisheries Library in R, a generic toolbox that can be used to construct OMs for MSE.

Generic MP: An MP that has been tested for potential use for a wide range of resources (e.g. the single-stock component of the IWC's RMP), as distinct from a case-specific MP tested using OMs conditioned on data for a specific resource.

Harvest strategy: Intended meaning may be synonymous with MP, MP (implicit), HCR, or HCR+ assessment; in the last case, the assessment method may change at each application rather than remain fixed as for an MP.

HCR: Harvest control rule (also termed harvest control law)—a set of well-defined rules used for determining a management action in the form of a TAC or allowable fishing effort given input from an estimator or directly from data.

Implementation: The process of testing followed by practical application of an MP to provide resource management recommendations.

MCM: Marine and Coastal Management, DEAT, which became Fisheries Branch, DAFF in mid-2010

MP: Management procedure—the combination of pre-defined data, together with an algorithm to which such data are input to provide a value for a TAC or effort control measure; this combination has been demonstrated, through simulation trials, to show robust performance in the presence of uncertainties. Additional rules may be included, for example to spread a TAC spatially to cater for uncertainty about stock structure. Two types of MP may be distinguished:

- Empirical MP: An MP where resource-monitoring data (such as survey estimates of abundance) are input directly into a formula that generates a control measure such as a TAC without an intermediate (typically population-model based) estimator;

- Model-based MP: An MP where the process used to generate a control measure such as a TAC (this process is sometimes termed a catch limit algorithm or CLA) is a combination of an estimator and an HCR.

MP approach: Management of a resource using a fully specified set of rules incorporating feedback control; the approach is explicitly precautionary through its requirement for simulation trials to have demonstrated robust performance across a range of uncertainties about resource status and dynamics.

MSE: Management strategy evaluation—usually synonymous with MP approach; also often used to describe the process of testing generic MPs or harvest strategies.

MP (implicit): A set of rules for management of a resource that contains all the elements of an MP, but has not yet been evaluated through simulation trials.

Management strategy: Usually synonymous with MP but some authors use it to mean an HCR.

Observation model: The component of the OM that generates fishery-dependent and / or fishery-independent resource monitoring data for input to an MP.

Objectives: General goals for managing a resource as set by decision-makers—these often include the aims of maximizing catches, minimizing interannual changes in catch limits and the risk of unintended depletion of the resource and related species, and considerations of transparency and cost effectiveness.

OM: Operating model—a mathematical–statistical model used to describe the actual resource dynamics in simulation trials and to generate resource monitoring data when projecting forward.

OMP: Operational management procedure—analogous to an MP, except that this term is typically reserved to signify MPs that have actually been implemented, in contrast to the ones that are conceptual only.

Performance statistics: Statistics that summarize different aspects of the results of a simulation trial used to evaluate how well a specific MP achieves some or all of the general objectives for management for a particular scenario.

Plausibility: The likelihood of a scenario considered in simulation trials representing reality relative to other scenarios also under consideration; scenarios considered implausible (e.g. because of incompatibility with available data) are eliminated from the simulation trials.

Reference case (RC): A single, typically central, conditioned OM for evaluating CMPs that provides a pragmatic basis for comparison with results of other OMs.

Reference set (RS) (also termed base-case or evaluation scenarios): a limited set of scenarios, with their associated conditioned OMs, which include the most important uncertainties in the model structure, parameters, and data, i.e. alternative scenarios which have both high plausibility and major impacts on performance statistics.

Research-conditional option: Temporary application of an MP that does not satisfy conservative performance criteria, provided accompanied by both a research programme to check the plausibility of the scenarios that gave rise to this poor performance and an agreed subsequent reduction in catches should the research prove unable to demonstrate implausibility.

Robustness tests: Tests to examine the performance of an MP across a full range of plausible scenarios.

Scenario: A hypothesis concerning resource status and dynamics, represented mathematically as an OM.

Selection: The choice of an MP from a set of CMPs through comparing performance statistics from tests over a wide range of scenarios.

Significant: In this thesis, unless otherwise stated, this word is used only with the meaning of statistically significant at the 5% level.

Simulation trial (or test): A computer simulation to project resource dynamics for a particular scenario forward for a specified period, under controls specified within an MP, to ascertain performance; such projections will typically be repeated a large number of times to capture stochasticity.

TAC: Total allowable catch (or catch limit) to be taken from a resource within a specified period.

Trade-offs: Comparisons of gains in some performance statistics against losses in others when selecting among CMPs; these trade-offs arise because some objectives for management conflict (e.g. maximizing catch vs. minimizing risk of unintended depletion).

Weights: Either qualitative (e.g. high, medium, low) or quantitative measures of relative plausibility accorded across a set of scenarios.

Worm plots: Plots showing a number of possible realizations of simulated projections of, for example, catch or spawning biomass under application of an MP.

Chapter 1

Introduction and overview of thesis

1.1 Introduction

Since the 1990s Operational Management Procedures (OMPs), as recognised under the South African Marine Living Resources Act (Act 18 of 1998), have provided the basis for annual scientific TAC recommendations for the major South African fisheries to the Minister responsible. These recommendations are first developed in the Demersal Scientific Working Group[1] of the Marine and Coastal management (MCM) section of the Department of Environmental Affairs and Tourism (DEAT)[2]. South Africa is one of the world leaders in implementing this Management Procedure approach, which satisfies the requirements of the FAO's Precautionary Approach (as required by the MLRA).

The South African hake fishery, which consists of two species, the deep-water *Merluccius paradoxus* and the shallow-water *M. capensis*, has been managed using OMPs since 1990. This thesis summarises the management of the hake resource, focusing on the development of two MPs: OMP-2007, which was the basis for the 2007 to 2010 TAC recommendations and OMP-2011, which was first used to provide the 2011 TAC recommendation and which is intended to be used for a further three years.

A brief review of the biology of hake and of the current fishery is given below. In May 2004, the hake trawling fishery was certified by the Marine Stewardship Council

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[1] This Working Group is appointed by MCM and comprised of scientists from MCM and external organisations (e.g. the University of Cape Town) who are conducting research on the species for which the Group is responsible for providing advice. Stakeholders such a (representatives of) industry and NGOs attend meetings of the Group as observers and participate in the Group's discussions.

[2] Late during the period upon which this thesis focuses, governmental responsibility for fisheries was passed from DEAT to the Department of Agriculture, Forestry and Fisheries (DAFF), with MCM's fisheries management responsibilities transferred to DAFF's newly created Fisheries Branch. For simplicity though, this thesis will refer throughout to MCM, even though for 2011 and some of 2010 this actually means the DAFF Fisheries Branch.

(MSC), with a re-certification granted in March 2010. The process is summarized in Section 1.4.

1.2 Review of the biology of hake

The two species of hake inhabiting the waters off South Africa are known collectively as the Cape hakes. *M. paradoxus* was originally regarded as a sub-species of *M. capensis*, but the two are now recognised as full species (Franca 1962). Aspects of the general taxonomy, anatomy, biology and distribution of adult Cape hakes have been reviewed in detail by Botha (1980), Payne and Punt (1995) and Gordoa *et al*. (1995).

Figure 1.1 maps the distribution of the two species. *M. capensis* is distributed between about 16°S lat. on the West Coast of Africa to about 31°E long. on the South Coast, while *M. paradoxus* has a more restricted geographic distribution, between 17°S lat. on the West Coast to about 27° E long. on the South Coast (Payne 1989). Although both species are found around the entire South African coast, the deep-water hake is dominant off the West Coast while the shallow-water hake is dominant on the Agulhas Bank. Payne (1989) suggests that the differing abundances of the two species of hake off different parts of southern Africa may be related to the width of the continental shelf and the relative steepness of the adjacent continental slope. Possibly the temperature at the depths preferred by each species is also a factor contributing to the differing distributions.

M. capensis is usually found in depths of less than 400 m, with the largest biomass in the 100-200 m depth range. The depth distribution of *M. paradoxus* ranges mainly from 150 to 500 m (Badenhorst and Smale 1991), although this species has been found down to 1000 m water depth (Mas-Riera 1991). The two species overlap in their depth distribution between 150 and 400m in ratios that change with depth (Botha 1985). Because there is a size gradation by depth for both species, with larger fish generally found deeper than smaller ones, medium to large *M. capensis* co-habit with, and feed extensively on small *M. paradoxus* (Botha 1980, Inada 1981).

Morphological features distinguishing the two species include differences in gill structure, otolith morphology, pectoral fin length, number of vertebra and gill rakers, relative eye size, colour of the anal fin and body shape. These characteristics have been described and documented by Konchina (1987), Van Eck (1969), Inada (1981) and Botha (1980).

There appears to be some seasonal movement of adults inshore and offshore (Payne *et al*. 1989), but although many species of hake show seasonal longshore migrations (Inada 1981), there is no direct indication of seasonal longshore movement in concentrations of South African hake. However, Le Clus *et al.* (2002) suggest that *M. capensis* might be moving to the south as they grow older, based on different size-classes examined from research surveys. Maps of the distribution of *M. capensis*, by size-classes, show that while juveniles and small *M. capensis* are concentrated on the West Coast, the bulk of the medium to large shallow-water hake is found on the southern West Coast and on the western Agulhas Bank off the South Coast.

Stock structure for both hake species remains uncertain and several hypotheses have been proposed. Since both species also extend into Namibia, the possible need for transboundary management of the Cape hake stocks has been under discussion in recent years. The preponderant scientific view up to the early 2000s was that the shallow-water species *M. capensis* consists of separate stocks in Namibia and South Africa, while the deep-water species *M. paradoxus* was suggested to be a shared stock (Grant *et al*. 1987, 1988; Burmeister 2005). More recent analyses (Van der Heyden *et al*. 2007, 2010; Bloomer *et al*. 2009) however served to undermine the certainty of these views. Evidence of spawning of *M. capensis* in both Namibia and South Africa lends weight to the hypothesis of separate stocks for this species, though considerable mixing could still be occurring. MtDNA analyses revealed no structure for this species (Van der Heyden *et al*. 2007), while microsatellite analyses suggest three likely stocks (Bloomer *et al*. 2009). For *M. paradoxus*, there seems to be some genetic evidence for structure at the South Africa/Namibia marine boundary, despite the fact that there is no direct evidence of spawning in Namibia (though mature fish are found there). MtDNA analyses revealed significant genetic differentiation present in adult *M. paradoxus* (>3 year old), with two population corresponding to Namibian and South African populations (to the north and south of the Orange River), while no genetic structure was found for fish less than three year old (Van der Heyden *et al*. 2010). Again in contrast with the mtDNA results, microsatellite analyses indicate only one likely stock of *M. paradoxus* (Bloomer *et al*. 2009).

Cape hakes are believed to have a life span of about 12 years and may grow to more than 1 m in length (Botha 1971). Botha (1971) reported that growth rate of the two species each differ by sex, females generally growing faster than males. Males mature earlier than females, reaching 50% sexual maturity at 28 cm and 34 cm (compared to 42 cm and 41 cm for females) for *M. paradoxus* and *M. capensis* respectively (Fairweather and Leslie 2008). This difference in sexual maturity might explain why the male growth rate is slower as more energy is used for spawning (Payne 1989). Payne and Punt (1995) suggest that life expectancy may also be longer for females as very few males above an age of eight years (*M. capensis*) and six years (*M. paradoxus*) are found in the commercial catches .

Cape hakes are generally described in the literature as being opportunistic predators, with seasonal and regional differences in their diet reflecting local variations in food availability rather than prey selection (Payne *et al*. 1987, Roel and Macpherson 1988, Punt *et al.* 1992, Pillar and Barange 1993). The diet of both species changes from a largely crustacean one during the juvenile stages to almost exclusively piscivorous (a large proportion of which is hake itself) as predator length increases (Botha 1980). The main prey items of Cape hake differ between the two coasts.

Cape hakes are preyed upon by other fish (e.g., snoek *Thyrsites atun*, Cape gurnard *Chelidonichthys capensis*, jacopever *Helicolenus dactylopterus*), cephalopods (mainly chokka squid *Loligo vulgaris reynaudii*) and marine mammals such as the Cape fur seal *Arctocephalus pusillus pusillus* and several species of dolphins (e.g., common dolphin *Delphinus delphis*, dusky dolphin *Lagenorhynchus obscurus*) (Pillar and Wilkinson 1995). However, predation on the Cape hakes by other predators appears to be considerably less than that attributable to cannibalism and inter-specific (hake-on-hake) predation (Payne *et al.* 1987). Indeed, small hakes form by far the most common item (by mass) in the diet of large (>50cm) hake (Punt *et al.* 1992). This is not all true cannibalism however; the ratio of *M. paradoxus* to *M. capensis* in the diet is close to 100:0 for *M. capensis* and approximately 75:25 for *M. paradoxus* (Pillar and Wilkinson 1995). This is due to the different depth distributions of the two species, which result in large shallow-water Cape hake being found in the vicinity of juvenile deep-water Cape hake. True cannibalism in *M. paradoxus* is less common than in *M. capensis* because small deep-water hakes are not available in the vicinity of adults of that species, as size segregation by depth is more pronounced than in *M. capensis* (Gordoa and Duarte 1991). Cannibalism (including inter-specific – hake-on-hake – predation) is argued to be an important factor in regulating hake abundance off South Africa, especially on the West Coast where the deep-water species is more abundant than elsewhere (Lleonart *et al*. 1985; Payne and Punt 1995). Cannibalism may affect the structure of the population as well as the natural mortality rate, which may have important implications for the management of hake.

1.3 The current fishery

The hake resource is by far the most valuable of South Africa's exploited fish resources, generating an annual income of approximately R 5.2 billion and providing approximately 30 000 people with employment in 2011 (R. Bross, pers. commn). Historically the hake sector accounts (by value) for more than 50% of all of the other South African commercial fisheries combined.

The demersal hake fishery off South Africa is split into four sub-sectors according to factors such as species, geographical area, method, gear and vessel size. These four sectors are deep-sea trawl, inshore trawl and more recently, hake-directed longline and hake-directed handline. The deep-sea trawling is concentrated in the Western Cape and operates mainly out of Cape Town and Saldanha Bay (see Figure 1.1). On the South Coast, this offshore fishery is restricted to depths greater than 110 m or, since 2002, to 20 nautical miles from the coast, whichever is the greatest distance offshore. There are no such restrictions on the West Coast; in practice however, offshore vessels do not operate in waters shallower than about 180 m (R. Leslie, pers. commn). Being capital intensive, deep-sea trawling has traditionally been the domain of a few large fishing companies operating their own trawlers (freezers and wet fish, i.e., delivering frozen and fresh fish). However, with the introduction of a policy to broaden access in the mid-1980's, the number of rights holders[3] in the deep-sea sector increased from 7 in 1986 to about 60 currently (ESS 2000). The number of vessels in the offshore trawl fishery has been increasing in the first half of the 2000s with a peak of 81 vessels operating in 2005. In 2007 secondary effort controls have been put in place (SADSTIA 2007) and the number of vessels has been reduced to 52 in 2010 (Jean Glazer, pers. commn).

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[3] Note that different rights holders may share use of the same vessel.

The inshore trawl fishery operates mainly from Mossel Bay and Port Elizabeth (see Figure 1.1), taking fish on the Agulhas Bank, and tends to operate inside the 110 m isobath. Due to the restricted depth range, very few *M. paradoxus* are caught by this sector. The inshore trawling fleet is characterised by relatively small vessels, less than 30 m long and less than 750 hp; during the early 2000s, there were a maximum of 35 such trawlers operating in this industry (BCLME 2006a).

The longline fishery operates around the whole coast although most longline vessels operate from Cape Town. Longlining started only in 1983, targeting principally kingklip (*Genypterus capensis*) and Cape hakes (Japp 1988). At that stage kingklip catches were not restricted, while the hake catches were offset against the quotas of the rights holders. For this reason and because of the high value of kingklip, fishing effort increased considerably on the kingklip stock (catches peaked at more than 10 thousand tons in 1986), which declined sharply from 1984 to 1989 (Punt and Japp 1994). Kingklip catches fell dramatically and although a longline kingklip TAC was introduced for two years over 1988 and 1989, this fishery was stopped altogether by the end of 1990 (Punt and Japp 1994). It was only in 1994 that hake-directed longlining was allowed again on an experimental basis, although some ‘illegal’ longlining continued on the South Coast after 1990 (ESS 2000). On the West Coast, longlining targets both species, but on the South Coast the bulk of the longline catch is *M. capensis*.

A commercial handline hake fishery started in the late 1980’s with the development of a viable market for fresh whole hake, predominantly in Spain (ESS 2000). The handline fishery operates up to about 100 m depth, mainly from Plettenberg Bay (PE) (see Figure 1.1.) where hake is found relatively close to the coast. The handline catch consists almost entirely of shallow-water Cape hake of premium quality. Generally the sizes of fresh fish sold by the handliners are smaller than those caught by bottom trawl and longline. Handline hake catches peaked in the early 2000s (with an estimated catch of 7300 tons in 2001) but have substantially declined in recent years, with an average of less than 300 tons caught in the last four years.

1.4 Marine Stewardship Council certification

A factor that enhanced the economic viability, and employment potential, of the South African hake fishery was the certification, in May 2004, of the hake offshore trawl fishery by the Marine Stewardship Council (MSC), an internationally recognised body established with the aim of improving responsible fisheries management by way of consumer awareness strategies. The MSC is an eco-labelling initiative launched by two international organisations with high global profiles: the international conservation organisation, the World-Wide Fund for Nature (WWF) and the multi-national industrial giant Unilever. The certification of the hake trawling fishery assisted in the penetration of European markets by South African hake exporters, opening doors to high value-added markets.

MSC allows consumers to promote sustainable fishing through a mainly market-based (rather than regulation-based) mechanism. There are (in 2011) 122 certified fisheries in the MSC program, representing close to 6% of the annual global harvest of wild capture fisheries. The South African hake trawl fishery was one of the first to be certified and is still one of the most important in terms of volume.

The process of assessing a fishery starts with a confidential pre-assessment, carried out for a client by a certification body. If the results are such that the client decides to go ahead with a full assessment, an expert team is appointed. This team develops performance indicators and scoring guidepoints. The fishery is then scored against these indicators, which are aggregated to obtain a score for each of three principles (see below). Depending on the score, a fishery can be rejected, asked to fulfil some pre-conditions before obtaining certification, certified with conditions that need to be addressed within a certain period or certified with no conditions. Fisheries that are certified are subject to annual audits. After five years, a new assessment has to be carried out (MSC 2010a). MSC certification is granted against a specific standard called the ‘‘Principles and Criteria for Sustainable Fishing’’, which is structured around three principles: (1) the health of the stock, (2) the integrity of the ecosystem and (3) the effectiveness of the management system (MSC 2010b).

In the 2004 assessment, the South African hake trawl industry attained a relatively high score on stock management (88 points out of 100; the minimum pass is 80); the certifiers only required the development of a sampling programme (to be implemented within 2 years from certification) to address deficiencies in understanding the variability of recruitment to the populations and the age structure of both hake species (Powers *et al*. 2004). South Africa's use of the OMP approach and conscientious implementation of the management advice arising from OMPs for the hake resource had an important influence on this score. On ecosystem impact, the South African demersal industry just passed (80 points), gaps being identified in four areas: by-catch management, ecosystem relations, impact of trawling on the benthic habitat and impact of trawling on seabird populations (Powers *et al*. 2004). In relation to the fishery management system, the industry's score was also relatively high (88 points), the only reservation relating to the compliance system (Powers *et al*. 2004).

Since 2004, appreciable progress has been made in addressing many of the impacts of the fishery, as a consequence of the fishery being required to fulfil management plans specifying measurable improvements as part of the certification decision. There have been improvements in by-catch management, reduced impacts on the benthic habitat, stricter monitoring of compliance by all companies involved in the fishery and substantial reductions in the impact of trawling on seabird populations (Tori lines are now part of permit conditions, reducing seabird mortalities by an estimated 90% since 2006 (Watkins *et al*. 2008)).

In 2006 MSC decided to make its ecolabelling programme fully consistent with the guidelines for ecolabelling of fish and fishery products developed in 2005 by the Food and Agriculture Organization of the United Nations (FAO 2009). The most recent set of MSC principles and criteria was developed in 2010.

The 2009 re-assessment encountered some problems on principle (1), the health of the stock. The certification in 2004 had been based on a species-aggregated assessment. Two years after that species-disaggregated assessments were performed which indicated a healthy *M. capensis* population, but a depleted *M. paradoxus* stock requiring a recovery program. Re-certification of the hake trawl fishery was nevertheless granted in March 2010 based on the old criteria and with a condition regarding certain aspects of the OMP revision process to be finalised by October 2010, which had a bearing especially on recovery of the *M. paradoxus* stock.. This is discussed in more detail in Chapter 10.

1.5 Overview

This thesis is comprised of three sections. Section I describes Management Procedures in general, while Sections II and III focus on the application of Management Procedures to the South African hake resource. Section II deals with the development of OMP-2007 while Section III is focused on OMP-2011.

1.5.1 Overview of Section I – Overview of Management Procedures

Chapter 2 provides background information on the history, philosophy and application of MP approach, while Chapter 3 offers simple guidelines to assist in the construction, evaluation and implementation of MPs.

1.5.2 Overview of Section II – Managing South African hake using OMP-2007

There is a need to regularly update models used for management, in synchrony with increases in understanding and information available for a resource. Specifically, there was a need to move from a species-combined to a species-disaggregated assessment for South African hake, given important differences in the population dynamics and fishing effort applied to the two species.

Chapter 4 describes the first fully species-disaggregated coast-wide assessment of the South African hake resource. By taking into consideration the primary sources of uncertainty in this assessment, a Reference Set of Operating Models is constructed to be used in the development and testing of OMP-2007.

The bases for historical catch limits placed on the hake fishery are reviewed in Chapter 5. This Chapter also describes the development of OMP-2007 on which the 2007 to 2010 hake TAC recommendations were based. Chapter 6 summarises the TAC recommendations for the period 2007-2010 which were based on OMP-2007.

1.5.3 Overview of Section III – Paving the way for OMP-2011

Section III focuses on an in-depth critical evaluation of the hake models used for management, drawing on the findings to refine and improve interpretation of the data and representation of the underlying population dynamics. The appreciable technical challenges encountered during each step of the process are described. Statistical analyses and stakeholder inputs as to a range of key uncertainties are used to inform the choice of an appropriate set of models to underpin testing of alternative management options. The research described integrates biological, mathematical and statistical tools to address the question as to selection of appropriate management options which simultaneously satisfy pre-specified objectives, such as those of sustainability, risks to the ecosystem and economic performance.

Chapter 7 investigates the reasons underlying the current estimates of depletion for the *M. paradoxus* (well below its MSYL) and *M. capensis* (well above its MSYL) and aims to identify which data source(s) is the primary determinant of these current estimates.

In Chapter 8 the assessment methodology for the hake resource is refined to include gender-disaggregation and to fit directly to age data and estimate growth curve parameters directly in the likelihood maximisation process.

In Chapter 9 a RS of 12 OMs is selected as the primary basis to be used to test Candidate MPs for the revised hake OMP, OMP-2011. A full set of robustness/sensitivity tests are also described and conditioned. Constant catch projections are used to select a core set of robustness tests. The process of selecting OMP-2011 is described in detail in Chapter 10.

Finally Chapter 11 summarises future research priorities for the South African hake resource and provides overall conclusions.

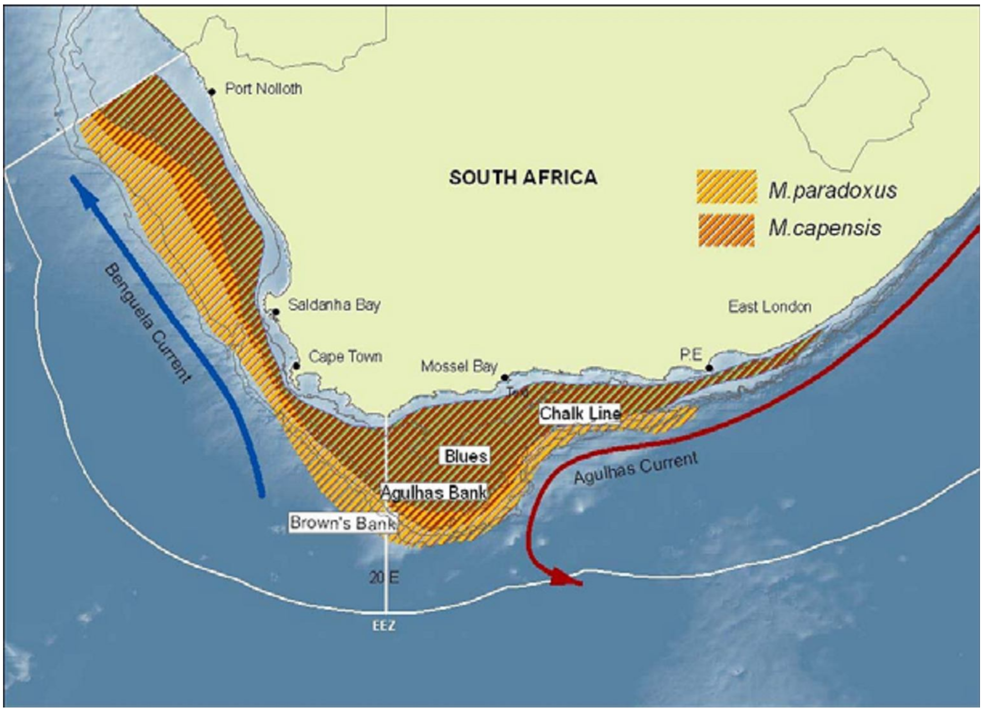

Figure 1.1: Schematic showing the approximate distribution of *M. paradoxus* and *M. capensis* off South Africa (reproduced from Wilkinson and Japp 2005, with permission).

SECTION I

AN OVERVIEW OF MANAGEMENT PROCEDURES

Chapter 2

Management Procedures

2.1 Introduction

Uncertainty confounds all natural resource management decisions. Within fisheries management, calls to take uncertainty and risk into account in decision-making have become commonplace (e.g., Walters 1986; Hilborn *et al.* 1993; Rosenberg and Restrepo 1994), as required under the Precautionary Approach (FAO 1995), and a primary task faced by stock assessment scientists is therefore to provide fishery managers with a quantitative evaluation of the potential consequences of alternative management actions in these circumstances. The Management Procedure (MP; Butterworth and Punt 1999) or the analogous Management Strategy Evaluation (MSE; Smith *et al.* 1999) frameworks are key examples of formal methods for addressing uncertainty issues, given their focus on identifying and modelling uncertainties as well as on considering different possible resource dynamics.

The MP approach was first developed by the Scientific Committee of the International Whaling Commission (IWC) during the 1980s (Punt and Donovan 2007) and has been applied to a number of fisheries since. De Oliveira *et al.* (2008) review the implementations and uses of this framework in the IWC, the Commission for the Conservation of Southern Bluefin tuna (CCSBT), South Africa, Australia, Europe and the USA. The development of MPs has played a central role in the management of South African fisheries since the early 1990s (Punt 1992; Butterworth *et al.* 1997; Cochrane *et al*. 1998, Geromont *et al*. 1999; Rademeyer 2003; Johnston and Butterworth 2005). Amongst others, the three major South African fisheries, namely hake (consisting of the deep-water *Merluccius paradoxus* and shallow-water *M. capensis*), sardine and anchovy (*Sardinops sagax* and *Engraulis encrasicolus*) and West Coast rock lobster (*Jasus lalandii*) are all managed using this approach, making South Africa one of the world leaders in putting this process into practice (Plagányi *et al*. 2007).

This Chapter describes the MP approach, and some of its advantages, as well as some of the processes needed to implement it successfully. A glossary of the terminology that has developed in the field is provided earlier in this thesis.

2.2 What is a Management Procedure?

There are many contributions providing details of the MP approach/MSE (e.g. Butterworth and Punt 1999; Smith *et al*. 1999, Kell *et al*. 2006, De Oliveira *et al*. 2008; Holland 2010), but briefly it is defined as the simulation-testing of a set of rules used to specify exactly how the regulatory mechanism (e.g., a TAC or allowable fishing effort) is to be computed each year. In applications such as in South Africa, the IWC and CCSBT, the data, the methods for analysing the data as well as the control rule are pre-agreed and pre-specified (Butterworth *et al.* 1997). Simulation testing is used to ensure that the extent to which a MP is robust to uncertainty is known. Figure 2.1 provides a schematic representation of the approach. In the development of a MP, the expected performance (for both the resource and the industry using the resource) of alternative combinations of monitoring data, analytical procedures, and control rules are evaluated in order to provide advice on management measures that are robust to inherent uncertainties in all inputs and assumptions used (Cooke 1999). Unlike traditional assessment (which typically includes only constant catch or effort projections), the decision framework incorporates the future data into the decision process, and hence the simulation system includes dynamic feedback. This feedback control mechanism adjusts (at least to some extent) for unavoidable errors in current perception of resource status due to uncertainties (Butterworth 2007).

The implementation of a MP approach requires the development a set of Operating Models (OMs) that simulate alternative plausible scenarios for the "true" dynamics of the resource and generate "data" that are used by the MP. This contrasts with the traditional approach of basing management recommendations on a "best" assessment of the resource at the time. Although an OM is analogous to an assessment model, in the MP approach the emphasis is on realistically representing current uncertainty (in stock status, stock recruitment curves, natural mortality or stock structure for example) and future stochastic variability in dynamic processes and errors in the data observed (De

Oliveira *et al*. 2008). Section 3.2 in the next Chapter provides more details on the construction of OMs.

The MP itself does not necessarily incorporate a fairly complex assessment process; MPs can be model-based (with the model details specified and not subject to annual changes, and where the models themselves may be relatively simple) or empirical (see Sections 3.3.1 and 3.3.2 for further discussion). In model-based MPs, typically the current abundance of the resource, estimated by applying some assessment procedure to the available data, is input to a control rule to provide the TAC recommendation. In empirical MPs, resource monitoring data are entered directly into the control rule. Model-based procedures tend to show less inter-annual variability in TAC levels than empirical data-based procedures (Butterworth and Punt 1999) as they incorporate a more developed form of feedback control, with the model parameters automatically adjusted each year as further data become available. However, in South Africa at least, the recent trend has been for empirical procedures to be preferred, primarily because of their simplicity, which enhances the transparency and saleability of the MP (Butterworth 2008). Since limiting TAC variability is of particular importance to the industry, annual TAC variability is then generally constrained in the interest of enhanced socio-economic stability by imposing limits on the extent of interannual TAC changes.

The simulated performance of each candidate MP is evaluated and compared in terms of the projected risks and rewards, as different candidate MPs (CMPs) will involve differing trade-offs (Cochrane *et al*. 1998). Performance is generally assessed in terms of the conflicting objectives of high average annual catch, low risk of unintended depletion and low inter-annual variability in catches (Punt 1993). Higher average catch is associated with higher biological risk, while for the same level of biological risk, higher average catches are associated with more catch variability from year to year. It is for the decision-makers to select their preferred risk/reward trade-off. Butterworth (2008) notes that the process of specifying objectives is usually an iterative one, and that as computations develop, and key trade-offs are identified and quantified, decision makers can become fully aware of the constraints within which they are limited to operate, and hence become able to quantify their objectives meaningfully.

2.3 Advantages of the approach

The advantages of the MP approach to management are potentially considerable. An MP could be put in place, unrevised, over a number of years, considerably reducing the time spent otherwise on agreeing to annual "best" assessments as the basis for annual TAC recommendations, as these are often based on complex models and can involve lengthy debates and bureaucratic processes (Geromont *et al*. 1999). Furthermore, the MP approach provides a transparent and objective basis for setting TACs; the rules are understood and agreed by all as part of the "management game". This enhances credibility between fishery scientists and members of the industry, and renders the demarcation between scientific and policy responsibilities clearer: the anticipated performance of different candidate MPs is calculated by the scientists, while the managers select one of the procedures based on their preferred risk/reward trade-off, and the TAC is then calculated automatically over the next few years (Butterworth *et al*. 1997). The longer-term objectives of the MP approach are also consistent with the inability to sensibly evaluate risk in fisheries management for short-term actions (Cochrane *et al*. 1998).

This longer-term approach of the MP, combined with the results from the simulated projections, also gives the industry a better basis for future planning, both in the short- and the longer-term (Butterworth *et al*. 1997). Finally, one of the greatest advantages of the MP approach is that it emphasizes the development of decision rules that are robust (i.e. likely to perform reasonably well under a broad range of situations and avoid catastrophe in the most pessimistic scenarios), rather than decision rules which may be "optimal" but then only given a particular resource assessment.

2.4 Adopting a Protocol

A MP should be agreed upon by all involved parties (scientists, industry, managers, conservationists) and put into place for a number of years (typically 3 to 5 years), after which it could be revised as necessary (Cochrane *et al*. 1997). Between these regular MP reviews, baseline assessments of the resource are run, typically on an annual basis to check that the circumstances as then estimated are not outside the range for which the MP was designed. Butterworth (2008) stresses that the agreement of a Protocol is a necessary and important component of successful MP implementation. This Protocol should include:

i. a precise description of the data to be used as input to the control rule, the quality of the data and its availability, as well as how these data should be analysed;
ii. a mathematical description of the control rule, and
iii. clear specifications of the defaults to apply in the special circumstances ("Exceptional Circumstances", EC) under which the recommendation provided by a MP might be changed or the regular review of the MP brought forward. EC are described below.

2.4.1 Exceptional Circumstances

A MP is intended to be used on a routine basis to provide scientific management advice, subject to regular reviews. However, occasionally 'Exceptional Circumstances' can arise which may indicate the need for recommendations to deviate from the outputs from such MPs, or necessitate bringing the regular review forward. These circumstances should be clearly specified to avoid the very tinkering with recommendations that the MP approach is intended to avoid (Butterworth 2008). An example of such a document is given in Appendix 5.II for the hake OMP-2007. The primary criterion to call for "Exceptional Circumstances" would be if, during annual baseline assessment, the resource is estimated to have moved outside the range over which earlier simulation testing had shown the MP to be robust.

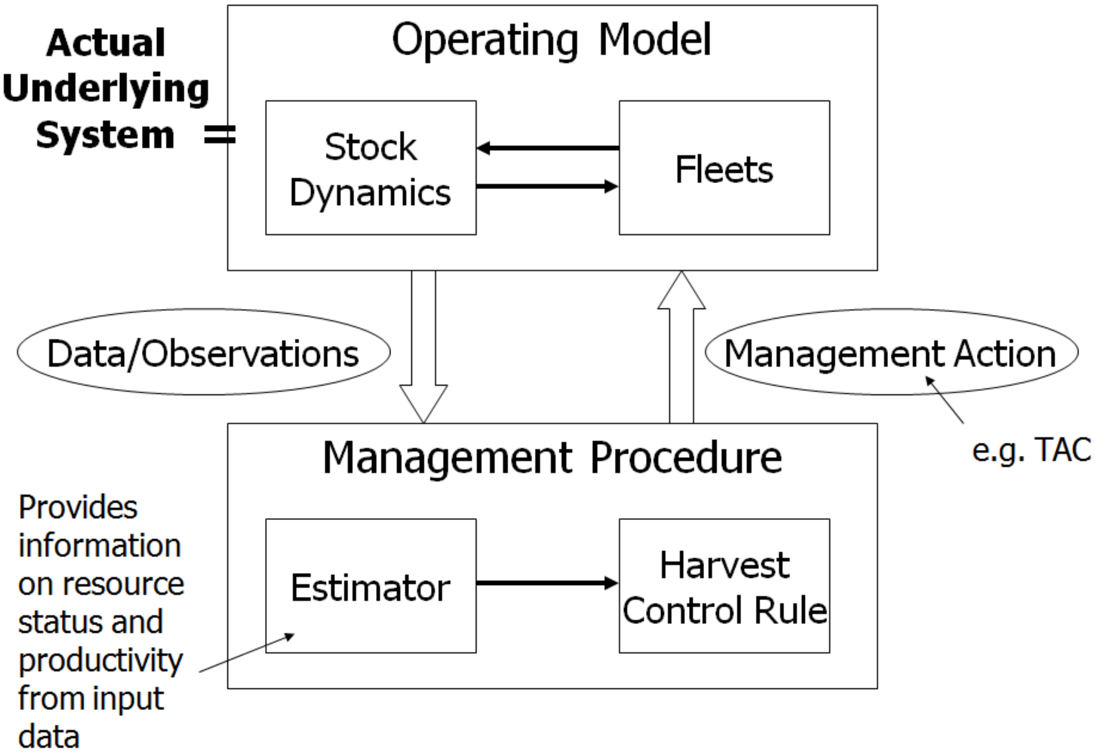

Figure 2.1: A schematic representation of the Management Procedure approach. In contrast to model-based MPs, in empirical MPs the estimator component of the MP falls away, with monitoring data input directly to the Harvest Control Rule.

Chapter 3

Tips and tricks in designing Management Procedures

Summary

Management procedures (MPs) are becoming widely used in fisheries management, but guidelines to assist in their construction, evaluation, and implementation are few. Simple guidelines are provided by drawing on experience from developing and applying MPs in southern Africa and internationally. Suggestions are made on how to choose amongst candidate MPs and on key trade-offs in selecting between data-based (empirical) and model-based formulations. Assistance is also provided in dealing with different sources of uncertainty, such as deciding which operating models should be included in a reference set used for primary simulation testing and tuning (in contrast to robustness or sensitivity tests), and on how some form of weights for the associated alternative hypotheses are most practically assigned. Finally, some guidelines are given for presenting the results effectively, which is one of the key challenges of a successful implementation process.

3.1 Introduction

Management procedures (MPs) (Butterworth and Punt 1999) and similar frameworks such as management strategy evaluation (MSE) (Smith *et al*. 1999) are becoming more widely used in fishery management because they provide formalizations of long term, robust strategies that are designed to satisfy multiple conflicting objectives. However, there are few guidelines available to assist in their construction, evaluation, implementation and presentation. Here practical guidelines are provided for new developers by drawing on experience in southern Africa (Plagányi *et al*. 2007) and internationally.

MPs involve assessing the consequences of alternative options for management actions for both the target resource(s) and associated fisheries. Simulation trials ensure that the associated decision rules lead to performance that is robust to uncertainties about the dynamics of the resource being managed. The simulation framework essentially consists of an operating model (OM) to simulate the "true" system of resource dynamics and fishery and generate future resource-monitoring data typical of what would become available in practice, an estimator that provides information on resource status and productivity from these data, and a harvest control rule (HCR) that outputs a management action in the form of a total allowable catch (TAC) or allowable fishing effort (Kell *et al*. 2006). Key steps in designing MPs are described below, with suggestions for selecting the best option at each step.

3.2 Constructing OMs

The first step in assessing the consequences of different management options is to model several possible scenarios for the underlying true dynamics of the resource population(s) of interest and the impact of exploitation. These OMs are used as the basis to compute how the resource responds to different future levels of catch or effort. Typical population dynamics models include age structure, growth, natural mortality, and a stock–recruitment relationship with associated variability, but they may also include associated species or even the entire ecosystem (Smith *et al*. 2007). The models are fit to data just as in a typical stock assessment process (Geromont *et al*. 1999; Rademeyer 2003; De Oliveira and Butterworth 2004). Robustness to alternative models needs to extend only to those consistent with available data. This fitting process is also termed conditioning the OM to the information available (Butterworth 1999; IWC 2005).

The reason a range of OMs is required is that various uncertainties, which are always present in any assessment of the status and productivity of a resource, can affect the consequences of management measures. These uncertainties relate not only to the fit of the model to the data (i.e. uncertainty in the parameter values within a single model structure), but also to specification of the model structure (i.e. uncertainty about the processes operating in the real world, Butterworth and Punt 1999).

In the initial phase of evaluating candidate MPs (CMPs), typically a single OM may be selected as a reference case. However, experience suggests that usually it is desirable to select a core set of OMs, termed the reference set (Rademeyer and Butterworth 2006a), which includes the most important uncertainties, i.e. alternative scenarios that are both highly plausible and have major impacts on results. For example, in the 2006 development of an MP for the South African hake resource, which is described in Chapter 5, three key aspects of the assessment account for most of the uncertainty regarding resource status and productivity. The reference set was constructed by incorporating variations around these three aspects: (i) two (age-dependent) upper bounds for natural mortality; (ii) three assumptions about the species split in pre-1978 catches (surveys provide information on species composition thereafter); and (iii) four upper bounds for the steepness parameter of two stock recruitment functions. The reference set therefore consisted of 24 components.

Generally, one should always ensure that the final choice of OMs in the reference set covers a sufficiently representative range of potential estimates of current population status and productivity (Cooke 1999). The most uncertain parameters in terms of population productivity tend to be the steepness parameter of the recruitment relationship and natural mortality. OMs, therefore, should cover the full range of plausible values for these parameters. In applications to whale populations, alternative hypotheses about population structure generally score high for inclusion in the reference set (IWC 2000, Section 10; IWC 2004a; Danielsdottir *et al*. 2006). Debates in South Africa (e.g. BCLME 2006b) indicate that such considerations may become more important in future revisions of MPs for South African hake as well as sardine (*Sardinops sagax*) and anchovy (*Engraulis encrasicolus*) fisheries.

Once a sufficiently promising reference set has been agreed, a wider range of robustness-test scenarios needs to be identified (Cooke 1999). Such scenarios reflect the true dynamics that may vary more widely and be less plausible or have less impact than those included in the reference set. The types of robustness tests may differ among fisheries, but as a guideline, experience suggests that they could include different hypotheses on:

- *past data*: bias in survey estimates of absolute abundance (IWC 2003), undetected trends in catch efficiency affecting catch per unit effort (CPUE) (Rademeyer 2003), or errors in catch statistics (Punt and Smith 1999);
- *future availability of data*: the consequences of anticipated resource-monitoring data not becoming available (Geromont and Butterworth 1998a);
- *resource dynamics*: different forms of the stock–recruitment relationship (Punt and Smith 1999) and incorporation of spatial structure and/or species interactions;
- *the environment*: changes in productivity/recruitment levels (Johnston and Butterworth 2005) or carrying capacity (Rademeyer 2003);
- *dynamics of the fishery*: changes in selectivity-at-age.

Currently, few ecosystem models can be applied reliably in a management context, and so are able to serve as OMs to take account of the ecosystem effects of fishing. As a first step, proxies may be included in robustness tests to mimic ecosystem effects (such as time-dependent changes in natural mortality and/or carrying capacity to reflect an increased abundance of an important predator).

Because of time constraints, a practical suggestion is to perform initial evaluations of alternative CMPs only for those robustness tests yielding the results which differ most from those of the reference case/set (Butterworth and Punt 1999). For example, in the 2006 revision of the MP for the South African hake fishery, the resource was projected forward under a constant catch for a fixed period for each of 28 different robustness tests initially identified (Rademeyer and Butterworth 2006b). After comparing performance statistics, it was agreed to discontinue tests for a subset that provided results very similar to those of the reference set. However, before the ultimate MP is selected, a final check is desirable to confirm that this MP indeed performs robustly across the full set of robustness scenarios.

In principle, the performance of each CMP should be integrated over all possible scenarios considered, with relative weights assigned to the output statistics, to account formally for the relative likelihoods of the hypotheses postulated (Butterworth *et al*. 1996; McAllister and Kirchner 2002). These relative weights may prove important in evaluating the results of CMPs because they can affect the balance in choosing the appropriate trade-off between higher catches and lower risk of unintended depletion of the resource.

Such integration is helpful because a consistent evaluation of the results for individual tests is an onerous and difficult task. Overall performance statistics across the entire set of trials aid managers in making the final selection among candidates. By giving plausibility weights to all trials, their performance statistics can be ranked simply (of course, this requires that OMs are sufficiently similar; e.g. performance statistics for OMs ranging across different numbers of populations (stocks) would be difficult to combine meaningfully). However, integrated statistics may obscure differences in expected performance between MPs by "hiding" low plausibility tests in the tails of distributions where they receive little attention. If performance deteriorates appreciably under specific scenarios for some MPs, this should be brought to the attention of decision-makers before they make their choice.

To assign weights to all tests, formal methods (such as likelihood-based or Bayesian methods) can rarely be used. One practical approach that has been used to reach agreement on numerical weights is a Delphi-like method in which committee members independently table their initial suggestions, and consensus is then sought through subsequent debate (CCSBT 2003; Johnston and Butterworth 2005). IWC (2004b) has opted for a high, medium, and low plausibility classification rather than a numerical weighting, discarding the low-plausibility trials and assigning a risk standard that is lower for medium- than for high plausibility trials.

3.3 Defining a CMP

3.3.1 Empirical *vs* model-based MPs

The estimator is the population-model-based framework within which the data obtained from the fishery are analysed and the current status and productivity of the resource is assessed. Related outputs are then fed into the HCR to provide a recommendation for management action. The combination of estimator and HCR provides the feedback mechanism within the MP. Assume that the management action refers to the setting of TAC. If the monitoring data derived from the OM turn out to indicate a stock status that is worse than that predicted the previous year, the new assessment coupled to the HCR will recommend a lower TAC (and *vice versa*). Hence, the

MP is able to self-correct over time, even if some assumptions made in developing a "best assessment" (typically corresponding to the OM given most weight) were wrong (Butterworth and Punt 1999).

An MP of this estimator-plus-HCR type incorporates estimation of the status of the resource through the use of some population model and hence is referred to as model-based. The model may be an age-structured population model or an age-aggregated production model (e.g. Fox 1970) fitted to relative or absolute abundance data (IWC 1994; Geromont *et al*. 1999). Examples of HCRs that convert outputs from the estimator into a recommended management action are constant fishing mortality/effort approaches (Kell *et al*. 2006). More conservative approaches reduce catch to zero if abundance is estimated to drop below some threshold, as, for example, in the revised MP (RMP) for baleen whales (IWC 1994).

In contrast, MPs can also be constructed, which are "model-free" (data-based, empirical) and which provide TAC recommendations directly (rather than through a two-stage model-based process), for example, through appropriate feedback in the form of recent upward or downward trends in abundance indices. HCRs for both model-based and empirical MPs typically include several free "control" parameters that can be adjusted to tune their performances to achieve the desired balance among performance statistics over the range of scenarios simulated.

3.3.2 Which approach to select?

Model-free approaches are typically simple to develop and easily understood by stakeholders (such as the industry). Moreover, they require relatively little computer power for testing (because no iterative minimization routines are required for fitting models to data), and consequently allow for many simulations to be performed quickly (McAllister *et al*. 1999). This approach has been used for the interim MP developed by Butterworth and Geromont (2001) for the Namibian hake resource, whose aim was to provide TAC recommendations that would perform well (in terms of catch and risk of resource depletion) across the wide range of possible levels of status of the resource which were argued in the mid-1990s. The inputs were measures of the recent trend (relative change over five years) in survey and CPUE abundance indices. The first MP developed for the

South African West Coast rock lobster was also empirical (Johnston 1998). However, with the longer time-series of CPUE and survey data available in 2000, the MP for that species was able to move to a model-based approach that allowed more data to be considered, and hence produced reduced variance (Johnston and Butterworth 2005).

McAllister *et al*. (1999) suggest that the performance of model-free estimators may not prove entirely satisfactory in the long term, particularly if there are large uncertainties about bias and variance in the abundance index used. However, such estimates can provide good results if abundance estimates are in absolute numbers or biomasses, and if associated errors are small. An MP developed for Namibian seals was based directly on triennial aerial counts of pup production, providing estimates with relatively small coefficients of variation (CVs) (Butterworth *et al*. 1998).

Although the empirical approach may move a resource in the desired direction (such as reversing a declining trend in an overexploited population), it has the disadvantage (if it is based on the values of trends in resource indices) that information on the level at which resource abundance will eventually equilibrate is lacking. Therefore, if the management objective is to drive resource abundance to a level at which it provides MSY (MSYL), one can never be sure whether an empirical MP might stabilize abundance below MSYL (so forfeiting higher CPUE) or above MSYL (so sacrificing potential catches).

Although empirical MPs have the advantage of simplicity, population-model-based approaches tend to perform better, for instance, in terms of less interannual variability in TACs (Butterworth and Punt 1999; Punt and Smith 1999). This outcome can be explained by the tendency of empirical approaches to estimate short-term trends, considering only data for the most recent years; in contrast, population-model-based MPs reflect the behaviour of the resource over much longer periods, and hence exhibit less variability in forecasts.

Importantly, the objective in choosing a particular model for use as an estimator in an MP is not to achieve a high degree of realism, but rather to ensure, in combination with a suitable HCR, good management performance (Cooke 1999). Estimators based on simple population models have often been shown to perform as well or better than those based on more complex ones (Punt 1993; Punt and Smith 1999). Comparing MP performances based on an age-aggregated production model and on an *ad hoc* tuned Virtual Population

Analysis (VPA) for the South African West Coast hake resource, Punt (1993) showed that the former performed better, although it lacked the realism of the underlying dynamics of the OM. The latter MP tended to follow noise rather than signal, resulting in an increased interannual variation in TACs without this being compensated by any gains in other performance statistics.

Sometimes, however, more complex estimators prove necessary. For example, for species where year-class strength is important, a model accounting for age structure may be required (Cooke 1999). Rademeyer (2003) developed an MP for the Namibian hake resource in which the estimator was an age-structured production model of the same structural form as used for the OM. However, only two parameters (the pre-exploitation spawning biomass and the steepness parameter of the stock–recruitment relationship) were estimated annually in the simulation tests, whereas natural mortality, selectivity parameters and variance, in addition to the sampling CV in survey estimates of abundance and historical stock–recruitment residuals, were all fixed, so would not always equate to those used in the OM in any particular trial. Certain parameter values were fixed not only to avoid the high variance that may result from multi-parameter estimation in the face of limited data, but also to keep computing time within reasonable bounds. In this instance, a problem also arose with multimodality of the likelihood functions associated with an age-aggregated production-model approach.

In summary, experience suggests that it is useful to investigate the performance of both types of approach, at least in the early phase of the development process, but to use simplicity as a guiding principle in making the final choice(s). A helpful diagnostic is whether the estimators (or, typically, the trend lines estimated for derivative-based empirical approaches) provide reasonable fits to the simulated data—if not, more complexity is usually required. A further guideline (if the CMPs allow) is to experiment first with generating noise-free future data: if a CMP does not perform reasonably for “perfect” data, it certainly should not be retained for further testing against more realistic situations where the data are noisy.

3.3.3 Other aspects

The form of the MP to be tested determines the input data required. Their nature, quantity and statistical properties have to be specified clearly (Cooke 1999). Typical future data assumed to be available as input are indices of absolute and relative abundance (e.g. CPUE from the fishery and biomass estimates from fishery-independent surveys, possibly by age or size group). In simulated projections, the variances used to generate future data are typically set to those estimated from the fits of the model to past data. Changes in estimates of resource status and productivity, and hence in future TACs, may follow from these future data.

Further constraints may be applied to the initial output from the MP, such as limitations on the maximum permissible change in TAC from one year to the next (Geromont *et al*. 1999; Kell *et al*. 2006), in the interests of greater industry stability. Inputs from industry are desirable to guide the selection of such control parameter values.

3.4 Evaluating CMPs

The performance of each CMP has to be evaluated through simulation over a range of scenarios. This is achieved by projecting the biomass forward under the prescribed HCR for a period defined by the longevity of the resource (typically 10–20 years for fish, but longer for long-lived resources with slow dynamics, such as whales). The performance is then assessed by inspecting the values of a set of performance statistics developed to measure the different management objectives predefined by decision makers. The candidate providing the best trade-off between performances for what are often conflicting objectives is selected as the most appropriate.

For each MP/scenario combination, multiple replicate projections (typically 100 or more) have to be run to account for stochastic effects, particularly those resulting from observation errors and process errors (Butterworth and Punt 1999; Cooke 1999). To this end, random noise is generated when simulating future data and process effects, such as variations about stock–recruitment relationships. Typically, coefficients of variation will be set to values estimated from historical data.

3.4.1 Performance statistics

The objective of many fishery management policies is to balance three conflicting objectives: high annual catches, low risk of unintended depletion, and maximum industrial stability (Punt 1993). Social objectives, such as fairness and equity in resource allocation among users, might also be considered. The performance statistics used in the evaluation have to be specified in relation to these first three objectives (at least):

- *catch-related*: an obvious choice is the average catch obtained over the projection period;
- *stability-related*: the average annual variation (AAV) in TAC from one year to the next (usually expressed in proportion terms by averaging absolute values of annual percentage changes) gives an indication of the extent of industrial stability to be anticipated;
- *risk-related*: commonly used statistics include the probability of depleting the (spawning-stock) biomass below some threshold, or the median biomass expected at the end of the simulation period (compared with the biomass at the onset of this period).

In some cases, sufficient reliable information might be available for economic performance measures to be used, such as current net value and number of loss-making years (Holland *et al*. 2005).

3.4.2 Communication of results

Performance statistics should be chosen to relate readily to the fishery, so that they are meaningful to managers and stakeholders (Francis and Shotton 1997). South African experience is that statistics supplementary to those indicated above may be helpful, including projected CPUE because this provides the industry with a simple proxy for economic performance.

When testing a particular CMP, once stochastic effects and model uncertainty across the reference set have been taken into account, the resulting outputs constitute distributions arising from alternative realizations. Results are frequently reported in the form of the medians and 95% quantiles of these distributions. However, tabulations of such statistics can be voluminous and difficult to interpret, even for scientists with experience in this area, so the form of plot shown in Figure 3.1 has become widely used to summarize such results conveniently. The example shown compares different CMPs for a single trial, but this format is also useful for comparing the performances of the same MP across several trials. It is always useful, as a reality check, to include the results for a zero catch and for a constant-catch or constant-effort strategy for comparison: CMPs warranting consideration should always perform better than these in terms of all objectives except variation in catch or effort. Plots of some individual trajectories of projected catch or biomass ("worm plots") are usually easier for stakeholders to understand than numerical statistics, and combining the two types of information in a single plot (Figure 3.2) may lead to better insight into the extent of the variability to be expected.

The primary purpose of computing performance measures is to permit stakeholders (and particularly the decision-makers, who have the responsibility for selecting the appropriate trade-offs) to compare the different MP algorithms and their variants (Cooke 1999). The challenge then is to summarize a large amount of information in a way as brief, meaningful and stakeholder-friendly as possible. Even so, the choice may prove difficult, with many performance statistics to compare across many trials. The best way to undertake this process is case-dependent, but South African experience is that a straightforward procedure is to select a few of the most important performance statistics (weighted across the scenarios comprising the reference set) and to use these in the comparison. The associated robustness trials then play the role of "tick tests": to check (after an initial choice of MP has been made) that this chosen MP does not result in an unacceptably large drop in performance for any of these trials (while taking account of their relative plausibilities). The approach of insisting that a minimum-risk standard be met for every trial (the so-called worst-case scenario management) is not recommended, because it fails to take due account of anticipated trade-offs with performance on meeting other objectives or of the relative plausibilities of different trials.

3.5 Summary

The steps necessary in developing an MP are shown in Figure 3.3. The following guidelines are suggested for the simulation-testing process:

- If uncertainties in the resource assessment are large, the construction of a reference set of OMs is preferable to the use of a single reference case OM. CMPs are then tuned to secure the desired trade-offs. Work should focus first on developing CMPs that perform satisfactorily for the reference set.
- Initial evaluations of CMPs should focus on robustness tests for OMs which, demonstrate the widest difference in resource behaviour from the reference set.
- The basis for selecting the final MP among CMPs has to be clear to all stakeholders and should be made as simple as can be justified. A useful approach is to focus on a few key performance statistics whose results are combined over all OMs included in a reference set, after appropriate weighting by their relative plausibilities.
- It is always useful to compare performances for both empirical and model-based MPs, but the latter, when based on an age-aggregated population model, often proves a prudent choice.
- The performance statistics chosen to aid a selection among CMPs need to be meaningful to all stakeholders, and careful thought needs to be given on how best to present these to permit easy comparison.

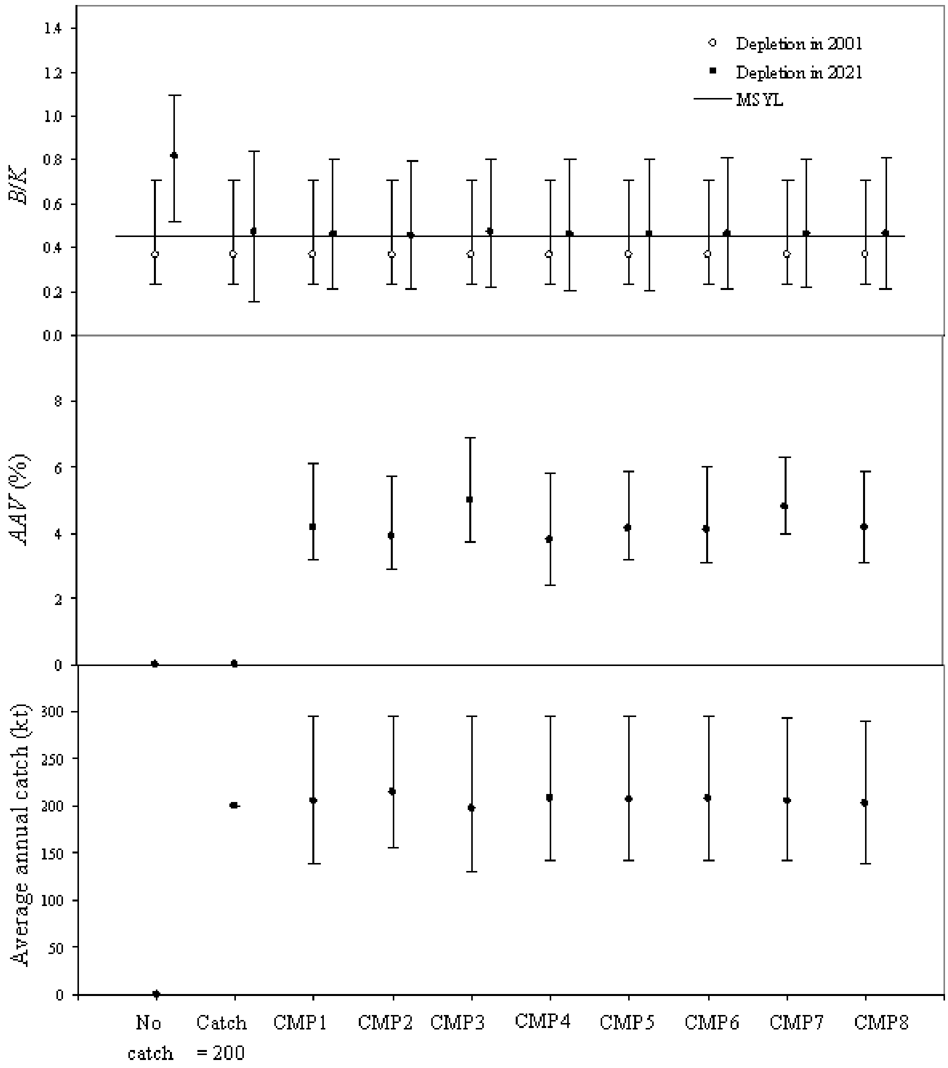

Figure 3.1. An example (in this case, for Namibian hake; from Rademeyer 2003) of a widely used form of graphical summarization of the values of performance statistics for comparing across CMPs (in this case eight, CMP8 being the final choice; a no catch and a constant catch of 200 000 tons option are also included in the comparison): (a) initial (2001) and projected final (2021) depletion (*B*/*K*; *B*, simulated biomass; *K*, virgin biomass) and level of biomass providing MSY (MSYL); (b) AAV in catch; (c) average annual catch. Bars show the 90% probability intervals.

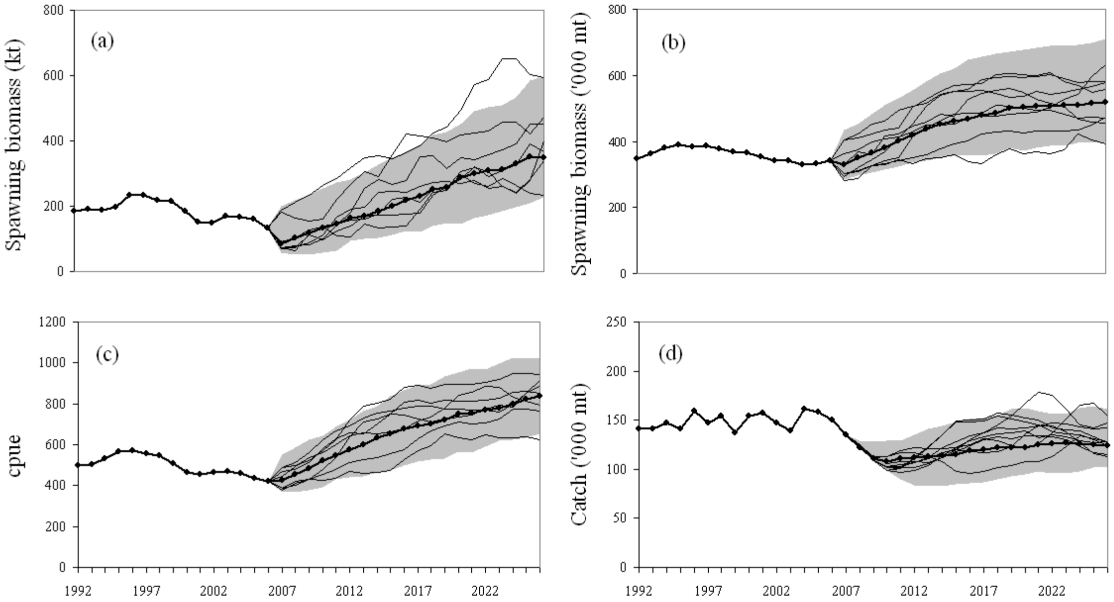

Figure 3.2. “Worm plots” showing ten possible trajectories of spawning biomass for the two hake species off South Africa: (a) *M. paradoxus* and (b) *M. capensis*; (c) offshore trawler CPUE for species combined (proxied by exploitable biomass); and (d) total catch for one CMP and the reference set of OMs (from Rademeyer and Butterworth 2006a). Annual medians (connected dots) and 90% probability envelopes (shaded) are also indicated.

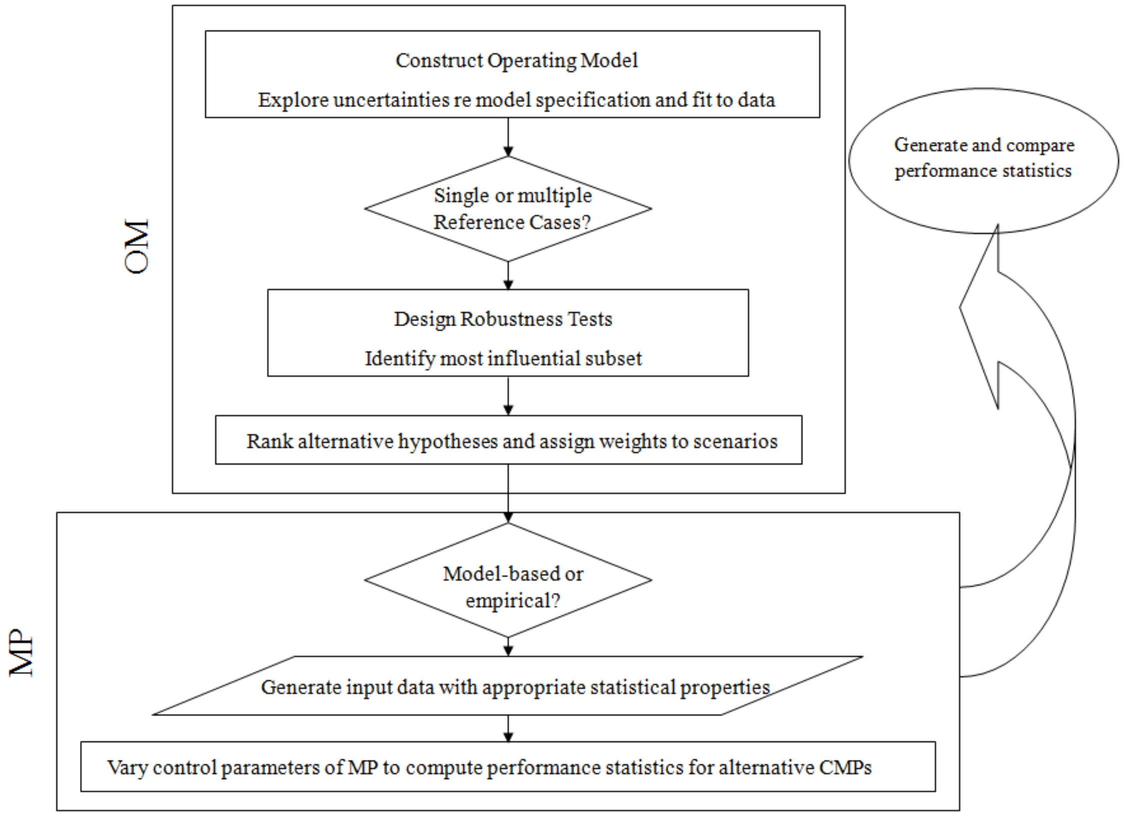

Figure 3.3. Flowchart to guide the MP development process.

SECTION II

Managing South African hake using OMP-2007

Chapter 4

Assessment of the South African hake resource taking its two-species nature into account

Summary

The commercially valuable hake fishery off South Africa consists of two morphologically similar species, the shallow-water Cape hake *Merluccius capensis* and the deep-water Cape hake *M. paradoxus*. Because catch-and effort statistics collected from the fishery are not species-disaggregated, quantitative assessment analyses prior to the turn of the century had treated the two hake species as one, but approaches to incorporate species disaggregation had been initiated. Furthermore, various sources of evidence closely examined in the early 2000's suggested that (although treated as two separate populations in past assessments) the South and West coasts components of each species formed single stocks. This Chapter describes the development of the first fully species-disaggregated coast-wide baseline assessment of the South African hake resource. *M. paradoxus* is estimated to be at <10% of its pre-exploitation level in 2006, whereas *M. capensis* is estimated to be well above its maximum sustainable yield level. By taking the primary sources of uncertainty in this assessment into consideration, a Reference Set of 24 operating models is developed to be used in Operational Management Procedure testing.

4.1 Introduction

Two species of hake inhabit the waters off South Africa, the shallow-water Cape hake *Merluccius capensis* and the deep-water Cape hake *M. paradoxus*. The demersal trawl fishery off South Africa developed before the turn of the 19th century, originally targeting mainly Agulhas sole *Austroglossus pectoralis*, with hake landed essentially as an incidental catch. Trawlers started making larger annual catches (of about one thousand tons) of hake only after the First World War. Thereafter, catches increased steadily, peaking in the early 1970s when they approached 300 thousand tons per year (see Figure 4.1). With the introduction of a 200 nmi Exclusive Economic Zone (EEZ) in 1977 and the resulting decreased foreign activity, annual catches fell substantially to the 120–150 thousand tons range. Annual catches have remained relatively stable since, averaging approximately 150 thousand tons over 1995-2005.

Hake currently provides the basis for the most important fishing industry in South Africa in terms of both revenue and local employment. The fishery has four sectors (differentiated by species focus, geographical area, gear and vessel size): the offshore trawl and the longline fleets operate on both the South and West coasts, whereas the inshore trawl and the handline fleet operate on the South Coast only. Over the period 2001–2005, the offshore and inshore trawl, longline and handline fleets accounted for approximately 85%, 6.5%, 6.5% and 2% respectively of the total catch. The two species are morphologically very similar and the landed (processed) product cannot be easily identified to species. On-board observer coverage which would allow the splitting of the catches by species did not take place before 2002. From July 2002, only intermittent coverage occurred, which was insufficient to split the catches to species reliably and, the annual commercial catches are therefore not available by species.

Figure 4.2 shows the distribution of the two species, and the boundary between West and South coasts adopted for analysis purposes. There is the possibility that the populations of both species (*M. paradoxus* in particular, Burmeister 2005) are shared with Namibia, but the evidence is not conclusive (BCLME 2006b). This paper follows past practice of assessing the South African populations separately from the Namibian populations, with the boundary between the two countries' EEZs providing the dividing line.

Catch-and-effort statistics collected from the fishery are not species-disaggregated and as a result the assessment methods applied until the mid-1990s treated the two hake species as one (Punt 1994). Furthermore, the resource was then assumed to consist of two separate populations on the West and South coasts. The justification for aggregating the two species of hake in this way was based upon simulation studies by Punt (1993), which suggested that managing two such stocks as if they were a single one was not problematic, provided that the species composition and the age-selectivity pattern of the fishery remain unchanged. The development of a longline fishery for hake in the 1990s, proportionately greater on the South Coast and targeting principally the shallow-water hake *M. capensis*, brought about the need to modify this practice. The assessments of the hake resource were therefore subsequently split into a West Coast, species-combined component (the longline fleet taking only a relatively small proportion of the total hake catch off the West Coast, so that a species-disaggregated assessment was not seen as an immediate priority there) and a South Coast *M. capensis* component (Geromont *et al.* 1999). An attempted separate assessment of *M. paradoxus* on the South Coast did not yield sensible results; this was attributed to these fish likely being a component of the West Coast *M. paradoxus* stock (Geromont and Butterworth 1999). Similarly, evidence from research surveys (such as the relatively low proportions of two- to three-year-old *M. capensis* in South Coast surveys, see Tables App.4.II.11 and 4.II.12) suggested that the *M. capensis* found on the two coasts must be more closely related than previously thought (Le Clus 2005).

Therefore, the development of two-population models (coast-combined but species-disaggregated) for assessment purposes was considered necessary. However, to be able to take account of historical resource monitoring data that apply to both species combined, these models are fitted to the available monitoring data within a unified framework. Other studies for which data for multiple stocks have similarly been fitted simultaneously include the New Zealand hoki *Macruronus novaezelandiae* assessment (Francis 2008) and the assessment of school shark *Galeorhinus galeus* in Australia (Punt *et al.* 2000).

This Chapter describes the development of the first such fully species-disaggregated assessment of the South African hake resource. It focuses on providing detailed results for a baseline assessment which provided the core Operating Model (OM) around which this Reference Set was developed. It updates and refines earlier hake assessment results reported in Rademeyer (2003) and Rademeyer and Butterworth (2005). This species-disaggregated, coast-combined assessment is the first step in the development of an Operational Management Procedure (OMP) for this resource (see Chapter 5). A core set of OMs, termed the Reference Set (RS), which includes the major uncertainties, should ideally be used for the initial phase of testing of Candidate Management Procedures (CMPs) (see Chapter 5). The scenarios included should be both highly plausible and have major impacts on the results. A wider range of scenarios that are either less plausible or that have less impact on the results are generally also included, as 'robustness tests', in the MP testing process. Sensitivities to some of the uncertainty factors considered in the RS are also reported.

4.2 Data

The data used for this 2006 assessment come primarily from three sources:

1. annual catch data prior to 1955 from Chalmers (1976);
2. annual catch and catch per unit effort (CPUE) data from 1955 to 1977 from the International Commission for South East Atlantic Fisheries (ICSEAF 1989); and
3. remaining data from Marine and Coastal Management (MCM), South Africa (R Leslie and J Glazer, unpublished data).

It should be noted that the ICSEAF data do not relate to exactly the boundaries shown in Figure 4.2 but for the West and South coasts to the closely related ICSEAF Divisions 1.6 and 2.1+2.2, for which the corresponding boundaries were 30° S and 20° E.

All the data utilised in this study are documented in Appendix 4.II.

4.2.1 Annual catches

The species split of the catches that is needed for an assessment that distinguishes the two species is carried out external to the model. A summary of the assumptions made to disaggregate the catches by species for the baseline assessment is given below. The reported or assumed catches by fleet and species are given in Tables App.4.II.1–4.II.4.

4.2.1.1 Offshore trawl fleet

From 1978 onwards, the catches made by the offshore trawl fleet have been split by species by applying the size-based species proportion-by-depth relationships for the

West and South coasts (summarised in Appendix 4.I), which were developed by Gaylard and Bergh (2004) from research survey data. They assumed logistic functions to describe the proportion of *M. capensis* found at various depths. Separate algorithms were developed for the West and South coasts; these include not only depth but also the size of hake, year (in the West Coast algorithm only) and longshore position as determinants of the respective proportions of *M. capensis* and *M. paradoxus* in the hake catches. The use of the commercially reported size categories of small, medium and large (the only data available at this level) presents some problems due to differences in the definitions of these categories among fishing companies and over time, and some *ad hoc* assumptions (e.g. the use of a median size-categories classification for all companies) need to be made, as detailed in Gaylard and Bergh (2004).

Prior to 1978, there is no depth information recorded for the landings so that the proportion of *M. capensis* caught cannot be estimated using the method above. The catch data for the period 1917–1977 are split by assuming that the proportion of *M. capensis* caught follows a logistic function over this period, starting at 1 and then decreasing to stabilise at the 1978–1982 average value. Because trawling was concentrated in inshore areas around Cape Town and to the east when the fishery began (i.e. probably catching *M. capensis* exclusively) and progressively moved offshore, this seems a defensible approach. To reflect a change centred on year P_1 the changing proportion with year y of *M. capensis* in the offshore trawl catch on coast c is modelled by:

$$prop_{cy}^{prop} = \frac{1-\Delta_c}{1+\exp\left[\left(y-P_1\right)/P_2\right]} + \Delta_c \qquad (4.1)$$

where

Δ_c is the average proportion of *M. capensis* in the offshore catch over the period 1978–1982 for coast c (24% and 60% for the West and South coasts respectively), and

P_1, P_2 are parameters of the logistic function; P_1 is the year in which the proportion of *M. capensis* in the catch is midway between 100% and Δ_c, while P_2 determines how rapidly this change in proportion occurs.

For reasons that are discussed later, the baseline assessment assumes: P_1 = 1950 and P_2 = 1.5.

4.2.1.2 Longline fleet

Longline catches on the West Coast are assumed to consist of 30% *M. capensis* for the whole period, whereas on the South Coast, catches by this fleet are assumed to consist of *M. capensis* exclusively (A Penney, pers. commn).

Although there is some uncertainty about the catches and species split for the longline and handline fisheries, they account for <10% of the total catch; hence this uncertainty would not have any appreciable consequence for assessment results.

4.2.1.3 Inshore trawl and handline fleets

Catches made by these fleets are assumed to consist of *M. capensis* only, because they operate in relatively shallow-water on the South Coast.

4.2.2 Abundance indices

Four CPUE time-series are available for assessing the status of the resource (Table App.4.II.5): a CPUE series for each of the South and West coasts developed by the International Commission for South East Atlantic Fisheries (ICSEAF 1989) and a GLM-standardised (coasts combined) CPUE series for each of *M. paradoxus* and *M. capensis* (Table App.4.II.5) from the offshore trawl fleet (Glazer 2006). The two historical CPUE series cannot be disaggregated by species, because there are no effort-by-depth data available for this pre-1978 period. The GLM-standardised CPUE indices are species specific (the catch data being based on the algorithm outlined in Appendix 4.I).

Research surveys have been conducted on board the *FRS Africana* from 1986 in spring and/or autumn on the South Coast and from 1985 in summer and/or winter on the West Coast, and provide fully species-specific information. In 2000 and 2001, the *RV Dr Fridtjof Nansen* substituted for the West Coast summer surveys, because of technical problems with the *FRS Africana*. Resultant swept-area estimates of abundance are treated as a separate series because of the unknown calibration factor between the catchabilities for the two vessels. Since 2003, new fishing gear has occasionally been used on the *Africana*, for which a calibration factor is available (Appendix 4.III). Survey biomass estimates and their estimated (sampling) standard errors are listed in Tables App.4.II.6–4.II.7. Only surveys extending to the deepest depth (500 m) normally included in the survey design are considered for reasons of comparability.

4.2.3 Catches-at-age

Species-disaggregated survey catch-at-age data, based on species-disaggregated length frequency and species-specific age–length keys, are shown in Tables App.4.II.8–4.II.12. The annual age–length keys are based on the count of annual growth rings in otoliths, with individual fish selected for ageing based on a random stratified sampling design (Leslie 1998).

Length frequency information from the commercial catch is not available by species, because it is often based on cleaned (headed and gutted) fish, which cannot be easily identified to species. As a result, it is not possible to disaggregate the commercial catches-at-age by species. A species-aggregated annual age–length key has been developed and applied to the length distribution data for the two species combined to obtain the species-aggregated catches-at-age (Leslie 1998). Commercial catches-at-age for the offshore (both coasts combined) and for the inshore and longline (South Coast only) fleets are shown in Tables App.4.II.13–4.II.15. The South Coast inshore and longline fleet catches are assumed to consist of *M. capensis* only.

4.3 Methodology for the Baseline Assessment

The model used in the assessment of the coast-wide South African *M. paradoxus* and *M. capensis* hake stocks is a fleet-disaggregated Age-Structured Production Model (ASPM). When the data fitted by an ASPM include catch-at-age information, this approach is equivalent to Statistical Catch-at-Age Analysis (SCAA) (e.g. Fournier and Archibald 1982, Deriso *et al.* 1985). The model involves assessing the two species as two independent stocks. It is fitted to species-disaggregated data as well as species-combined data. A method is developed to relate the pre-1978 CPUE series for the two species combined to their underlying abundances. The general specifications and equations of the overall model are set out in Appendix 4.III, followed by details of the contributions to the log-likelihood function from the different data considered, though some key choices in the implementation of the methodology are set out below. The parameters that are estimated in the maximum likelihood fit of the baseline assessment are listed in Appendix 4.III. Quasi-Newton minimisation is used to minimise the total negative log-likelihood function (implemented using AD Model Builder(Fournier *et al.* 2011)).

4.3.1 Natural mortality

Natural mortality for both species is estimated in the fitting procedure, with the form of age dependence assumed shown in Equation App.4.III.31. However, upper bounds of 1.0 and 0.5 on ages 2 and 5 respectively are implemented in the baseline assessment to maintain biological realism (likelihood maximisation prefers higher values for large ages in many cases, but this seems unlikely given there are few known predators of large hake). The natural mortalities estimated for the plus-groups into which the data are aggregated (5+ and 7+ for *M. paradoxus* and *M. capensis* respectively) are assumed to apply to older ages including the 15+ age group in the model.

4.3.2 Fishing selectivity

The selectivity patterns characterising each of the four fleets all take the form of logistic curves (Equation App.4.III.33). Periods of fixed and changing selectivity have been assumed for the offshore trawl fleet to take account of the change in the selectivity at low ages over time in the commercial catches (note the decrease in the one- and two-year old proportions in these catches over time evident in Table App.4.II.13), likely due to the phasing out of the (illegal) use of netliners to enhance catch rates. The offshore trawl fleet selectivity for *M. paradoxus*, as well as the inshore trawl and handline fleet selectivities for *M. capensis*, are assumed to decrease exponentially for older ages (Equation App.4.III.34). This exponential decrease, whose magnitude is estimated in the likelihood maximisation, is assumed to continue to age 15. For the other combinations of fleet and species, the selectivity is assumed to be flat at older ages.

The survey selectivities are estimated directly for ages 1–5 for *M. paradoxus* and 1–7 for *M. capensis*. An exponential decrease in selectivity is assumed from age 5 for *M.*

paradoxus and from age 7 for *M. capensis* with the slope parameters of these exponentials fixed at 0.5 y^{-1} and 1.0 y^{-1} respectively (see Appendix 4.III for details).

4.3.3 Steepness of the stock-recruitment curve

A Beverton-Holt form is assumed, as has been past practice for earlier assessments. In the baseline assessment, steepness for both species, which is estimated in the likelihood maximisation, is restricted so that it does not exceed 0.95; thus recruitment starts falling towards zero as spawning biomass is reduced and before this biomass reaches zero.

4.3.4 Stock-recruitment residuals

The stock-recruitment residuals are estimated for years 1985–2006, with recruitment for other years being set deterministically (i.e. exactly as given by the estimated stock-recruitment curve) as there is insufficient catch-at-age information to allow reliable residual estimation for earlier years. Because of the recent change in gear on the *Africana*, and consequently a possible change in selectivity of the surveys, one cannot be entirely confident that a recent strong recruitment signal in the catch-at-age data is quantitatively reliable. For this reason, a limit on the recent recruitment fluctuations is set by having the σ_R (which measures the extent of variability in recruitment — see Equation App.4.III.30) decreasing linearly from 0.25 in 2001 to 0.1 in 2006, effectively forcing recruitment over the last years to lie closer to the stock-recruitment relationship curve.

4.4 Results for the Baseline Assessment

Estimates of management quantities for the baseline assessment are listed in Table 4.1, and Figure 4.3 plots the corresponding spawning biomass trajectories. The results are given (where appropriate) for each species in turn and for both species combined. The reason for the species combined plots is that, given uncertainties about the historic species split of the catches, some scientists regard them as providing more reliable indications of the overall status of the resource. Table 4.2 shows the relative contributions of each data source to the total negative log-likelihood. Figures 4.4 and 4.5 show fits to the CPUE and survey biomass series (the two longest time-series only) for the baseline assessment — the fits are reasonable for all indices. The standardised residuals for the commercial and survey catch-at-age proportions are shown in Figures 4.6 and 4.7. The model tends to overestimate the proportion of zero-year-olds in all surveys pre-1999 for both *M. capensis* and *M. paradoxus*. After this period, the model tends to underestimate this proportion, particularly for *M. capensis* on the West Coast. The standardised stock recruitment residuals for each species are plotted in Figure 4.8. The estimated *M. paradoxus* and *M. capensis* fishing selectivities for the commercial fleet and the research surveys are shown in Figure 4.9.

4.5 Primary Uncertainties in the Baseline Assessment

CMPs should be robust to a range of uncertainties. To test this, the DWG considered scenarios including different hypotheses about the following aspects of the assessment:

1. the level of discarding;
2. the splitting of the past catches into species;
3. other uncertainties concerning past catches, such as the inclusion of small unreported catches from the South Coast inshore trawl fleet and changes in the handline catches;
4. natural mortality;
5. the shape of the stock-recruitment curve, as well as the extent of variability about this curve;
6. age at maturity and spawning effectiveness at age;
7. past changes in carrying capacity;
8. the current level of depletion (expressed in terms of spawning biomass B^{sp}_{2006}/K^{sp}) for both species; and
9. the calibration factor between the *Africana* with old and new gear.

A number of other tests of sensitivity to some technical specifications of the baseline assessment were carried out. These included use of an age <15 for the plus-groups and alternative selectivity assumptions for the longline fishery. These were found not to impact estimates of important management-related quantities appreciably, and so were not considered further. From the list above, three aspects were found to account for most of the uncertainty regarding the key considerations of resource status and productivity: (a) the natural mortality of each species, (b) the species split in the pre-1978 catches, and (c) the steepness parameter of the stock-recruitment functions. It is essential that the full range of plausible values for these parameters be covered so that the RS includes a sufficiently representative range of potential estimates of current population status and productivity. The DWG decided that the RS therefore include the following variations:

M — Natural mortality

M1: upper bounds of 0.5 and 0.3 on ages 2 and 5 respectively are implemented; and

M2: upper bounds of 1.0 and 0.5 on ages 2 and 5 respectively are implemented.

The upper bounds were imposed to avoid the unrealistically high estimates that arose if such bounds were not enforced. Values forced lower than 0.3 on age 5 lead to severe deterioration in the value of the log-likelihood, arising particularly from poorer fits the to CPUE series and to the commercial catch-at-age data. Diet studies show that predation by both hake species on hake of age 2 is fairly substantial (Punt and Leslie 1995).

C — Species catch split

The logistic function used to split the pre-1978 offshore commercial catches by species has the parameter values:

C1: P_1 = 1950 and P_2 = 1.5;

C2: P_1 = 1940 and P_2 = 1.5;

C3: P_1 = 1957 and P_2 = 1.5.

Unsurprisingly the estimated status of *M. capensis* in 2006 is sensitive to variations of the centre of the ogives, though this has much less impact on estimates for *M. paradoxus*. A wider range was initially considered, with the centre of the ogive taken to be as recent as 1970. However, those scenarios reflected a 2006 spawning biomass ratio for *M. capensis* compared with *M. paradoxus* of between 6:1 and 8:1, results that were deemed implausible by the DWG (Figure 4.10). The figure also shows that varying the slope of the ogive (parameter P2) has little impact on the results. The *M. capensis* proportions for the three variants selected are plotted in Figure 4.11.

H — Steepness parameter

H1: the steepness parameters (*h*) for both *M. capensis* and *M. paradoxus* are estimated in the minimisation process;

H2: for *M. paradoxus*, *h* is fixed at 0.8, whereas this parameter is estimated for *M. capensis*;

H3: for *M. capensis*, *h* is fixed at 0.7, whereas this parameter is estimated for *M. paradoxus*; and

H4: for *M. paradoxus*, *h* is fixed at 0.8 and for *M. capensis*, *h* is fixed at 0.7.

Scenarios H2–H4 are included because estimates of steepness for both species tend to be rather high. This can be a concern when a low level of spawning biomass for the most recent years of the assessment is estimated, for which taking expected recruitment to remain unchanged might be dangerously inappropriate. The fixed values selected for *h* move the estimated values in the direction of the generally accepted 0.7–0.8 range (Myers *et al.* 2002). Greater modifications than considered here lead to appreciable deterioration in the log-likelihoods. The values of 0.8 for *M. paradoxus* and 0.7 for *M. capensis* were chosen so that the decrease in log-likelihood in the H2 and H3 scenarios compared with the H1 scenario would be in the same range (approximately five log-likelihood points).

4.6 Results for the Reference Set

The overall median and range of estimates of management quantities for the RS are shown in Table 4.3, and Figure 4.12 plots the corresponding spawning biomass trajectories, again focusing on the median, maximum and minimum values for each year. Figure 4.13 shows stock recruitment relationships, both for the baseline assessment and for a component of the RS that forces the steepness values for both resources lower (i.e. includes the H4 variant).

4.7 Discussion

Broad historical trends in estimated resource status across the RS are very similar to those of the baseline assessment. The *M. paradoxus* resource shows a substantial decline from the late 1940s to the mid-1970s to <20% of its pristine level, increases slightly for two decades but then decreases again over the last decade (Figures 4.3, 4.12). The *M. capensis* resource shows qualitatively similar trends, but the initial drop in spawning biomass (to about 30% of pristine level) is not as substantial as in the case of *M. paradoxus*, and this resource also shows some recovery over the 1980s and 1990s. Whereas *M. paradoxus* is estimated to be well below MSYL in 2006 (in median terms, below 10% of its pre-exploitation level), *M. capensis* is estimated to be above MSYL and near 50% of its pre-exploitation level. The median MSYL values are relatively low (0.22 and 0.28 for *M. paradoxus* and *M. capensis* respectively) because of the generally high values for steepness h (see Table 4.3).

The estimated status for *M. paradoxus* being considerably worse than for *M. capensis* is not attributable to any single factor. However, an important insight is provided by consideration of the cumulative catch of each species since the inception of the fishery in 1917. The cumulative catch of *M. paradoxus* is estimated to have been approximately double that of *M. capensis*; furthermore, whereas the estimated *M. capensis* catch has been broadly steady at about 50 000 tons since about 1940, that for *M. paradoxus* climbed rapidly to reach some three times that level in the 1960s and early 1970s, during which period most of the depletion of this population occurred. As is the case for the deep-water hake, the shallow-water hake show a decline over the last decade. These key results are quite robust, both in terms of estimation precision (Figure 4.3) and assessment assumptions (Figure 4.12). The primary reason for the decrease in spawning biomass for both species from the mid-1990s is poor recruitment (Figure 4.8). *M. paradoxus* shows particularly poor recruitment in 1996 and 1997, whereas *M. capensis* is characterised by below-average recruitment virtually throughout the 1990s.

Why was this recent decline not detected earlier? Butterworth and Rademeyer (2005), for example, report a clear upward trend estimated for the West Coast hake resource (species-combined) from the mid-1970s to the beginning of the 21st century and a stable South Coast *M. capensis* resource. The primary reason is that the high survey biomass estimates in 1998 and 1999 for *M. paradoxus* in particular were misleading (Figure 4.5), and they were unfortunately followed by two years with no surveys because of technical problems with the *Africana*. Although the *Nansen* carried out surveys on the West Coast in 2000 and 2001, no calibration factor was available and the resulting estimates had to be treated as a separate relative abundance index. A retrospective analysis has been conducted, with some results compared with the baseline assessment in Figure 4.14. For this analysis, the baseline assessment was run with data to 2000 only and then projected forward under the catches that occurred subsequently. As in the baseline assessment, the recruitment variability is decreased for the last few years with data (i.e. here decreased linearly from 0.25 in 1996 to 0.1 in 2000). Figure 4.14 shows that the effect of the 1999 survey results in particular is linked primarily to the recruitment strength determination, though it also related to important changes in biomass projections.

The survey selectivity estimates (Figure 4.9) suggest that there is some movement of hake as they grow. Young (up to age 3) *M. capensis* are primarily restricted to the West Coast. At intermediate ages, a large proportion of these fish move to the South Coast. However, for the oldest fish (ages 6+), there is some movement back to the West Coast. Similarly for *M. paradoxus*, the smaller fish tend to be found more on the West Coast (see Tables App.4.II.8 and 4.II.12; and Inada (1981) for evidence of movement in *merlucciid* fish). Furthermore, survey selectivity is estimated to decrease at older ages (from age 4/5 for *M. paradoxus* and 6/7 for *M. capensis*). Upper bounds on natural mortality have been enforced to avoid unrealistically high estimates, so that the shortage of older fish observed in the catch-at-age data is explained by a decrease in selectivity. The movement of bigger fish to deeper waters and possibly rocky grounds (areas which are not sampled/untrawlable and constitute of 12% and 18% of the overall region fished on the West and South coasts respectively (Leslie and Fairweather 2008)) could explain this low proportion of large fish in the catches. Similarly, the inshore fleet selectivity decreases rapidly for fish of age 6 and older as this fleet operates in relatively shallow-water and therefore does not have access to the large *M. capensis*.

The upper bounds enforced on natural mortality *M* can still be argued to be relatively high for a gadoid. However, although natural mortality rates are often fixed at a value in the range 0.2–0.3 for gadoid assessments, similar values have been used or estimated for species such as the Chilean hake *M. gayi* (0.38–0.44 and 0.24–0.38 estimated for males and females respectively, Cubillos *et al.* 1999) or the US silver hake *M. bilinearis* (fixed 0.4, Helser and Brodziak 1998). The high natural mortality considered for younger fish can be motivated by the large extent of cannibalism (and inter-species predation, Payne *et al.* 1987).

Although the model is coast-combined, it is fitted to the coast-specific survey data. The constants of proportionality, or multiplicative biases q^i, implicitly include a coast component which accounts for the fact that the resources are distributed with different proportions on the South and West coasts. The estimated *q*'s are shown in Table 4.4. Furthermore, coast-specific survey selectivities are used as a basis to reflect differing proportions by age of each species on each coast (Figure 4.4). *A priori*, *q* estimates <1 would be expected to account for the presence of fish outside the survey area concerned. In this regard, estimates >1 for *M. paradoxus* for the West Coast summer surveys may appear surprising. However, the swept-area method used to transform survey results into absolute estimates involves a number of assumptions about herding, escapement and densities in untrawlable areas, which likely vary with one or more of age, species and area, and may bias results.

4.8 Future work

At the time the 2006 assessment was completed, the following issues were seen to have priority for future attention.

The use of the species proportion-by-depth relationship from the surveys to disaggregate the offshore catches post-1978 depends on the extent to which survey data are representative of the commercial fishery. The reliability of the algorithm for splitting the commercial catches among species and over time needs to be tested using the on-board observer data. Towards this end, industry funded an enhanced collection programme that commenced in 2006. Initial comparison of estimated species-disaggregated catches from on-board observer data for November 2005 to May 2006 with that predicted by the Gaylard and Bergh (2004) algorithm suggest that no significant bias exists.

The next step in the assessment process needs to involve explicit spatial disaggregation by distinguishing different areas by depth and longshore coordinates, and estimating age-specific movement rates between these areas. It has also been shown (for example, Punt *et al.* 1992) that the most important form of predation on Cape hakes is inter-specific (hake-on-hake) predation and to a lesser extent cannibalism. For that reason, inter- and intra-specific predation are considered to be very important factors in regulating hake abundance. The models that need to be developed would also attempt to take account of inter- and intra-species consumption of smaller hake by larger hake in computing losses to natural mortality.

Further issues that require consideration in future hake assessment analyses include indications of unrealistically large natural mortality M at older ages (is the ageing incorrect?), accounting for bias in research surveys related to untrawlable proportions of the areas surveyed, possible disaggregation by sex, given sex-specific differences in the longline fishery, and in somatic growth (this might also help resolve the natural mortality problem above), and more detailed allowance for discards. Furthermore, rather than using possibly inappropriate age–length keys (such as the combined species age–length keys), future analyses would attempt to fit to age–length keys and length frequencies as separate data components (e.g. Punt *et al.* 2006). This may also underlie the surprisingly low level of recruitment variability (Figure 4.10) estimated for both species (σ_R = 0.18 for *M. paradoxus* and 0.14 for *M. capensis*), which could reflect the effect of averaging over ageing errors.

Some of these issues have been investigated in subsequent analyses. Very little difference was found in the trends over time between the survey biomass estimates extrapolated to the whole shelf and those to the trawlable areas only (Leslie and Fairweather 2008). The updated assessment described in Chapter 8 is sex-disaggregated and is fitted to length frequencies and age-length keys directly.

Table 4.1: Estimates of management quantities (with Hessian-based CVs in parenthesis) for the baseline assessment of the *M. paradoxus* and *M. capensis* coast-combined resources. MSY and associated quantities are given in relation to the selectivity for the offshore trawl fleet. Biomass units are thousand tons.

	M. paradoxus		*M. capensis*		Species combined	
-lnL total					-196.9	
K^{sp}	1271	(0.09)	620	(0.15)	1891	(0.07)
h	0.95	*	0.95	*	-	-
MSY	117	(0.05)	65	(0.09)	182	(0.04)
B^{sp}_{2006}	88	(0.17)	317	(0.18)	405	(0.15)
B^{sp}_{2006}/K^{sp}	0.07	(0.19)	0.51	(0.14)	0.21	(0.19)
$B^{sp}_{2006}/MSYL^{sp}$	0.35	(0.19)	2.33	(0.19)	0.80	(0.17)
$MSYL^{sp}$	0.20	(0.13)	0.22	(0.23)	0.21	(0.11)
M_2	0.53	(0.31)	1.00	*	-	-
M_5	0.36	(0.10)	0.40	(0.13)	-	-

* constraint boundary

Table 4.2: Relative contribution of each data source to the total negative log- likelihood for the baseline assessment.

	M. paradoxus	*M. capensis*	Species combined
Abundance indices:			
West coast ICSEAF CPUE (1955-1977)			-10.1
South coast ICSEAF CPUE (1969-1977)			-29.5
GLM-standardised CPUE (1978-2005)	-45.7	-44.5	
West coast summer survey	-11.1	-2.0	
West coast winter survey	-4.3	0.6	
West coast *Nansen* survey	-2.0	-1.5	
South coast spring survey	-1.0	-3.3	
South coast autumn survey	6.2	-9.3	
Catch-at-age data:			
West coast offshore commercial			-39.701
West coast summer survey	-45.8	106.6	
West coast winter survey		7.8	
West coast *Nansen* survey	-14.5	-6.0	
South coast spring survey	-8.7	2.8	
South coast autumn survey	28.7	-42.0	
South coast inshore		-26.4	
South coast longline		-15.2	
Recruitment residual penalty:	9.0	3.8	

Table 4.3: Medians, with ranges in parenthesis, of estimates of management quantities for the *M. paradoxus* and *M. capensis* coast-combined resources over 24 OMs in the RS. MSY and associated quantities are given in relation to the selectivity for the offshore fleet. Biomass units are thousand tons.

	M. paradoxus		*M. capensis*		Species combined	
	Median	Range	Median	Range	Median	Range
-lnL total					-189.6	(-197.3; -174.2)
K^{sp}	1509	(893; 2307)	734	(544; 1063)	2217	(1505; 3294)
h	0.87	(0.80; 0.95)	0.82	(0.70; 0.95)	-	
MSY	115	(108; 119)	60	(54; 70)	175	(166; 184)
B^{sp}_{2006}	116	(85; 242)	338	(265; 452)	464	(381; 689)
B^{sp}_{2006}/K^{sp}	0.09	(0.06; 0.13)	0.47	(0.36; 0.54)	0.21	(0.15; 0.31)
$B^{sp}_{2006}/MSYL^{sp}$	0.40	(0.29; 0.56)	1.68	(1.14; 2.45)	0.93	(0.66; 1.32)
$MSYL^{sp}$	0.22	(0.18; 0.24)	0.28	(0.22; 0.33)	0.24	(0.20; 0.27)
M_2	0.51	(0.50; 0.80)	0.75	(0.50; 1.00)	-	
M_5	0.33	(0.30; 0.49)	0.34	(0.30; 0.49)	-	

Table 4.4: Estimates of the constant of proportionality for the West Coast summer and South Coast autumn surveys for the baseline assessment (maximum likelihood estimate with Hessian-based CV in parenthesis) and the Reference Set (median with range in parenthesis).

		M. paradoxus				*M. capensis*			
		Baseline		Reference Set		Baseline		Reference Set	
west coast summer	old gear	1.89	(0.19)	1.91	(1.12; 2.11)	0.50	(0.24)	0.80	(0.39; 1.35)
	new gear	1.79	(0.19)	1.82	(1.07; 2.01)	0.42	(0.24)	0.68	(0.33; 1.14)
south coast autumn	old gear	0.53	(0.07)	0.50	(0.40; 0.56)	0.78	(0.18)	0.84	(0.64; 1.11)
	new gear	0.48	(0.07)	0.45	(0.37; 0.51)	0.59	(0.18)	0.63	(0.48; 0.83)

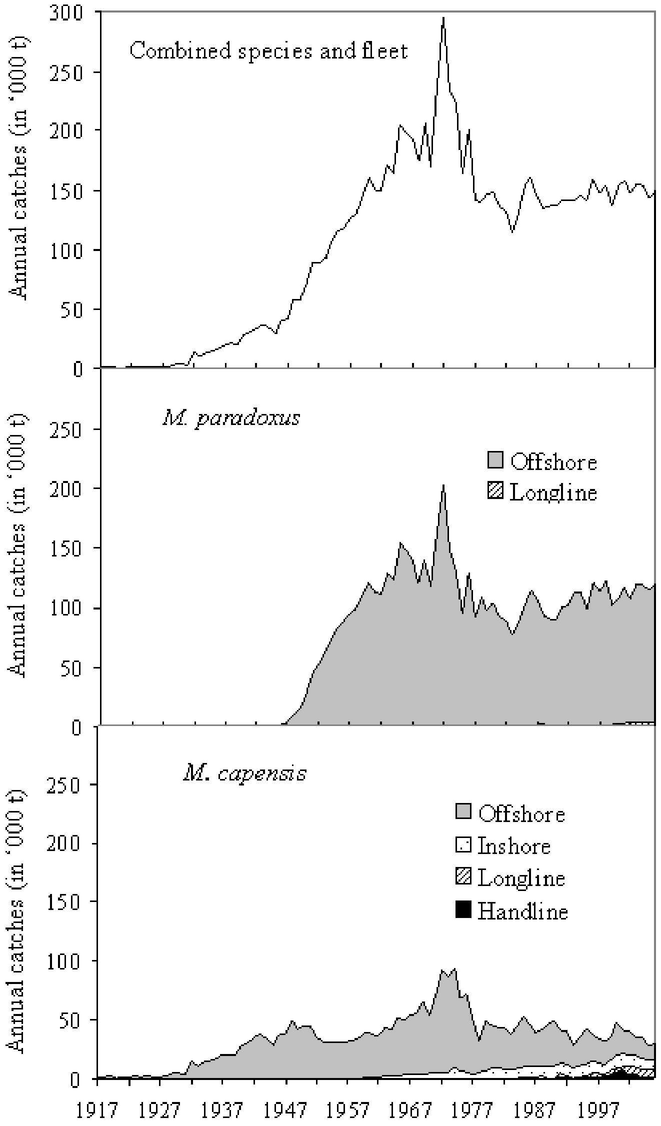

Figure 4.1: Annual catch time-series for South African (West and South Coasts combined, species combined) hake for the period 1917 to 2005. The series of total catches (species and fleet combined) is shown in the top plot, while the middle and bottom plots distinguish the catches by species and fleet for the C1 species catch split variant (see text).

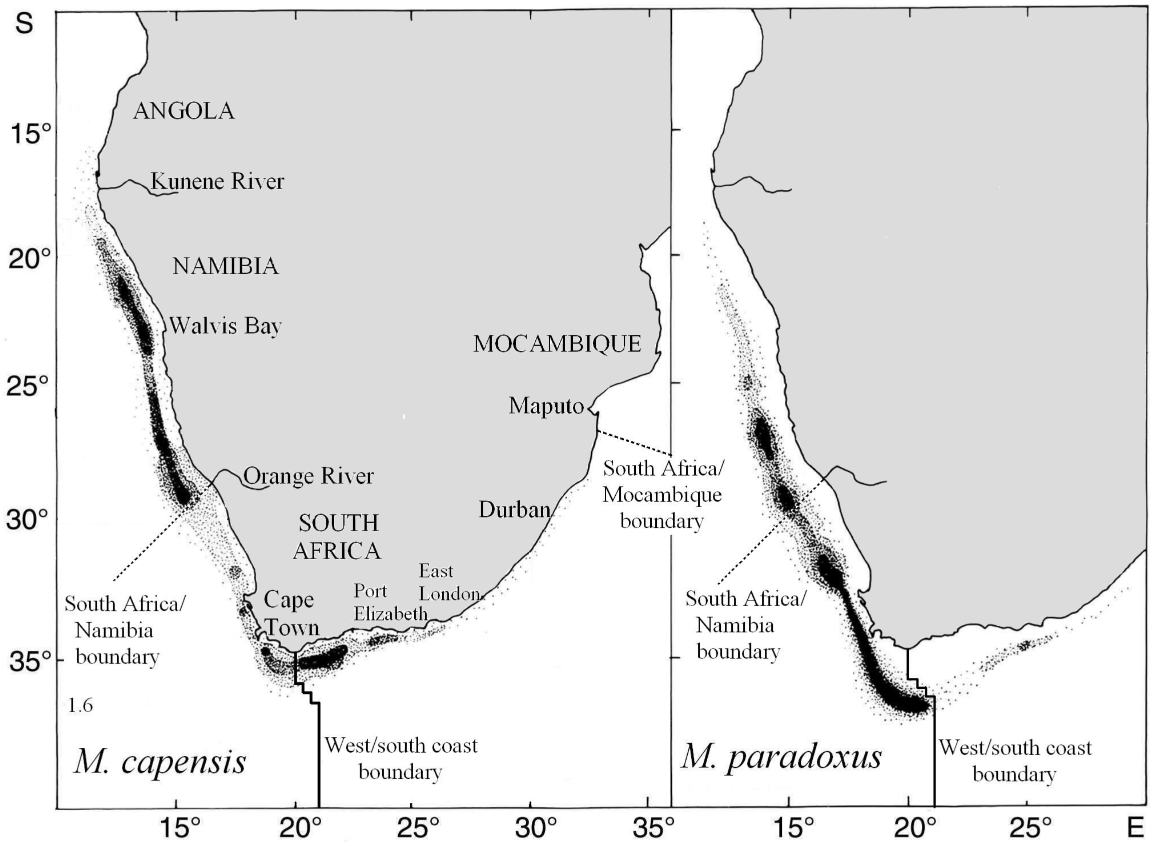

Figure 4.2: Management units and species distribution for southern African hake (adapted from Payne 1989).

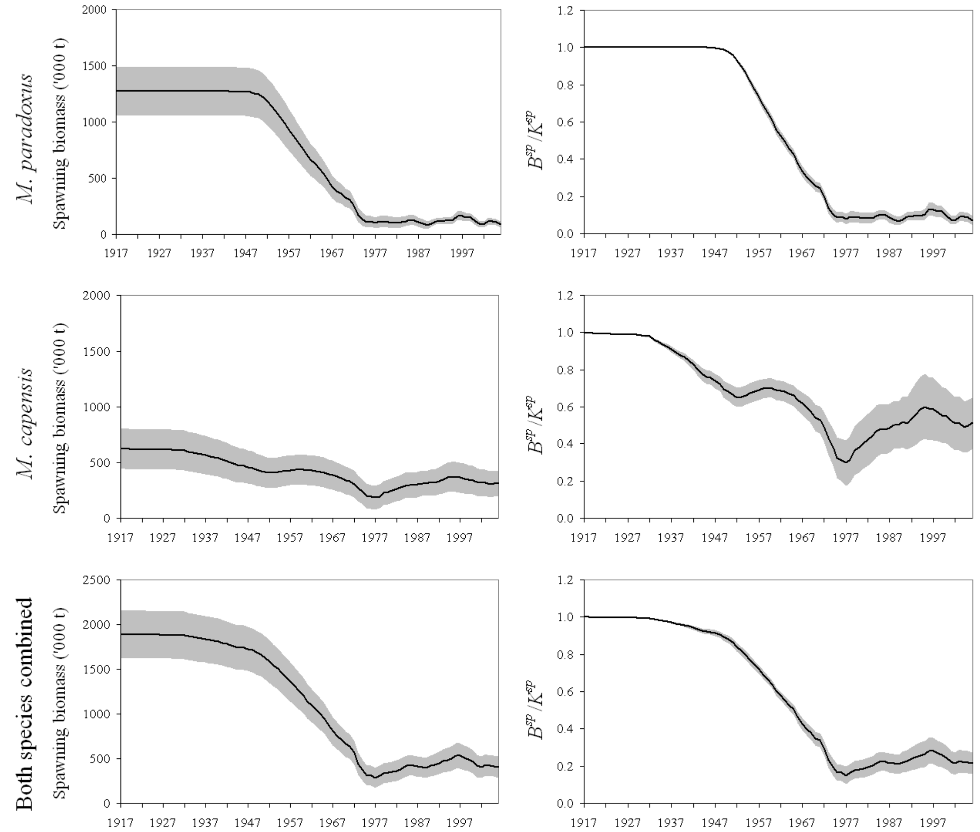

Figure 4.3: Trajectories of spawning biomass (in absolute terms and as a proportion of the pre-exploitation level) for the baseline assessment. The best estimate is indicated by a thick line while the shaded areas represent the associated Hessian-based 90% probability intervals.

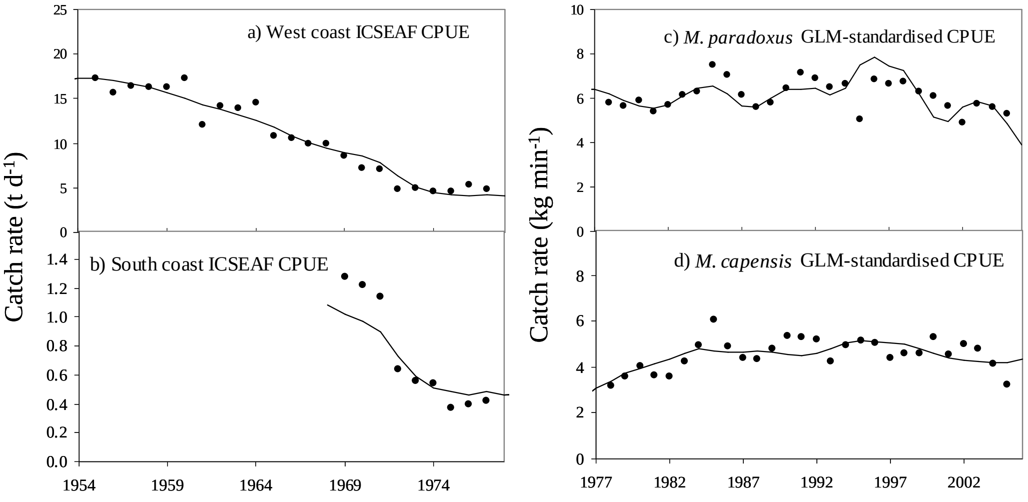

Figure 4.4: Fits to the four CPUE abundance indices for the baseline assessment. The historic (pre-1978) CPUE data [a) and b)] are for both *M. capensis* and *M. paradoxus* combined and are disaggregated by coast while the GLM-standardised CPUE [c) and d)] are disaggregated by species.

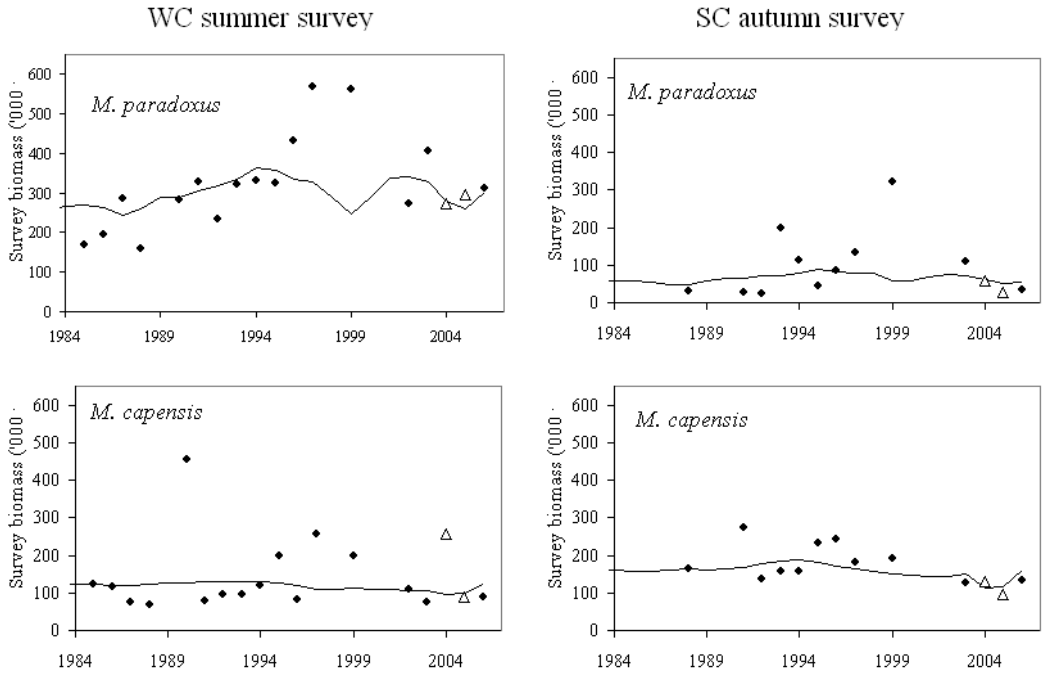

Figure 4.5: Fits to the West Coast summer and South Coast autumn abundance series from surveys by *Africana* (the two longest series) for the baseline assessment. The 2004 and 2005 observed values are shown as Δ, because they were conducted by the *Africana* with the new gear and have been rescaled by the calibration factor (see Appendix 4.III, Section 2.2 for details).

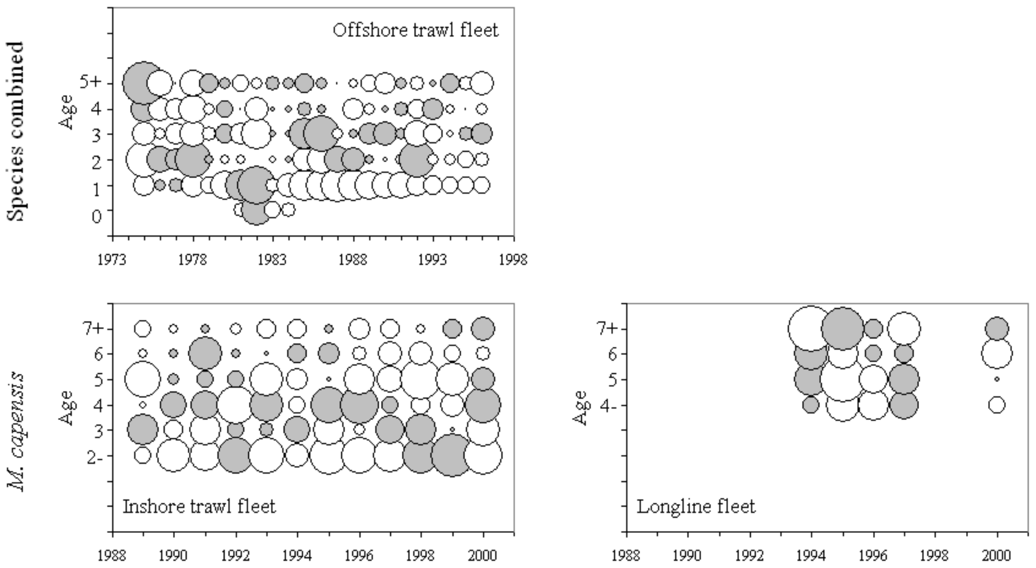

Figure 4.6: Bubble plots of the commercial catches-at-age standardised residuals for the baseline assessment. The size (area) of the bubble is proportional to the magnitude of the corresponding standardised residuals. For positive residuals the bubbles are grey, whereas for negative residuals they are white.

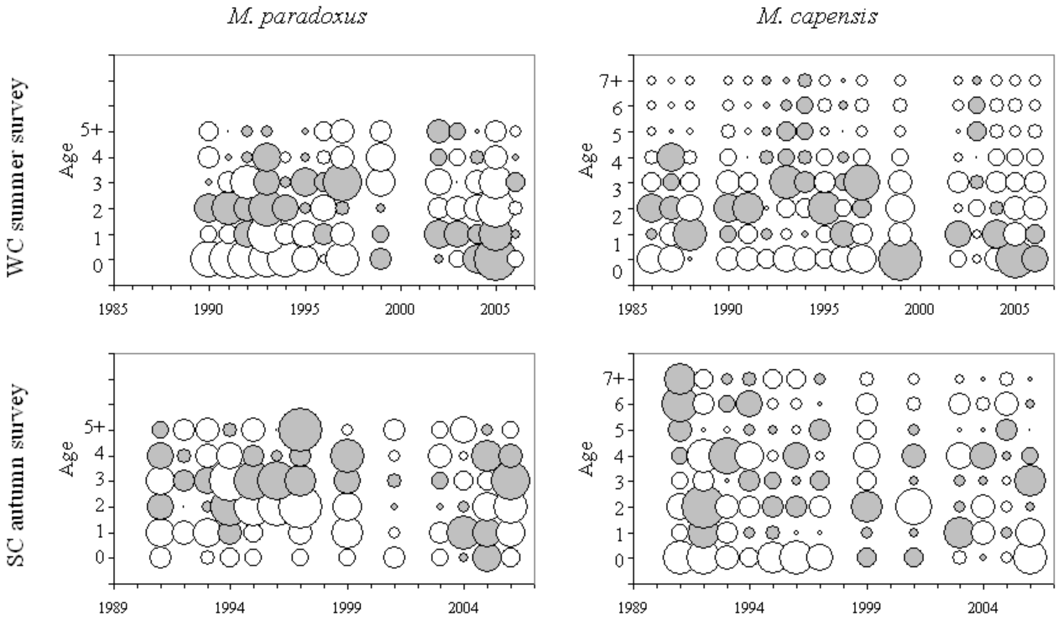

Figure 4.7: Bubble plots of the survey catches-at-age standardised residuals for the baseline assessment. The size (area) of the bubble is proportional to the magnitude of the corresponding standardised residuals. For positive residuals the bubbles are grey, whereas for negative residuals the bubbles are white.

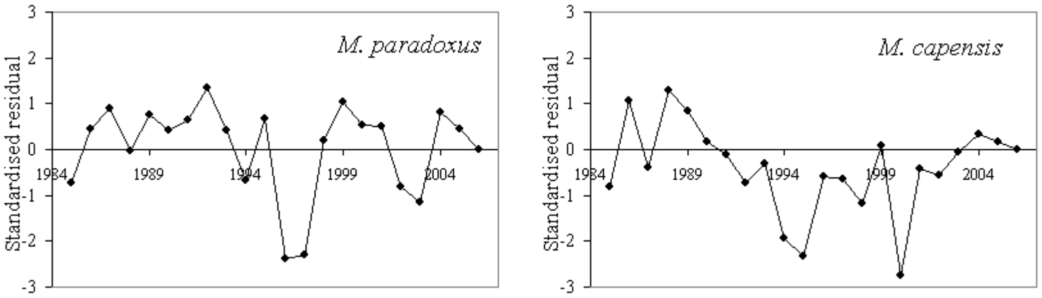

Figure 4.8: Time series of standardised stock-recruitment residuals for the baseline assessment.

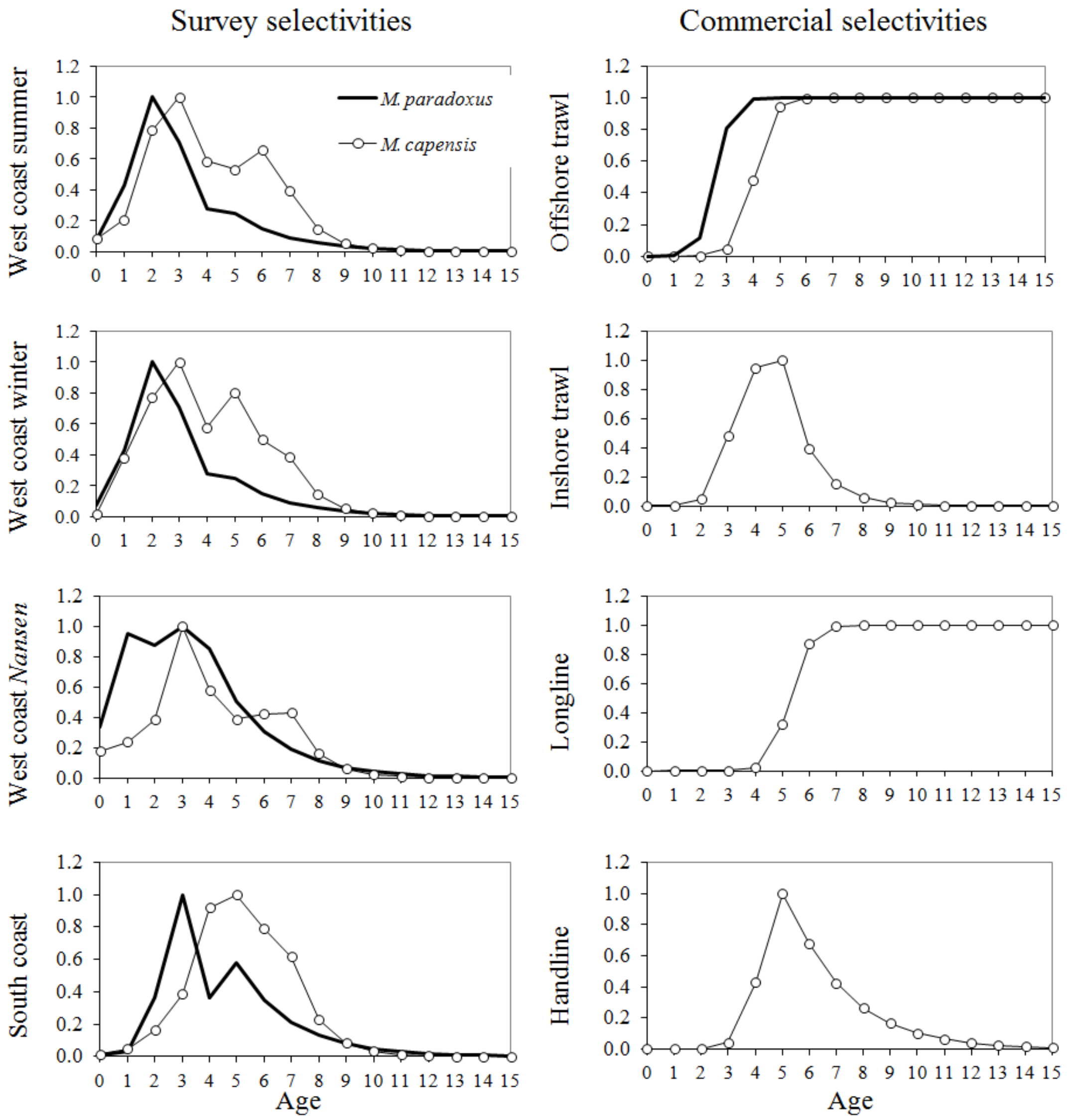

Figure 4.9: Estimated survey and commercial fishing selectivities-at-age for the baseline assessment. The inshore and handline fleet are assumed to catch *M. capensis* exclusively. The selectivity of the longline fleet is assumed to be the same for both species. Except where *Nansen* is indicated, the survey selectivities pertain to the *Africana*.

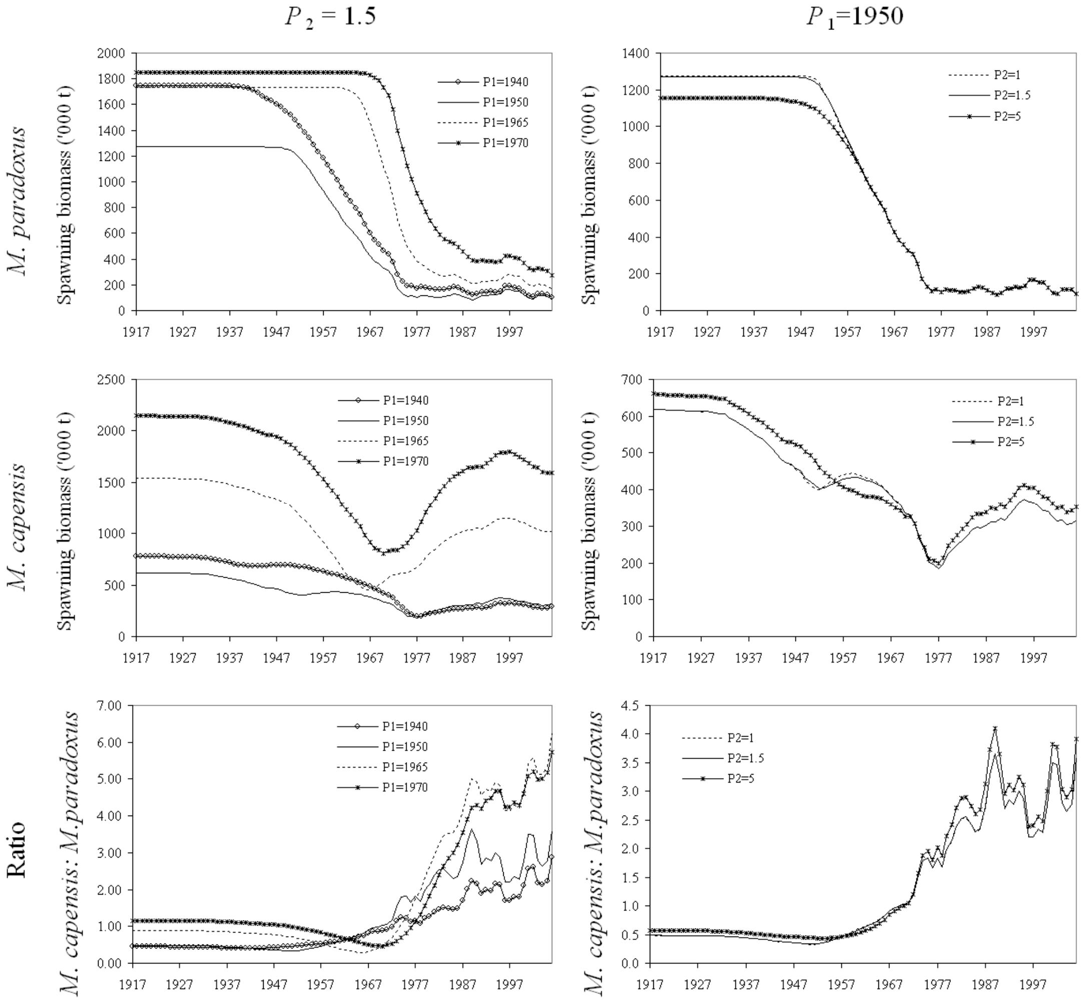

Figure 4.10: *M. paradoxus* and *M. capensis* spawning biomasses trajectories and the resulting species ratios under a series of P_1 (P_2 fixed at 1.5) and P_2 (P_1 fixed at 1950) parameter values for the logistic function used to split the pre-1978 offshore trawl commercial catches by species, with baseline assumptions for other parameters. Note that the baseline assessment assumes catch splitting variant C1 for which P_1=1950 and P_2=1.5.

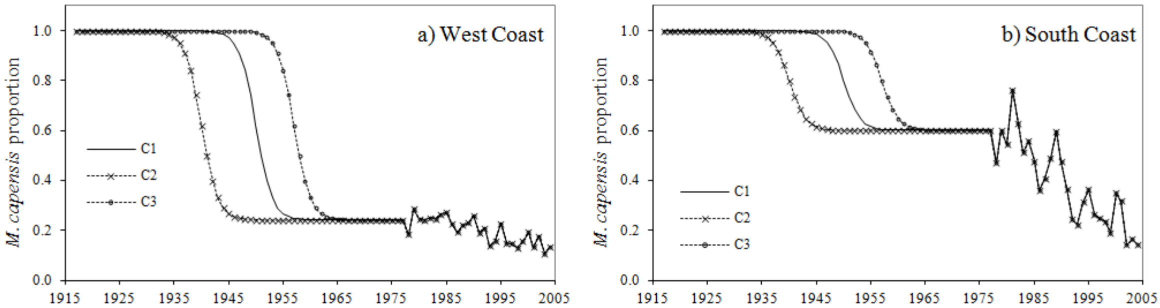

Figure 4.11: Assumed proportion of *M. capensis* in the offshore catches for the West Coast and South Coast for the catch splitting variants C1-C3 (the baseline assessment assumes variant C1). Note that C1, C2 and C3 correspond respectively to P_1=1950, 1940 and 1957 and P_2=1.5.

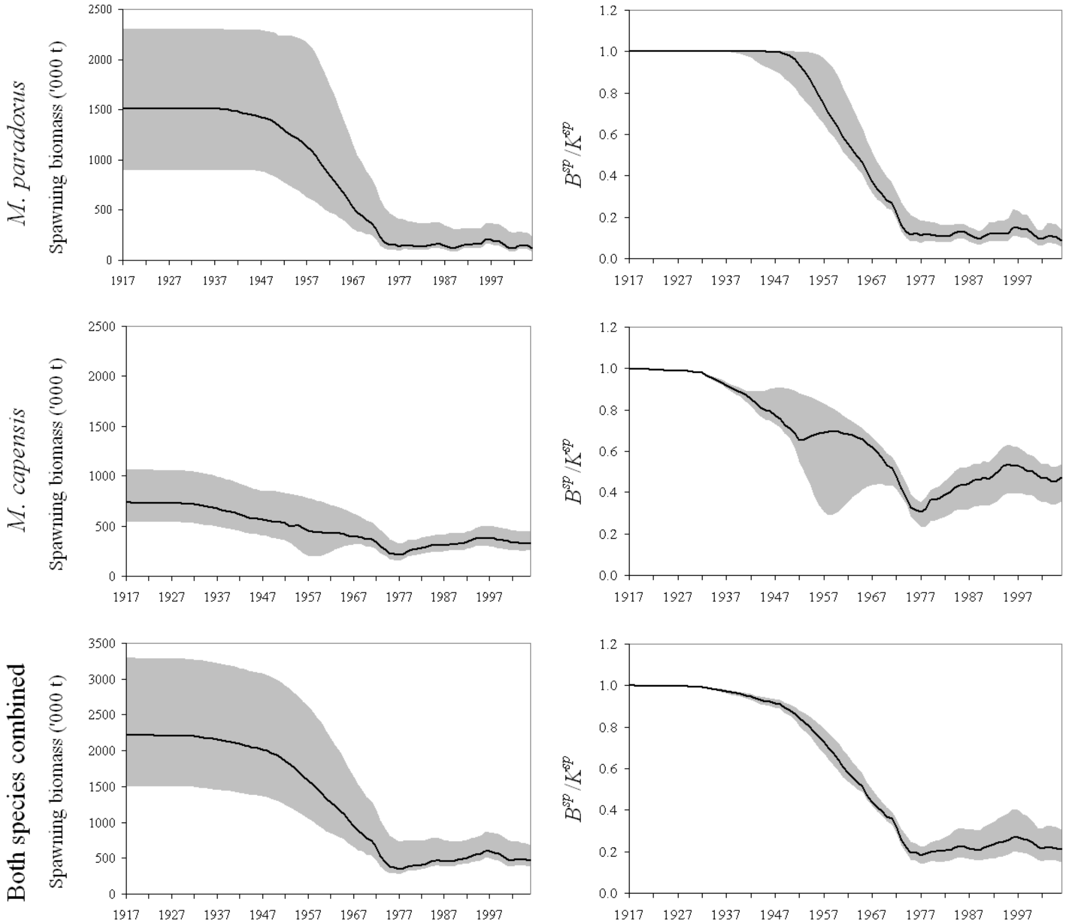

Figure 4.12: Trajectories of spawning biomass (in absolute terms and as a proportion of its pre-exploitation level) for the Reference Set. The median is indicated by a thick line while the shaded area represents the full uncertainty of the Reference Set (minimum to maximum for each year).

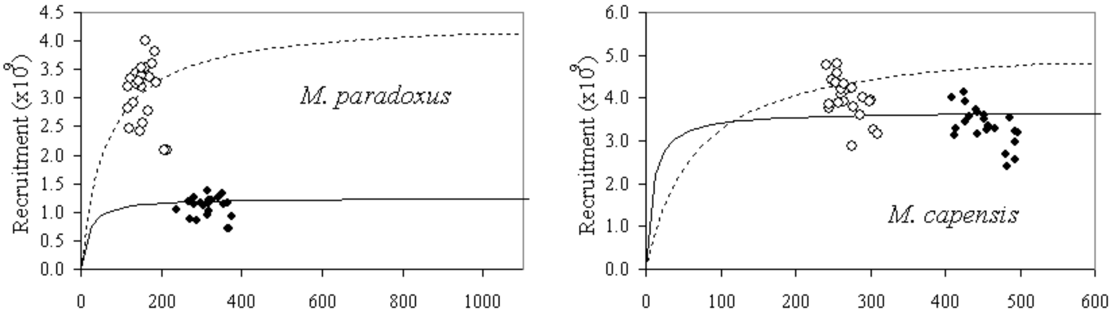

Figure 4.13: Estimated stock-recruitment relationship for the baseline assessment (M4-H1-C1) (full line and black circles) and the corresponding Reference Set scenario with the steepness parameter for both species fixed at lower values (at 0.8 for *M. paradoxus* and 0.7 for *M. capensis*, M4-H4-C1) (dashed line and open circles).

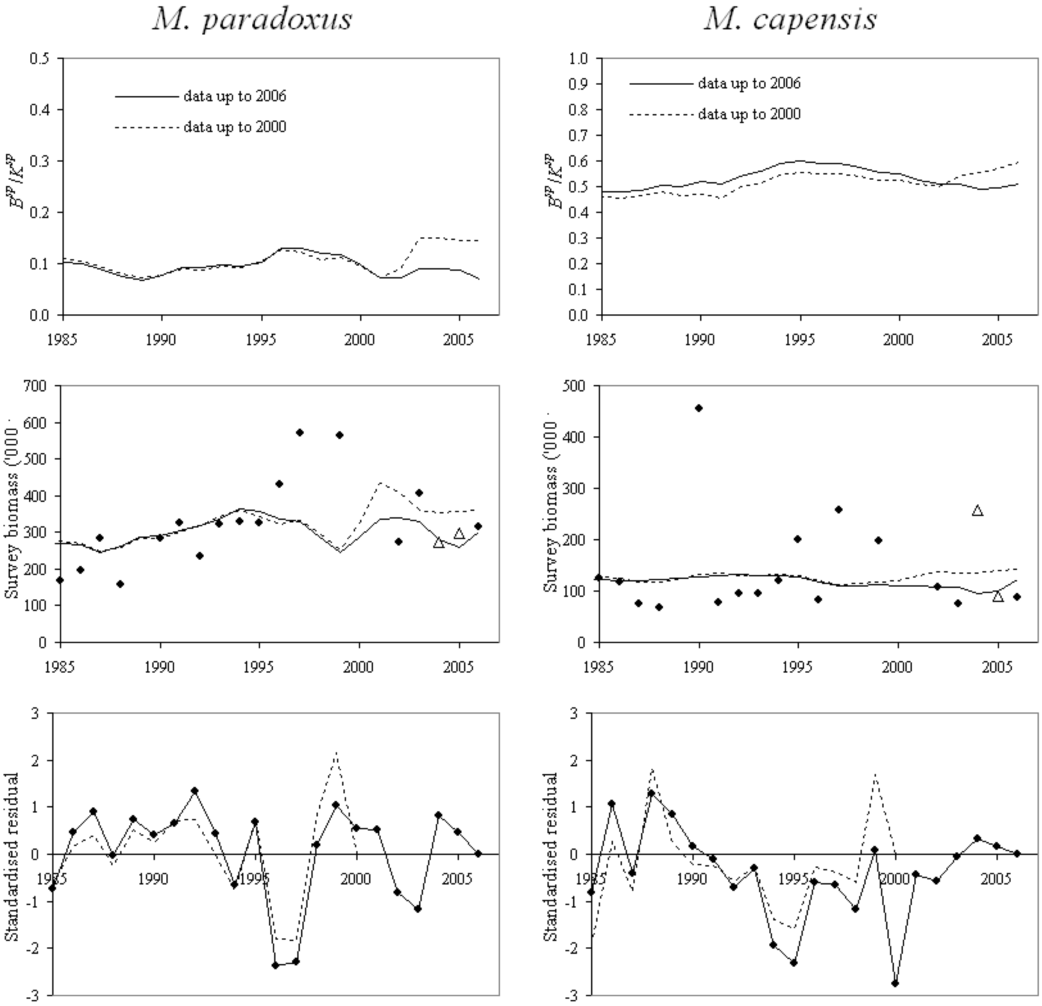

Figure 4.14: Comparison of spawning biomass (relative to pre-exploitation level), the fits to the West Coast summer surveys (with the 2004 and 2005 observed values shown as Δ, because they were conducted by the *Africana* with the new gear and have been re-scaled by the calibration factor) and the standardised residuals about the stock-recruitment relationships for the baseline assessment. The retrospective assessment fits to data up to 2000 only, and thereafter projects under the same catches as actually taken subsequently, and with deterministic recruitment (see text for further details), for *M. paradoxus* and *M. capensis*.

APPENDIX 4.I

Species-splitting algorithm for the offshore trawl catches

The coast-specific algorithms developed by Gaylard and Bergh (2004) from research survey data that are used to split the offshore trawl catches by species (for the period 1978 to the present) are summarized below.

The proportion of *M. capensis* in size category *s* in each trawl is given by a logistic function:

$$\bar{p}_s = \frac{1}{1+e^{B_s}} \qquad \text{(App.4.I.1)}$$

For the West Coast:

$$B_s = \kappa_s \left[d - \left(d_s^* + \alpha_y + \beta_L + 0.5\gamma_{summer}\right)\right] \qquad \text{(App.4.I.2)}$$

and for the South Coast:

$$B_s = \kappa_s \left[d - \left(d_s^* + \beta_L\right)\right] \qquad \text{(App.4.I.3)}$$

where

κ_s is the slope parameter for size category *s*,

d is the trawl depth in metres,

d_s^* is the shift parameter for size category *s*,

α_y is the year parameter for year *y*,

β_L is the longshore parameter for longshore category L, and

$0.5\gamma_{summer}$ is the average of the summer and winter season factors.

The three size categories s considered are small, medium and large as commercially-reported. The parameter values estimated for the West and South coasts are shown in Tables App.4.I.1 and 4.I.2 respectively.

Table App.4.I.1: Parameter values for substitution into equation (App.4.I.2) - the West Coast size-specific algorithm (Gaylard and Bergh 2004).

Parameter		Value
∴	small	0.0472
	medium	0.0333
	large	0.0278
$d*$	small	177.46
	medium	282.76
	large	325.60
$∴_y$	pre-1985	14.04
	1985	21.95
	1986	13.52
	1987	8.02
	1988	0.50
	1989	11.34
	1990	32.73
	1991	11.45
	1992	21.14
	1993	16.31
	1994	4.84
	1995	26.70
	1996	-6.60
	1997	7.22
	1998	5.25
	1999	4.07
	2000	5.25
	2001	5.25
	2002	21.51
	2003	0.00
	post-2003	5.25
$∴_L$	North of 29° S	0.00
	29° to 30° S	-4.02
	30° to 31° S	4.81
	31° to 32° S	1.99
	32° to 33° S	5.75
	33° to 34° S	14.93
	34° to 35° S	34.81
	South of 35° S	36.27
γ_{summer}		-17.02

Table App.4.I.2: Parameter values for substitution into equation (App.4.I.3) - the South Coast size-specific algorithm (Gaylard and Bergh 2004).

Parameter		Value
δ	small	0.0907
	medium	0.0379
	large	0.0209
d^*	small	181.62
	medium	257.29
	large	386.85
δ_L	West of 21°E	0.00
	21-22°E	-4.02
	22-23°E	4.81
	23-24°E	1.99
	24-25°E	5.75
	25-26°E	14.93
	East of 26°E	34.81

APPENDIX 4.II

The Data Utilized

Table App.4.II.1a: Species-disaggregated offshore trawl catches of South African hake from the South and West coasts combined. For 1917 to 1977, the split by species assumes that the proportion of *M. capensis* caught follows a logistic function over this period (see equation 4.1, here applied for the C1 variant with P_1=1950 and P_2=1.5). From 1978 onwards, this split is obtained by applying the size-based species proportion-by-depth relationships for the West and South coasts developed by Gaylard and Bergh (2004) from research survey data. Sources for the species-aggregated annual catch data upon which this and Tables App.4.II.1b-d are based are detailed in the main text.

Offshore trawl catches ('000t)								
Year	*M. paradoxus*	*M. capensis*	Year	*M. paradoxus*	*M. capensis*	Year	*M. paradoxus*	*M. capensis*
1917	-	1.000	1947	3.743	37.657	1977	92.370	46.930
1918	-	1.100	1948	9.304	49.496	1978	108.110	26.988
1919	-	1.900	1949	14.770	42.630	1979	98.133	42.309
1920	-	0.000	1950	27.306	44.694	1980	103.714	36.274
1921	-	1.300	1951	44.856	44.644	1981	92.900	33.516
1922	-	1.000	1952	53.304	35.496	1982	89.230	35.477
1923	-	2.500	1953	62.466	31.034	1983	77.325	29.624
1924	-	1.500	1954	74.752	30.648	1984	86.647	35.543
1925	-	1.900	1955	84.517	30.883	1985	101.532	43.554
1926	-	1.400	1956	88.043	30.157	1986	113.619	36.151
1927	-	0.800	1957	94.982	31.418	1987	103.993	29.216
1928	-	2.600	1958	98.660	32.040	1988	90.389	30.709
1929	-	3.800	1959	110.468	35.532	1989	90.162	36.009
1930	-	4.400	1960	121.131	38.769	1990	88.679	37.749
1931	-	2.800	1961	112.716	35.984	1991	100.148	28.376
1932	-	14.300	1962	111.918	35.682	1992	101.802	27.947
1933	-	11.100	1963	128.545	40.955	1993	113.050	19.275
1934	-	13.800	1964	123.095	39.205	1994	111.927	22.992
1935	0.001	14.999	1965	153.970	49.030	1995	97.884	30.163
1936	0.001	17.699	1966	147.905	47.095	1996	119.576	22.888
1937	0.003	20.197	1967	139.687	51.199	1997	111.776	21.214
1938	0.005	21.095	1968	120.057	51.451	1998	121.650	20.156
1939	0.010	19.990	1969	140.365	62.666	1999	99.942	19.165
1940	0.028	28.572	1970	117.553	48.670	2000	103.980	27.252
1941	0.057	30.543	1971	165.235	66.880	2001	114.228	19.525
1942	0.126	34.374	1972	203.658	86.971	2002	102.197	21.318
1943	0.268	37.632	1973	148.551	81.587	2003	115.317	15.092
1944	0.465	33.635	1974	129.550	84.303	2004	115.003	17.998
1945	0.763	28.437	1975	94.895	62.185	2005	111.081	13.432
1946	1.991	38.409	1976	129.867	65.957	2006	116.021	14.029

Table App.4.II.1b: Inshore trawl catches of South African hake (assumed to be *M. capensis* exclusively) from the South Coast.

Inshore trawl catches ('000t)					
Year	*M. capensis*	Year	*M. capensis*	Year	*M. capensis*
1960	1.000	1976	5.740	1992	9.252
1961	1.308	1977	3.500	1993	8.870
1962	1.615	1978	4.931	1994	9.569
1963	1.923	1979	6.093	1995	10.630
1964	2.231	1980	9.121	1996	11.062
1965	2.538	1981	9.400	1997	8.834
1966	2.846	1982	8.089	1998	8.283
1967	3.154	1983	7.672	1999	8.595
1968	3.462	1984	9.035	2000	10.906
1969	3.769	1985	9.203	2001	11.836
1970	4.077	1986	8.724	2002	9.581
1971	4.385	1987	8.607	2003	9.883
1972	4.692	1988	8.417	2004	10.004
1973	5.000	1989	10.038	2005	7.881
1974	10.056	1990	10.012	2006	8.231
1975	6.372	1991	8.206		

Table App.4.II.1c: Species-disaggregated longline trawl catches of South African hake from the South and West coasts combined. The split by species assumes the catches consist of 30% and 100% *M. capensis* on the West and South coasts respectively.

Longline catches ('000t)								
Year	*M. paradoxus*	*M. capensis*	Year	*M. paradoxus*	*M. capensis*	Year	*M. paradoxus*	*M. capensis*
1983	0.161	0.069	1991	0.000	3.000	1999	1.963	4.985
1984	0.256	0.126	1992	0.000	1.500	2000	3.456	3.558
1985	0.817	0.642	1993	0.000	0.000	2001	2.793	2.885
1986	0.965	0.715	1994	1.130	1.111	2002	4.772	5.990
1987	2.500	1.424	1995	0.670	0.938	2003	4.668	6.878
1988	3.628	1.886	1996	1.676	2.546	2004	3.758	6.039
1989	0.203	0.119	1997	1.806	2.646	2005	4.172	6.347
1990	0.270	0.116	1998	0.647	1.748	2006	4.358	6.629

Table App.4.II.1d: Handline trawl catches of South African hake (assumed to be *M. capensis* exclusively) from the South Coast.

Handline catches ('000t)					
Year	*M. capensis*	Year	*M. capensis*	Year	*M. capensis*
1985	0.065	1993	0.278	2001	7.300
1986	0.084	1994	0.449	2002	3.500
1987	0.096	1995	0.756	2003	3.000
1988	0.071	1996	1.515	2004	1.600
1989	0.137	1997	1.404	2005	0.700
1990	0.348	1998	1.738	2006	0.731
1991	1.270	1999	2.749		
1992	1.099	2000	5.500		

Table App.4.II.2: South and West coast historic (ICSEAF 1989) and coast-combined GLM standardized CPUE data (Glazer 2006) for *M. paradoxus* and *M. capensis*. The historic CPUE series are for *M. capensis* and *M. paradoxus* combined.

	ICSEAF CPUE (tons/hr)			GLM CPUE (kg/min)	
	Species-aggregated			*M. capensis*	*M. paradoxus*
Year	South Coast	West Coast	Year	Coasts combined	
1955		17.31	1978	3.18	5.81
1956		15.64	1979	3.58	5.64
1957		16.47	1980	4.06	5.90
1958		16.26	1981	3.62	5.39
1959		16.26	1982	3.60	5.70
1960		17.31	1983	4.26	6.14
1961		12.09	1984	4.93	6.28
1962		14.18	1985	6.06	7.52
1963		13.97	1986	4.90	7.03
1964		14.60	1987	4.39	6.13
1965		10.84	1988	4.35	5.60
1966		10.63	1989	4.80	5.79
1967		10.01	1990	5.33	6.46
1968		10.01	1991	5.32	7.16
1969	1.28	8.62	1992	5.23	6.89
1970	1.22	7.23	1993	4.27	6.52
1971	1.14	7.09	1994	4.97	6.67
1972	0.64	4.90	1995	5.17	5.07
1973	0.56	4.97	1996	5.03	6.83
1974	0.54	4.65	1997	4.41	6.66
1975	0.37	4.66	1998	4.62	6.74
1976	0.40	5.35	1999	4.62	6.29
1977	0.42	4.84	2000	5.29	6.08
			2001	4.56	5.64
			2002	5.01	4.92
			2003	4.81	5.75
			2004	4.14	5.59
			2005	3.23	5.30

Table App.4.II.3: Survey abundance estimates and associated standard errors in thousand tons for *M. paradoxus* for the depth range 0-500m for the South Coast and for the West Coast. Values in bold are for the surveys conducted by the *Africana* with the new gear.

	South coast				West coast					
Year	Spring (Sept.)		Autumn (Apr./May)		Summer		Winter		*Nansen* summer	
	Biomass	(SE)	Biomass	(SE)	Biomass	(SE)	Biomass	(SE)	Biomass	(SE)
1985	-	-	-	-	168.139	(36.607)	264.916	(52.968)	-	-
1986	23.049	(5.946)	-	-	196.151	(36.366)	172.522	(24.129)	-	-
1987	21.545	(4.601)	-	-	284.859	(53.108)	195.530	(44.425)	-	-
1988	-	-	30.236	(11.084)	158.796	(27.390)	233.103	(64.016)	-	-
1989	-	-	-	-	-	-	468.928	(124.878)	-	-
1990	-	-	-	-	282.225	(78.956)	226.910	(46.016)	-	-
1991	-	-	26.604	(10.431)	327.105	(82.209)	-	-	-	-
1992	-	-	24.305	(15.197)	234.699	(33.963)	-	-	-	-
1993	-	-	198.403	(98.423)	321.782	(48.799)	-	-	-	-
1994	-	-	111.354	(34.622)	329.927	(58.332)	-	-	-	-
1995	-	-	44.618	(19.823)	324.626	(80.370)	-	-	-	-
1996	-	-	85.530	(25.485)	430.971	(80.614)	-	-	-	-
1997	-	-	134.656	(50.922)	570.091	(108.230)	-	-	-	-
1998	-	-	-	-	-	-	-	-	-	-
1999	-	-	321.328	(113.520)	562.988	(116.322)	-	-	-	-
2000	-	-	-	-	-	-	-	-	326.994	(36.816)
2001	19.930	(9.957)	-	-	-	-	-	-	276.604	(34.833)
2002	-	-	-	-	272.172	(35.586)	-	-	-	-
2003	**88.431**	(36.054)	108.756	(37.529)	405.457	(68.882)	-	-	-	-
2004	**63.759**	(17.864)	**55.914**	(23.926)	**259.566**	(56.034)	-	-	-	-
2005	-	-	**25.834**	(8.547)	**281.991**	(40.328)	-	-	-	-
2006			35.038	(8.981)	313.457	(47.265)	-	-	-	-

Table App.4.II.4: Survey abundance estimates and associated standard errors in thousand tons for *M. capensis* for the depth range 0-500m for the South Coast and for the West Coast. Values in bold are for the surveys conducted by the *Africana* with the new gear.

	South coast				West coast					
Year	Spring (Sept.)		Autumn (Apr./May)		Summer		Winter		*Nansen* summer	
	Biomass	(SE)	Biomass	(SE)	Biomass	(SE)	Biomass	(SE)	Biomass	(SE)
1985	-	-	-	-	124.652	(22.709)	181.517	(27.480)	-	-
1986	202.871	(27.845)	-	-	117.829	(23.639)	119.609	(18.492)	-	-
1987	162.282	(17.512)	-	-	75.705	(10.242)	87.407	(11.201)	-	-
1988	-	-	165.184	(21.358)	66.737	(10.767)	47.129	(9.570)	-	-
1989	-	-	-	-	-	-	323.879	(67.303)	-	-
1990	-	-	-	-	455.861	(135.253)	157.826	(23.565)	-	-
1991	-	-	273.897	(44.363)	77.369	(14.997)	-	-	-	-
1992	-	-	137.798	(15.317)	95.568	(11.753)	-	-	-	-
1993	-	-	156.533	(13.628)	94.564	(17.346)	-	-	-	-
1994	-	-	158.243	(23.607)	120.206	(35.885)	-	-	-	-
1995	-	-	233.359	(31.862)	199.173	(26.816)	-	-	-	-
1996	-	-	243.934	(25.035)	83.347	(9.287)	-	-	-	-
1997	-	-	182.157	(18.601)	257.332	(46.062)	-	-	-	-
1998	-	-	-	-	-	-	-	-	-	-
1999	-	-	190.864	(14.929)	198.748	(32.471)	-	-	-	-
2000	-	-	-	-	-	-	-	-	316.105	(42.077)
2001	133.533	(20.845)	-	-	-	-	-	-	191.068	(25.780)
2002	-	-	-	-	108.025	(16.086)	-	-	-	-
2003	**82.726**	(8.994)	126.749	(20.079)	74.771	(12.989)	-	-	-	-
2004	**93.338**	(8.813)	**103.356**	(12.688)	**205.976**	(33.221)	-	-	-	-
2005	-	-	**77.024**	(5.977)	**71.272**	(13.861)	-	-	-	-
2006			132.082	(14.891)	88.357	(22.748)	-	-	-	-

Table App.4.II.5: Summer survey catches-at-age (proportions) for *M. capensis* and *M. paradoxus* on the West Coast for the 0-500m depth range.

	M. capensis								*M. paradoxus*					
Age	0	1	2	3	4	5	6	7+	0	1	2	3	4	5+
1986	0.034	0.230	0.603	0.085	0.023	0.014	0.008	0.003	-	-	-	-	-	-
1987	0.024	0.113	0.465	0.223	0.139	0.022	0.010	0.004	-	-	-	-	-	-
1988	0.280	0.483	0.135	0.059	0.018	0.015	0.009	0.002	-	-	-	-	-	-
1989	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1990	0.004	0.325	0.635	0.023	0.009	0.003	0.001	0.000	0.029	0.310	0.492	0.158	0.009	0.002
1991	0.072	0.122	0.644	0.097	0.038	0.017	0.009	0.002	0.018	0.278	0.561	0.107	0.024	0.008
1992	0.131	0.260	0.313	0.162	0.078	0.025	0.019	0.010	0.010	0.383	0.485	0.082	0.023	0.012
1993	0.038	0.176	0.207	0.399	0.088	0.057	0.024	0.011	0.009	0.200	0.547	0.187	0.044	0.010
1994	0.081	0.253	0.208	0.262	0.075	0.054	0.048	0.020	0.011	0.244	0.551	0.166	0.017	0.008
1995	0.001	0.147	0.739	0.066	0.021	0.018	0.005	0.003	0.065	0.191	0.444	0.258	0.028	0.010
1996	0.065	0.368	0.205	0.237	0.066	0.023	0.025	0.011	0.057	0.394	0.302	0.210	0.030	0.005
1997	0.036	0.141	0.384	0.407	0.014	0.010	0.004	0.003	0.006	0.171	0.546	0.256	0.016	0.003
1998	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1999	0.867	0.059	0.024	0.026	0.011	0.008	0.005	0.001	0.161	0.410	0.336	0.081	0.008	0.003
2000	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2001	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2002	0.198	0.441	0.230	0.070	0.032	0.019	0.007	0.002	0.076	0.373	0.380	0.132	0.028	0.012
2003	0.247	0.209	0.254	0.156	0.046	0.047	0.032	0.009	0.063	0.322	0.400	0.181	0.023	0.012
2004	0.110	0.457	0.359	0.064	0.007	0.002	0.001	0.001	0.175	0.307	0.321	0.152	0.035	0.011
2005	0.679	0.092	0.133	0.076	0.012	0.005	0.002	0.001	0.218	0.493	0.208	0.069	0.009	0.003
2006	0.446	0.325	0.169	0.042	0.008	0.005	0.003	0.001	0.073	0.321	0.440	0.144	0.017	0.005

Table App.4.II.6: Winter survey catches-at-age (proportions) for *M. capensis* on the West Coast for the 0-500m depth range.

	M. capensis							
Age	0	1	2	3	4	5	6	7+
1986	0.005	0.305	0.267	0.318	0.051	0.027	0.017	0.010
1987	0.010	0.477	0.202	0.171	0.072	0.048	0.011	0.009
1988	0.031	0.432	0.388	0.063	0.042	0.029	0.012	0.004
1989	0.079	0.676	0.213	0.022	0.008	0.001	0.001	0.000
1990	0.006	0.267	0.514	0.098	0.052	0.042	0.013	0.008

Table App.4.II.7: *Nansen* summer survey catches-at-age (proportions) for *M. capensis* and *M. paradoxus* on the West Coast for the 0-500m depth range.

	M. capensis								*M. paradoxus*					
Age	0	1	2	3	4	5	6	7+	0	1	2	3	4	5+
2000	0.393	0.336	0.147	0.111	0.007	0.004	0.002	0.001	0.261	0.460	0.204	0.056	0.015	0.004
2001	0.493	0.109	0.157	0.157	0.050	0.018	0.009	0.007	0.199	0.378	0.237	0.143	0.031	0.011

Table App.4.II.8: Spring survey catches-at-age (proportions) for *M. capensis* and *M. paradoxus* on the South Coast for the 0-500m depth range.

	M. capensis								*M. paradoxus*					
Age	0	1	2	3	4	5	6	7+	0	1	2	3	4	5+
2001	0.158	0.106	0.091	0.171	0.264	0.139	0.039	0.033	0.007	0.085	0.518	0.369	0.015	0.006
2002	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2003	0.192	0.139	0.151	0.163	0.170	0.117	0.039	0.029	0.000	0.026	0.448	0.463	0.035	0.029
2004	0.457	0.103	0.109	0.122	0.104	0.067	0.021	0.016	0.034	0.034	0.358	0.499	0.042	0.033

Table App.4.II.9: Autumn survey catches-at-age (proportions) for *M. capensis* and *M. paradoxus* on the South Coast for the 0-500m depth range.

	M. capensis								*M. paradoxus*					
Age	0	1	2	3	4	5	6	7+	0	1	2	3	4	5+
1991	0.011	0.111	0.126	0.173	0.215	0.181	0.112	0.073	0.004	0.010	0.522	0.292	0.116	0.056
1992	0.015	0.203	0.358	0.145	0.118	0.110	0.038	0.014	0.000	0.001	0.370	0.541	0.065	0.024
1993	0.001	0.083	0.120	0.171	0.373	0.143	0.068	0.042	0.000	0.005	0.416	0.544	0.026	0.010
1994	0.061	0.140	0.123	0.219	0.137	0.159	0.116	0.045	0.005	0.090	0.656	0.186	0.017	0.046
1995	0.019	0.121	0.225	0.189	0.202	0.149	0.066	0.029	0.000	0.000	0.124	0.773	0.089	0.014
1996	0.005	0.104	0.188	0.192	0.288	0.131	0.061	0.031	0.000	0.000	0.097	0.749	0.100	0.054
1997	0.064	0.134	0.105	0.187	0.216	0.175	0.067	0.052	0.000	0.001	0.111	0.581	0.105	0.202
1998	-	-	-	-	-	-	-	-	-	-	-	-	-	-
1999	0.159	0.140	0.281	0.145	0.117	0.087	0.040	0.030	0.000	0.014	0.216	0.527	0.190	0.054
2000	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2001	0.149	0.112	0.085	0.175	0.279	0.137	0.036	0.027	0.006	0.053	0.444	0.462	0.027	0.007
2002	-	-	-	-	-	-	-	-	-	-	-	-	-	-
2003	0.109	0.214	0.195	0.142	0.161	0.116	0.035	0.028	0.008	0.023	0.385	0.530	0.034	0.020
2004	0.130	0.103	0.132	0.187	0.228	0.141	0.045	0.034	0.029	0.115	0.350	0.438	0.060	0.008
2005	0.110	0.159	0.169	0.161	0.216	0.126	0.035	0.023	0.065	0.142	0.240	0.370	0.130	0.053
2006	0.030	0.072	0.194	0.264	0.232	0.123	0.047	0.037	0.001	0.012	0.314	0.582	0.073	0.018

Table App.4.II.10: Offshore trawl fleet catches-at-age (proportions) (*M. capensis* and *M. paradoxus* combined) for both coasts combined.

				Species-aggregated				
Age	0	1	2	3	4	5	6	7+
1975	0.000	0.038	0.151	0.242	0.249	0.189	0.058	0.073
1976	0.000	0.076	0.435	0.302	0.120	0.035	0.022	0.010
1977	0.000	0.119	0.499	0.223	0.081	0.051	0.023	0.005
1978	0.000	0.069	0.683	0.174	0.046	0.018	0.007	0.003
1979	0.000	0.095	0.468	0.218	0.095	0.078	0.029	0.016
1980	0.000	0.048	0.458	0.284	0.120	0.053	0.023	0.014
1981	0.004	0.204	0.459	0.184	0.092	0.034	0.015	0.008
1982	0.030	0.248	0.469	0.130	0.056	0.038	0.020	0.009
1983	0.001	0.097	0.457	0.256	0.099	0.056	0.025	0.010
1984	0.002	0.068	0.460	0.265	0.111	0.052	0.028	0.014
1985	0.000	0.007	0.347	0.380	0.135	0.077	0.036	0.019
1986	0.000	0.011	0.315	0.446	0.119	0.055	0.033	0.019
1987	0.000	0.019	0.502	0.273	0.109	0.059	0.025	0.013
1988	0.000	0.018	0.551	0.265	0.075	0.050	0.028	0.011
1989	0.000	0.011	0.411	0.399	0.097	0.049	0.026	0.008
1990	0.000	0.002	0.282	0.470	0.167	0.050	0.020	0.008
1991	0.000	0.003	0.264	0.379	0.213	0.079	0.045	0.018
1992	0.000	0.010	0.380	0.328	0.149	0.084	0.035	0.014
1993	0.000	0.002	0.152	0.407	0.286	0.112	0.031	0.011
1994	0.000	0.001	0.158	0.468	0.191	0.140	0.032	0.011
1995	0.000	0.001	0.107	0.533	0.218	0.074	0.049	0.018
1996	0.000	0.001	0.096	0.533	0.260	0.066	0.032	0.013

Table App.4.II.11: Inshore fleet catches-at-age (proportions) (assumed to consist of *M. capensis* only) on the South Coast.

				M. capensis				
Age	0	1	2	3	4	5	6	7+
1989	0.000	0.000	0.081	0.478	0.285	0.109	0.039	0.008
1990	0.000	0.000	0.055	0.279	0.439	0.171	0.045	0.011
1991	0.000	0.000	0.053	0.281	0.367	0.219	0.067	0.014
1992	0.000	0.001	0.151	0.371	0.237	0.184	0.048	0.009
1993	0.000	0.000	0.026	0.332	0.457	0.139	0.039	0.006
1994	0.000	0.000	0.060	0.380	0.304	0.183	0.067	0.007
1995	0.000	0.000	0.015	0.232	0.455	0.209	0.072	0.018
1996	0.000	0.000	0.024	0.327	0.457	0.140	0.043	0.008
1997	0.000	0.000	0.034	0.369	0.394	0.159	0.034	0.011
1998	0.000	0.008	0.166	0.377	0.284	0.116	0.034	0.015
1999	0.000	0.012	0.190	0.365	0.248	0.116	0.044	0.024
2000	0.000	0.000	0.022	0.244	0.476	0.196	0.034	0.028

Table App.4.II.12: Longline fleet catches-at-age (proportions) (assumed to consist of *M. capensis* only) on the South Coast.

				M. capensis				
Age	0	1	2	3	4	5	6	7+
1994	0.000	0.000	0.000	0.001	0.030	0.248	0.404	0.318
1995	0.000	0.000	0.000	0.000	0.006	0.093	0.262	0.638
1996	0.000	0.000	0.000	0.000	0.007	0.134	0.297	0.561
1997	0.000	0.000	0.000	0.002	0.036	0.201	0.298	0.464
1998	-	-	-	-	-	-	-	-
1999	-	-	-	-	-	-	-	-
2000	0.000	0.000	0.001	0.003	0.020	0.148	0.203	0.626

APPENDIX 4.III

The Age-Structured Production Model (ASPM)

4.III.1 Population Dynamics

4.III.1.1 Numbers-at-age

The resource dynamics of the two populations (*M. capensis* and *M. paradoxus*) of the South African hake are modelled by the following set of equations:

$$N_{s,y+1,0} = R_{s,y+1} \qquad \text{(App.4.III.1)}$$

$$N_{s,y+1,a+1} = N_{sya}e^{-Z_{sya}} \qquad \text{for } 0 \le a \le m_s - 2 \qquad \text{(App.4.III.2)}$$

$$N_{s,y+1,m_s} = N_{sy,m_s-1}e^{-Z_{sy,m_s-1}} + N_{sy,m_s}e^{-Z_{sy,m_s}} \qquad \text{(App.4.III.3)}$$

where

N_{sya} is the number of fish of species *s* and age *a* at the start of year *y*[4],

R_{sy} is the recruitment (number of 0-year-old fish) of species *s* at the start of year *y*,

m_s is the maximum age considered (taken to be a plus-group) for species *s*,

$Z_{sya} = \sum_f F_{sfy}S_{sfya} + M_{sa}$ is the total mortality in year *y* on fish of species *s* and age *a*, where

M_{sa} denotes the natural mortality rate on fish of species *s* and age *a*,

F_{sfy} is the fishing mortality of a fully selected age class of species *s*, for fleet *f* in year *y*, and

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[4] In the interests of less cumbersome notation, subscripts have been separated by commas only when this is necessary for clarity.

S_{sfya} is the commercial selectivity (i.e. vulnerability to fishing gear, which may depend not only on the gear itself, but also on distribution patterns of the fish by age compared to the areal distribution of fishing effort) of species *s* at age *a* for year *y*, and fleet *f*; when $S_{sfya} = 1$[5], the age-class *a* is said to be fully selected.

These equations simply state that for a closed population, i.e. with no immigration or emigration, the only sources of loss are natural mortality (predation, disease, etc.) and fishing mortality (catch).

4.III.1.2 Recruitment

The number of recruits of each species (i.e. new zero-year old fish) at the start of year *y* is assumed to be related to the corresponding spawning stock size (i.e., the biomass of mature fish) by means of the Beverton-Holt (Beverton and Holt 1957) stock-recruitment relationship, parameterized in terms of the "steepness" of the stock-recruitment relationship, h_s, and the pre-exploitation equilibrium spawning biomass, K_s^{sp}, and associated recruitment, R_{0s}.

$$R_{sy} = \frac{4hR_{0s}B_{sy}^{sp}}{K_s^{sp}(1-h_s)+(5h_s-1)B_{sy}^{sp}} e^{(\varsigma_{sy}-\sigma_R^2/2)} \qquad \text{(App.4.III.4)}$$

where

ς_{sy} reflects fluctuation about the expected recruitment for species *s* in year *y*;

B_{sy}^{sp} is the spawning biomass of fish of species *s* at the start of year *y*, computed as:

$$B_{sy}^{sp} = \sum_{a=1}^{m} f_{sa} w_{sa} N_{sya} \qquad \text{(App.4.III.5)}$$

where

w_{sa} is the begin-year mass of fish of species *s* and age *a*, and

f_{sa} is the proportion of fish of species *s* and age *a* that are mature, and

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[5] Such specification is provided for all *sfy* combinations to avoid confounding with *F*.

$$R_{s0}=K_s^{sp}\Big/\left[\sum_{a=1}^{m_s-1} f_{sa}w_{sa}\,e^{-\sum_{a'=0}^{a-1}M_{sa'}}+f_{sm_s}w_{sm_s}\frac{e^{-\sum_{a'=0}^{m-1}M_{sa'}}}{1-e^{-M_{sm_s}}}\right] \tag{App.4.III.6}$$

4.III.1.3 Total catch and catches-at-age

The fleet-disaggregated catch by mass for species *s*, in year *y* is given by:

$$C_{sfy}=\sum_{a=0}^{m} w_{s,a+\frac{1}{2}}C_{sfya}=\sum_{a=0}^{m} w_{s,a+\frac{1}{2}}F_{fsy}S_{sfya}N_{sya}\left(1-e^{-Z_{sya}}\right)\Big/Z_{sya} \tag{App.4.III.7}$$

where

$w_{s,a+1/2}$ denotes the mid-year mass of fish of species *s* and age *a*, which is assumed to be the same for each fleet (as there are no data available to discriminate between fleets), and

C_{sfya} is the catch-at-age, i.e. the number of fish of species *s* and age *a*, caught in year *y* by fleet *f*.

The model estimate of the mid-year exploitable ("available") component of biomass for each species and fleet is calculated by converting the numbers-at-age into mid-year mass-at-age (using the mid-year individual weights) and applying natural and fishing mortality for half the year:

$$B_{sfy}^{ex}=\sum_{a=0}^{m_s} w_{s,a+\frac{1}{2}}S_{sfya}N_{sya}e^{-Z_{sya}/2} \tag{App.4.III.8}$$

The model estimate of the survey biomass at the start of the year (summer) for each species is given by:

$$B_{sy}^{surv}=\sum_{a=0}^{m_s} w_{sa}S_{sa}^{surv,sum}N_{sya} \tag{App.4.III.9}$$

and in mid-year (winter):

$$B_{sy}^{surv} = \sum_{a-0}^{m_S} w_{s,a+\frac{1}{2}} S_{sa}^{surv,win} N_{sya}\ e^{-Z_{sya}/2} \qquad \text{(App.4.III.10)}$$

where

$S_{sa}^{surv,sum/win}$ is the survey selectivity for age *a* for species *s*, and

$w_{s,a+\frac{1}{2}}$ is the mid-year weight of fish of species *s* and age *a* at the start of the year.

Note that both the spring and autumn surveys are taken to correspond to winter.

It is assumed that the resource is at the deterministic equilibrium that corresponds to an absence of harvesting at the start of the initial year considered, i.e., $B_{s1}^{sp} = K_s^{sp}$, and year *y*=1 corresponds to 1917 when catches are taken to commence (see Table App.4.II.1).

4.III.2 The likelihood function

The model is fit to CPUE and survey abundance indices, catch information and commercial and survey catch-at-age data, as well as to the stock-recruitment curve to estimate model parameters. Contributions by each of these to the negative of the log-likelihood (-$\ell\text{n}L$) are as follows[6].

4.III.2.1 CPUE relative abundance data

The likelihood is calculated by assuming that the observed abundance index (here CPUE) is log-normally distributed about its expected value:

$$I_y^i = \hat{I}_y^i e^{\varepsilon_y^i} \quad \text{or} \quad \varepsilon_y^i = \ell\text{n}\left(I_y^i\right) - \ell\text{n}\left(\hat{I}_y^i\right) \qquad \text{(App.4.III.11)}$$

where

I_y^i is the abundance index for year *y* and series *i* (which corresponds to a specified species and fleet),

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[6] Strictly it is a penalised log-likelihood which is maximised in the fitting process, as some contributions that would correspond to log-priors in a Bayesian estimation process are added.

$\hat{I}^i_y = \hat{q}^i \hat{B}^{ex}_{sfy}$ is the corresponding model estimate, where $\hat{B}^{ex}_{sfy}$ is the model estimate of exploitable resource biomass, given by equation App.4.III.8,

$\hat{q}^i$ is the constant of proportionality for abundance series *i*, and

ε^i_y from $N\left(0,\left(\sigma^i_y\right)^2\right)$.

In cases where the CPUE series are based upon species-aggregated catches (as available pre-1978), the corresponding model estimates are derived by assuming two types of fishing zones: z1) an "*M. capensis* only zone", corresponding to shallow-water and z2) a "mixed zone" (see Table App.4.III.1).

The total catch of hake of both species (*BS*) by fleet *f* in year *y* ($C_{BS,fy}$) can be written as:

$$C_{BS,fy} = C^{z1}_{C,fy} + C^{z2}_{C,fy} + C_{P,fy}$$

where

$C^{z1}_{C,fy}$ is the *M. capensis* catch by fleet *f* in year *y* in the *M. capensis* only zone (z1),

$C^{z2}_{C,fy}$ is the *M. capensis* catch by fleet *f* in year *y* in the mixed zone (z2), and

$C_{P,fy}$ is the *M. paradoxus* catch by fleet *f* in year *y* in the mixed zone.

Catch rate is assumed to be proportional to exploitable biomass. Furthermore, if γ is the proportion of the *M. capensis* exploitable biomass in the mixed zone ($\gamma = B^{ex,z2}_{C,fy} / B^{ex}_{C,fy}$) (assumed to be constant throughout the period for simplicity) and ψ_{fy} is the proportion of the effort of fleet *f* in the mixed zone in year *y* ($\psi_{fy} = E^{z2}_{fy} / E_{fy}$),then:

$$C^{z1}_{C,fy} = q^{i,z1}_C B^{ex,z1}_{Cfy} E^{z1}_{fy} = q^{i,z1}_C (1-\gamma) B^{ex}_{C,fy} \left(1-\psi_{fy}\right) E_{fy} \qquad \text{(App.4.III.12)}$$

$$C^{z2}_{C,fy} = q^{i,z2}_C B^{ex,z2}_{C,fy} E^{z2}_{fy} = q^{i,z2}_C \gamma \, B^{ex}_{C,fy} \psi_{fy} E_{fy} \qquad \text{(App.4.III.13)}$$

and

$$C_{P,fy} = q_P^i B_{P,fy}^{ex} E_{fy}^{z2} = q_P^i B_{P,fy}^{ex} \psi_{fy} E_{fy} \qquad \text{(App.4.III.14)}$$

where

$E_{fy} = E_{fy}^{z1} + E_{fy}^{z2}$ is the total effort of fleet *f*, corresponding to combined-species CPUE series *i* which consists of the effort in the *M. capensis* only zone (E_{fy}^{z1}) and the effort in the mixed zone (E_{fy}^{z2}),

$q_C^{i,zj}$ is the catchability for *M. capensis* (*C*) for abundance series *i*, and zone z*j*, and

q_P^i is the catchability for *M. paradoxus* (*P*) for abundance series *i*.

It follows that:

$$C_{C,fy} = B_{C,fy}^{ex} E_{fy} \left[q_C^{i,z1} (1-\gamma)(1-\psi_{fy}) + q_C^{i,z2} \gamma \psi_{fy} \right] \qquad \text{(App.4.III.15)}$$

$$C_{P,fy} = B_{P,fy}^{ex} E_{fy} q_P^i \psi_{fy} \qquad \text{(App.4.III.16)}$$

From solving equations App.4.III.15 and App.4.III.16:

$$s_{fy} = \frac{q_C^{i,z1}(1-\gamma)}{\left\{ \dfrac{C_{C,fy} B_{P,fy}^{ex} q_P^i}{B_{C,fy}^{ex} C_{P,fy}} - q_C^{i,z2}\gamma + q_C^{i,z1}(1-\gamma) \right\}} \qquad \text{(App.4.III.17)}$$

and

$$\hat{I}_y^i = \frac{C_{fy}}{E_{fy}} = \frac{C_{fy} B_{P,fy}^{ex} q_P^i \psi_{fy}}{C_{P,fy}} \qquad \text{(App.4.III.18)}$$

Table App.4.III.1: Summary regarding the two theoretical fishing zones.

Zone 1 (z1): *M. capensis* only	Zone 2 (z2): Mixed zone
M. capensis : biomass ($B_{C\,z1}$), catch($C_{C\,z1}$)	*M. capensis* : biomass ($B_{C\,z2}$), catch($C_{C\,z2}$)
	M. paradoxus : biomass (B_P), catch(C_P)
Effort in zone 1 (E_{z1})	Effort in zone 2 (E_{z2})

Two species-aggregated CPUE indices are available: the ICSEAF West Coast and the ICSEAF South Coast series. For consistency, *q*'s for each species (and zone) are forced to be in the same proportion:

$$q_s^{SC} = rq_s^{WC} \qquad \text{(App.4.III.19)}$$

To correct for possible negative bias in estimates of variance $\left(\sigma_y^i\right)$ and to avoid according unrealistically high precision (and so giving inappropriately high weight) to the CPUE data, lower bounds on the standard deviations of the residuals for the logarithm of the CPUE series have been enforced; for the historic ICSEAF CPUE series (separate West Coast and South Coast series) the lower bound is set to 0.25, and to 0.15 for the recent GLM-standardised CPUE series, i.e.: $\sigma^{ICSEAF} \geq 0.25$ and $\sigma^{GLM} \geq 0.15$.

The contribution of the CPUE data to the negative of the log-likelihood function (after removal of constants) is then given by:

$$-\ell n L^{CPUE} = \sum_i \sum_y \left[\ell n\left(\sigma_y^i\right) + \left(\varepsilon_y^i\right)^2 / 2\left(\sigma_y^i\right)^2 \right] \qquad \text{(App.4.III.20)}$$

where

σ_y^i is the standard deviation of the residuals for the logarithms of index *i* in year *y*.

Homoscedasticity of residuals for CPUE series is customarily assumed[7], so that $\sigma_y^i = \sigma^i$ is estimated in the fitting procedure by its maximum likelihood value:

$$\hat{\sigma}^i = \sqrt{1/n_i \sum_y \left(\ell n(I_y^i) - \ell n(\hat{I}_y^i)\right)^2} \qquad \text{(App.4.III.21)}$$

where n_i is the number of data points for abundance index *i*.

In the case of the species-disaggregated CPUE series, the catchability coefficient q^i for abundance index *i* is estimated by its maximum likelihood value, which in the more general case of heteroscedastic residuals, is given by:

$$\ln \hat{q}^i = \frac{\sum_y \left(\ln I_y^i - \ln \hat{B}_{srfy}^{ex}\right) / \left(\sigma_y^i\right)^2}{\sum_y 1 / \left(\sigma_y^i\right)^2} \qquad \text{(App.4.III.22)}$$

In the case of the species-combined CPUE, $q_C^{i,z1}$, $q_C^{i,z2}$, q_P^i and γ are directly estimated in the fitting procedure.

4.III.2.2 Survey abundance data

Data from the research surveys are treated as relative abundance indices in a similar manner to the species-disaggregated CPUE series above, with survey selectivity function $S_{sa}^{surv,sum/win}$ replacing the commercial selectivity S_{sfya} (see equations App.4.III.9 and App.4.III.10 above, which also take account of the begin- or mid-year nature of the survey).

An estimate of sampling variance is available for most surveys and the associated σ_y^i is generally taken to be given by the corresponding survey CV. However, these estimates likely fail to include all sources of variability, and unrealistically high precision (low variance and hence high weight) could hence be accorded to these indices. The contribution of the survey data to the negative log-likelihood is of the same form as that of the CPUE abundance data (see equation App.4.III.19). The procedure adopted takes into

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[7] There are insufficient data in any series to enable this to be tested with meaningful power.

account an additional variance $\left(\sigma_A^i\right)^2$ which is treated as another estimable parameter in the minimisation process. This procedure is carried out enforcing the constraint that $\left(\sigma_A^i\right)^2$ >0, i.e. the overall variance cannot be less than its externally input component.

In June 2003, the trawl gear on the *Africana* was changed and a different value for the multiplicative bias factor *q* is taken to apply to the surveys conducted with the new gear. Calibration experiments were conducted between the *Africana* with the old gear (hereafter referred to as the "old *Africana*") and the *Nansen*, and between the *Africana* with the new gear ("new *Africana*") and the *Nansen*, in order to provide a basis to relate the multiplicative biases of the *Africana* with the two types of gear (q_{old} and q_{new}). A GLM analysis assuming negative binomial distributions for the catches made (Brandão *et al.* 2004) provided the following estimates:

$\Delta\ell nq^{capensis} = -0.494$ with $\sigma_{\Delta\ell nq^{capensis}} = 0.141$ i.e. $\left(q^{new}/q^{old}\right)^{capensis} = 0.610$

and

$\Delta\ell nq^{paradoxus} = -0.053$ with $\sigma_{\Delta\ell nq^{paradoxus}} = 0.117$ i.e. $\left(q^{new}/q^{old}\right)^{paradoxus} = 0.948$

where

$\ell nq_{new}^s = \ell nq_{old}^s + \Delta\ell nq^s$ with *s* = *capensis* or *paradoxus* (App.4.III.23)

No plausible explanation has yet been found for the particularly large extent to which catch efficiency for *M. capensis* is estimated to have decreased for the new research survey trawl net. It was therefore recommended (BENEFIT 2004) that the ratio of the catchability of the new to the previous *Africana* net be below 1, but not as low as the ratio estimated from the calibration experiments. $\Delta\ell nq^{capensis}$ is therefore taken as -0.223, i.e. $\left(q^{new}/q^{old}\right)^{capensis} = 0.8$.

The following contribution is therefore added as a penalty (or a prior in a Bayesian context) to the negative log-likelihood in the assessment:

$$-\ell nL^{q-ch} = \left(\ell nq_{new} - \ell nq_{old} - \Delta\ell nq\right)^2 / 2\sigma_{\Delta\ell nq}^2 \quad \text{(App.4.III.24)}$$

This assessment assumes that the change from “old *Africana*” to “new *Africana*” involves a change in q alone, i.e. the pattern of age-specific selectivity remains unchanged.

4.III.2.3 Commercial catches-at-age

Commercial catches-at-age cannot be disaggregated by species. The model is therefore fit to the catches-at-age as determined for both species combined. The contribution of the catch-at-age data to the negative of the log-likelihood function when assuming an “adjusted” lognormal error distribution is given by:

$$-\ell\mathrm{n}\,L^{age} = \sum_i\sum_y\sum_a\left[\ell n\left(\sigma^i_{com}/\sqrt{p^i_{ya}}\right) + p^i_{ya}\left(\ell n p^i_{ya} - \ell n\hat{p}^i_{ya}\right)^2/2\left(\sigma^i_{com}\right)^2\right] \qquad \text{(App.4.III.25)}$$

where the superscript ‘*i*’ refers to a particular series of catch-at-age data which reflect a specified fleet and coast.

$p^i_{ya} = \dfrac{C_{BS,fya}}{\sum_{a'} C_{BS,fya'}}$ is the observed proportion of fish (*M. capensis* and *M. paradoxus* combined) caught by fleet f in year y that are of age a, and

$\hat{p}^i_{ya} = \dfrac{\hat{C}_{BS,fya}}{\sum_{a'}\hat{C}_{BS,fya'}} = \dfrac{\sum_s \hat{C}_{s,fya}}{\sum_{a'}\sum_s \hat{C}_{s,fya'}}$ is the model-predicted proportion of fish caught by fleet f in year y that are of age a, where

$$\hat{C}_{sfya} = N_{sya}\, e^{-M_{sa}/2}\, S_{sfya}\, F_{sfya} \qquad \text{(App.4.III.26)}$$

and

σ^i_{com} is the standard deviation associated with the catch-at-age data, which is estimated in the fitting procedure by:

$$\hat{\sigma}^i_{com} = \sqrt{\sum_y\sum_a p^i_{y,a}\left(\ell n\, p^i_{y,a} - \ell n\, \hat{p}^i_{y,a}\right)^2 / \sum_y\sum_a 1} \qquad \text{(App.4.III.26)}$$

The log-normal error distribution underlying equation App.4.III.25 is chosen on the grounds that (assuming no ageing error) variability is likely dominated by a combination of interannual variation in the distribution of fishing effort, and fluctuations (partly as a consequence of such variations) in selectivity-at-age, which suggests that the assumption of a constant coefficient of variation is appropriate. However, for ages poorly represented in the sample, sampling variability considerations must at some stage start to dominate the variance. To take this into account in a simple manner, motivated by multinomial distribution properties, the residuals are weighted by the observed proportions (as in equation App.4.III.25) to avoid undue importance being attached to data based upon a few samples only.

Commercial catches-at-age are incorporated in the likelihood function using equation App.4.III.25, for which the summation over age *a* is taken from age a_{minus} (considered as a minus group) to a_{plus} (a plus group). The ages for the minus- and plus-groups are chosen so that typically a few percent, but no more, of the fish sampled fall into these two groups.

4.III.2.4 Survey catches-at-age

The survey catches-at-age are incorporated into the negative of the log-likelihood in an analogous manner to the commercial catches-at-age, assuming an adjusted log-normal error distribution (equation App.4.III.25). In this case however, data that are disaggregated by species are available.

$p_{sya}^{surv} = \frac{C_{sya}^{surv}}{\sum_{a'=0}^{m_s} C_{sya}^{surv}}$ is the observed proportion of fish of species *s* and age *a* from survey *surv* in year *y*,

$\hat{p}_{sya}^{surv}$ is the expected proportion of fish of species *s* and age *a* in year *y* in the survey *surv*, given by:

$$\hat{p}_{sya}^{surv} = \frac{S_{sa}^{surv,sum} N_{sya}}{\sum_{a'=0}^{m_s} S_{sa'}^{surv,sum} N_{sya'}} \qquad \text{(App.4.III.28)}$$

for begin-year (summer) surveys, or

$$\hat{p}^{surv}_{sya} = \frac{S^{surv,win}_{sa} N_{sya} e^{-Z_{sya}/2}}{\sum_{a'=0}^{m_s} S^{surv,win}_{sa'} N_{sya'} e^{-Z_{sya'}/2}} \qquad \text{(App.4.III.29)}$$

for mid-year (autumn, winter or spring) surveys.

4.III.2.5 Stock-recruitment function residuals

The stock-recruitment residuals are assumed to be log-normally distributed. Thus, the contribution of the recruitment residuals to the negative of the (penalised) log-likelihood function is given by:

$$-\ell n L^{SR} = \sum_s \sum_{y=y1}^{y2} \varsigma_{sy}{}^2 / 2\sigma_R^2 \qquad \text{(App.4.III.30)}$$

where

ς_{sy} is the recruitment residual for species *s*, and year *y*, which is assumed to be log-normally distributed with standard deviation σ_R and which is estimated for year *y1* to *y2* (see equation App.4.III.4) (estimating the stock-recruitment residuals is made possible by the availability of catch-at-age data, which give some indication of the age-structure of the population); and

σ_R is the standard deviation of the log-residuals, which is input.

4.III.3 Model parameters

4.III.3.1 Estimable parameters

The primary parameters estimated are the species-specific virgin spawning biomass $\left(K_s^{sp}\right)$ and "steepness" of the stock-recruitment relationship (h_s). The standard deviations σ^i for the CPUE series residuals (the species-combined as well as the GLM-standardised series) as well as the additional variance $\left(\sigma_A^i\right)^2$ for each survey abundance series are treated as estimable parameters in the minimisation process. Similarly, in the case of the species-combined CPUE, $q_C^{i,z1}$, $q_C^{i,z2}$, q_P^i and γ are directly estimated in the fitting procedure.

The following parameters are also estimated in the model fits undertaken (if not specifically indicated as fixed).

4.III.3.1.1 Natural mortality

Natural mortality (M_{sa}) is assumed to be age-specific and is estimated using the following functional form:

$$M_{sa} = \begin{cases} M_{s2} & \text{for} \quad a \le 1 \\ \alpha_s^M + \dfrac{\beta_s^M}{a+1} & \text{for} \quad 2 \le a \le 5 \\ M_{s5} & \text{for} \quad a > 5 \end{cases} \qquad \text{(App.4.III.31)}$$

M_{s0} and M_{s1} are set equal to M_{s2} $(=\alpha_s^M + \beta_s^M/3)$ as there are no data (hake of ages younger than 2 are rare in catch and survey data) which would allow independent estimation of M_{s0} and M_{s1}.

4.III.3.1.2 Fishing selectivity-at-age

The fishing selectivity-at-age for each species and fleet, S_{sfa}, is either estimated freely:

$$S_{sfa} = \begin{cases} \text{estimated separately for each age} & \text{for } a \le a_{est} \\ \qquad =1 & \text{for } a > a_{est} \end{cases} \qquad \text{(App.4.III.32)}$$

or (where such shape is indicated by fits to the data to be appropriate) in terms of a logistic curve given by:

$$S_{sfa} = \begin{cases} 0 & \text{for } a = 0 \\ \left[1 + \exp\left(-\left(a - a_{sf}^c\right)/\delta_{sf}^c\right)\right]^{-1} & \text{for } a \ge 1 \end{cases} \qquad \text{(App.4.III. 33)}$$

where

a^c_{sf} years is the age-at-50% selectivity,

δ^c_{sf} year^{-1} defines the steepness of the ascending limb of the selectivity curve.

The selectivity is sometimes modified to include a decrease in selectivity at older ages, as follows:

$$S_{sfa} \to S_{sfa} \exp\left(-s_{sfa}\left(a - a_{slope}\right)\right) \quad \text{for } a > a_{slope}, \qquad \text{(App.4.III.34)}$$

where

s_{sfa} measures the rate of decrease in selectivity with age for fish older than a_{slope} for the fleet concerned, and is referred to as the “selectivity slope”.

Time dependence may be incorporated into these specification by estimating different selectivity parameters for specific time periods, so that $S_{sfa} \to S_{sfya}$.

4.III.3.1.3 Stock-recruitment residuals

Stock-recruitment residuals ς_{sy} are estimable parameters in the model fitting process. They are estimated separately for each species, from 1985 to 2006, the last year in the assessment, and set to zero pre-1985 because there are no catch-at-length or catch–at-age data for that period to provide the necessary information.

4.III.3.2 Input parameters and other choices for application to hake

4.III.3.2.1 Age-at-maturity

The proportion of fish of species *s* and age *a* that are mature is approximated by

$$f_{sa} = \begin{cases} 0 & \text{for } a < a^{mat}_s \\ 1 & \text{for } a \geq a^{mat}_s \end{cases} \qquad \text{(App.4.III.35)}$$

where $a^{mat}_s = 4$ for both *M. capensis* and *M. paradoxus* (Punt and Leslie 1991).

4.III.3.2.2 Weight-at-age

The weight-at-age (begin and mid-year) for each species is calculated from the combination of the von Bertalanffy growth equation and the mass-at-length function. Values of the parameters for these functions used here are listed in Table App.4.III.2 and were estimated from data for the West Coast (Punt and Leslie 1991).

4.III.3.2.3 Minus- and plus-groups

Because of a combination of gear selectivity and mortality, a relatively small number of fish in the youngest and oldest age classes are caught. In consequence, there can be relatively larger errors (in terms of variance) associated with these data. To reduce this effect, the assessment is conducted with minus- and plus-groups obtained by summing the data over the ages below and above a_{minus} and a_{plus} respectively. Combining certain age-classes in this way also helps reduce the effect of ageing error, which tends to be larger for older ages. The minus- and plus-groups used are given in Table App.4.III.2.

Although the survey and commercial data are grouped to age a_{plus}, the model nevertheless extends to a 15+ plus-group for both species as there can be important changes in mass within the plus-group over time if lower values are chosen; ages are then grouped for comparisons with data. As there are not enough data to inform on the fishing selectivities (survey and commercial) and natural mortalities at ages above 5 and 7 for *M. paradoxus* and *M. capensis* respectively, some assumptions are necessary. The natural mortalities estimated for the plus-groups into which the data are aggregated (5+ and 7+ for *M. paradoxus* and *M. capensis* respectively) are assumed to apply to older ages including the 15+ age group in the model. The assumptions made for the survey and commercial selectivities are listed in Table App.4.III.3.

Table App.4.III.2: Estimates of the parameter values of the von Bertalanffy growth-equation and mass-at-length equation for the West Coast Cape hakes (Punt and Leslie 1991).

	M. capensis	*M. paradoxus*
α (in gm)	0.0050	0.0062
β	3.113	3.046
l_∞ (in cm)	270.6	219.4
κ (in yr^{-1})	0.039	0.049
t_0 (in yr)	-0.730	-0.914

Table App.4.III.3: Minus- and plus-groups taken for the surveys and commercial catch-at-age data, with a description of how the selectivity was extended to age 15+ for the respective data plus-groups.

	Data		Model
	a_{minus}	a_{plus}	Selectivity extension to 15+
Combined species:			
Offshore trawl	1-	5+	-
M. paradoxus			
Surveys	0-	5+	Fixed 0.5* yr^{-1} exponential decrease from a_{plus} to 15+.
Offshore trawl	no data to fit		Exponential decrease estimated assumed to continue from a_{plus} to 15+.
Longline	no data to fit		Assumed flat from a_{plus}.
M. capensis			
Surveys	0-	7+	Fixed 1.0* yr^{-1} exponential decrease from a_{plus} to 15+.
Offshore trawl	no data to fit		Assumed flat from a_{plus}.
Inshore trawl	2-	7+	Exponential decrease estimated assumed to continue from a_{plus} to 15+.
Longline	4-	7+	Assumed flat from a_{plus}.
Handline	no data to fit		Exponential decrease estimated assumed to continue from a_{plus} to 15+.

*These values have been computed in a coarse manner from the average (over surveys and scenarios) decrease from age 4 to 5 for *M. paradoxus* and age 6 to 7 for *M. capensis* estimated in earlier work (Rademeyer and Butterworth 2005).

Chapter 5

A history of recent bases for management and the development of a species-combined Operational Management Procedure for the South African hake resource

Summary

The bases for historical catch limits placed on the hake fishery are reviewed in brief for earlier years and then in some depth over the period from 1991 when the Operational Management Procedure (OMP) approach was introduced for this fishery. The OMP implemented from 2007 was the first to be based on the use of rigorous species-disaggregated assessments of the resource as Operating Models. This Chapter describes the Reference Set and range of robustness trials, together with the associated Operating Models, which were used for the simulation testing of this OMP. Performance statistics for a number of candidate OMPs are compared, and the two key trade-off decisions in the selection process discussed (substantial *Merluccius paradoxus* and catch per unit effort [CPUE] recovery, and total allowable catch [TAC] stability constraints). Details of the OMP adopted and how its formulae depend on recent trends in CPUE and survey estimates of abundance are provided. OMP-2007, which is tuned to a median 20-year recovery target of 20% of pristine spawning biomass for *M. paradoxus* and a 50% increase in CPUE over the next 10 years, was adopted for recommending hake TACs over the 2007–2010 period until the next scheduled major review. A set of general guidelines

adopted for the process of possible overruling of recommendations from OMPs or of bringing forward their reviews within an otherwise intended four-year cycle is detailed.

5.1 Introduction

The South African hake fishery has been one of the first worldwide to move to a management system based on the implementation of an Operational Management Procedure (OMP). The models and methods used to manage the hake fishery have necessarily evolved in parallel with the available data and understanding of the dynamics of the resource. Here summaries are provided of the past management of the hake fishery and previous OMPs applied, and the development of the OMP that was first applied to provide recommendations for the 2007 TAC is described. This new OMP differed in a number of respects from previous hake OMPs, most notably in its treatment of the two hake species and in the way in which it attempted to encompass the major uncertainties in the split-species assessments which served as OMs.

5.2 Past management

Since its inception at the turn of the 19th century until 1977, although certain checks and restrictions were in place, the hake industry off South Africa operated largely as an open-access fishery. After South Africa declared a 200 nmi Exclusive Economic Zone (EEZ) in 1977, hake TACs were set by the South African authorities, at first taking account of recommendations made by the International Commission for South East Atlantic Fisheries (ICSEAF). Following the heavy exploitation of the late 1960s and early 1970s, a conservative stock rebuilding strategy was adopted. The recommended TACs were initially based on the use of steady-state surplus production models and later on dynamic surplus production models (Butterworth and Andrew 1984). In accordance with the accepted stock rebuilding strategy, a policy aimed at maintaining catches below annual sustainable yields was applied, in general by use of a $f_{0.1}$[8] -type strategy (Andrew and Butterworth 1987).

Since 1990, the South African hake fishery has been managed in terms of OMPs (except for some transitional periods while the OMP in place was revised). The annual TAC recommendations from 1991 to the present, the bases for these recommendations and the actual TAC adopted are detailed in Table 5.1. The *de facto* process followed in the mid-2000s was that the TAC recommendation was made by MCM's DWG and reviewed by the Chief Director: Resources Research, MCM, from whence it was passed on to the Chief Director: Resource Management, MCM, and eventually to the Minister of Environmental Affairs and Tourism for decision. Over the period covered in Table 5.1, the TACs implemented hardly differed from the scientific recommendations. Further, except in a few years where delays in allocating rights led to some quota holders being allowed partial carryovers to the next year, catches made had generally been very close to TACs allocated, so that implementation error in the management of the fishery is small.

Over the period 1990–1995, an OMP (referred to here as OMP-1991) was used to provide TAC recommendations for the years 1991–1996 for each of the West and South coasts, and was based on a species- and age-aggregated dynamic production model linked to a $f_{0.2}$ harvesting strategy. OMP-1991 incorporated a Schaefer production model using inputs comprising time-series of catches as well as catch per unit effort (CPUE) and survey abundance estimates (Punt 1992), although the OMs used for testing were age-structured and species-disaggregated.

OMP-1991 had been chosen following thorough prior simulation testing (Punt 1992, 1993), but by 1995 it had become apparent that it was in need of revision for two main reasons. First, the commercial CPUE on the West Coast had not increased as much as predicted five years earlier, suggesting some mis-specification in the base case operating model, which had been chosen in 1990 as the most appropriate representation of the hake resource dynamics (Geromont and Butterworth 1997). Changes in the fishing selectivity

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[8] If C is the equilibrium catch for effort E, the $f_{0.n}$ strategy is defined as the effort level $E_{0.n}$ satisfying the equation $\left.\frac{dC}{dE}\right|_{E=E_{0,n}} = 0.n\left.\frac{dC}{dE}\right|_{E=0}$, i.e. the point where the marginal return (at equilibrium) for additional effort has fallen to a fraction $0.n$ of its value for the pristine fishery.

over time (probably as a result of the phasing out the illegal use of small-mesh netliners in the late 1980s) were brought to light and needed to be taken into account (Geromont and Butterworth 1998b). These resulted in the CPUE series failing to provide a comparable index over the full 1978–1995 period for which detailed data had been collected from the local trawl fleet, and in the Schaefer model no longer providing adequate predictions of resource trends. Furthermore, general linear modelling (GLM) techniques applied to standardise the CPUE series suggested a lesser rate of recovery of the resource over recent decades than had the coarser standardisation methods used earlier.

For these reasons, the hake TAC was held fixed for the years 1997 and 1998, while a revised OMP was being developed. In August 1998, the Sea Fishery Advisory Council (SFAC — the primary body responsible for providing advice to the Minister at that time) adopted a revised OMP to provide recommendations for the West Coast component of the hake TAC (referred to here as WC-OMP-1999). This OMP was used until 2003. It was based on an $f_{0.075}$ harvesting strategy coupled to an age-aggregated Fox production model (Geromont and Glazer 1998). To avoid the problems associated with the non-comparability of the CPUE series over time, the OMP inputs omitted the period during which the fishing selectivity is believed to have changed (i.e. over which the use of netliners is thought to have been phased out) and used only the pre-1984 and post-1991 CPUE data, treating them as independent series.

The three main objectives considered in selecting WC-OMP-1999 were: (a) a high probability for the resource to recover to the Maximum Sustainable Yield Level (*MSYL*), expressed in terms of spawning biomass ($MSYL = B^{sp}_{MSY} / K^{sp}$) within the next 10 years, (b) a low probability of a net decline in the spawning biomass over this 10-year period and (c) a low probability of a decrease in TAC early in the 10-year period.

The need for a revised OMP for hake on the South Coast arose following the development, in this region in particular, of a longline fishery for hake. Previously, the OMP for hake on the South Coast was based upon aggregating over the two hake species (as for the West Coast), with the justification for this aggregation based upon simulations for the West Coast fishery which assumed that the species- and age-selectivity of the fishery had remained unchanged (Punt 1992). These assumptions had become invalid for the South Coast as the hake longline fishery targets mainly older *M. capensis*.

The revised OMP for the South Coast *M. capensis* component of the hake resource was adopted in June 2000 (referred to here as SCcapensis-OMP-2001). It was of the same form as the one used for the West Coast, based on a Fox-form age-aggregated production model but incorporating a $f_{0.3}$ harvesting strategy (Geromont and Butterworth 2000).

The objectives of the OMP for the South Coast *M. capensis* resource were somewhat different than for the West Coast hake resource. This is because the South Coast shallow-water Cape hake population was estimated to be in a healthy state, well above MSYL, and a resource strategy of 'rebuilding to MSYL' was not required for this component of the overall hake resource. Therefore, the choice of a candidate OMP involved a trade-off between catch and catch rate, rather than one between the average annual catch and the extent of resource recovery, as had been the case for WC-OMP-1999. Thus, the main consideration in selecting an OMP for the South Coast *M. capensis* resource became trying to keep catch rates relatively stable in the short to medium term. The $f_{0.3}$ harvesting strategy option was chosen as it projected roughly steady levels of both catch and catch rate over the next few years.

Unlike the situation for *M. capensis*, an attempted separate assessment for *M. paradoxus* on the South Coast did not yield sensible results, probably because the *M. paradoxus* found on the South Coast is a component of the West Coast *M. paradoxus* stock (Geromont and Butterworth 1999). In the absence of an OMP for this component of the resource, the TAC contribution for South Coast *M. paradoxus* for 2001 was computed as an *ad hoc* proportional addition to the West Coast OMP output; this assumed that changes in the South Coast *M. paradoxus* allowable catch should match trends in West Coast hake abundance. The following year (2002), concerns first developed that stock performance as indicated by an updated assessment fell outside (and below) the range covered in the WC-OMP-1999 trials. This is evident from the plots of probability intervals for projections of the reference case assessment at the time (1998) of the WC-OMP-1999 testing, which assume future catches equal to those subsequently made (Figure 5.1). These are compared with the intervals that follow if identical assessment methodology is applied taking account of the further monitoring data that became available since 1998. For this reason, the TAC was first held fixed for a year, and then phased down over a period of three years (later this phase-down was extended to a fourth year).

Although the OMP would have reacted in time, given its feedback nature, and in due course provided a recommendation of a (fairly substantial) TAC reduction, this option was considered inferior to a smoother phased decrease in the TAC. This was an interim arrangement pending agreement on a fully species-disaggregated assessment to serve as a basis for a revised OMP that fully distinguished the two hake species. In the meantime, the extent of phase-down was determined by a 20-year average Replacement Yield (RY) computation (i.e. the fixed catch which would result in a biomass in 20 years time equal to that at present) using the best assessment model available at that time. Towards the end of this period, given increasingly pessimistic assessments as a consequence of downward trends in resource abundance indices, there was recognition that further reductions would likely be necessary under the revised OMP once it was finalised and adopted.

In November 2006, a new coast- and species-combined OMP (referred to here as OMP-2007) was adopted as the default basis for TAC recommendations for the next four years, starting in 2007. It had as its primary objectives to recover *M. paradoxus* to MSYL over 20 years, given the poor status of this component of the resource that was indicated by the new species-disaggregated assessments (Chapter 4), and to increase the CPUE of the offshore trawl fleet by 50% over the next 10 years to enhance the economic viability of the fishery. The development of this OMP is described in detail below.

5.3 The Species-combined OMP-2007

5.3.1 The Operating Model/s

Given key uncertainties regarding the major considerations of resource status and productivity, a Reference Set (RS) of 24 Operating Models (OMs) spanning these uncertainties, rather than a single OM, was constructed for the South African hake resource. The model structure and results for this RS have been described in detail in Chapter 4. In 2006, both resources had shown a declining trend over the past decade, due principally to poor recruitment over that period.

5.3.2 Generating future data

'Future data' in the form of species-disaggregated CPUE series (one per species) and survey indices of abundance (two per species) are required by the Harvest Control Rule (HCR) to compute a TAC for each of the years in the projection period for the set of candidate OMPs eventually evaluated. These abundance indices (CPUE and surveys) are generated from the OM, assuming the same error structures as in the past, as follows.

(a) Coast-combined species-disaggregated CPUE series are generated from model estimates for mid-year exploitable biomass and catchability coefficients, with multiplicative lognormal errors incorporated where the associated variance is estimated within the OM concerned from past data. When computing the TAC for year *y*+1, such data are available to year *y*–1.

(b) Species-disaggregated biomass estimates from the West Coast summer and South Coast autumn surveys are generated from model estimates of mid-year survey biomass. Because the research survey vessel, the RV *Africana*, changed gear in 2003/2004, estimates from that date are adjusted by a multiplicative bias (see Section 4.III.2.2). Lognormal error variance includes the survey sampling variance with the CV set equal to the average historical value, plus survey additional variance (the variability that is not accounted for by sampling variability) which is estimated within the OM concerned from past data. For the TAC for year *y*+1, such data are available for year *y*.

The reason for this difference in periods for which data are available is that recommendations for a TAC, which applies over a calendar year (*y*+1), are required by October of the preceding year (*y*). By that time the results of the surveys conducted during year *y* will be available, but not those for CPUE which pertains to the full calendar year *y*. Thus, care is taken in developing and testing the OMP that only data that would actually be available at the time a TAC recommendation is required are used.

Furthermore, in order to project the resource biomass trajectory forward, the TAC needs to be disaggregated by species and by fleet. The OMP is species-disaggregated and hence may compute appropriate TAC values for *M. paradoxus* and *M. capensis* separately. However, given the difficulties that would be encountered in trying to set species-specific hake TACs (for example, fish processed on board cannot be easily identified by species), the TAC recommended by the OMP is an overall figure for the two species combined. The OM uses this total TAC value (i.e. the sum of the values for the two species) and re-apportions it between species when projecting forward by assuming a fixed fishing mortality (F) ratio (i.e. it assumes that the ratio of $F_{\text{para}}/F_{\text{cap}}$ remains the same, and hence that the current pattern of fishing remains approximately constant over the projection period — although some robustness tests do explore sensitivity to this). This fixed ratio is computed as the average over the last three years (2004–2006). Although this ratio has been very variable (Figure 5.2), this was nonetheless considered the most realistic way to proceed.

In addition, the total TAC recommended by the candidate MP is divided in fixed proportions among the various fleets, with the following values used for the sector allocations in a recent rights re-allocation process for the fishery: offshore trawl — 84%, inshore trawl — 6%, longline — 7% and handline — 3%.

The testing framework applied assumed that the split of the catches by species and fleet is known without error. Although this assumption is not exact in practice, particularly for the handline fishery, it is considered to be reasonably accurate.

5.3.3 Candidate management procedures considered

It was decided to focus on empirical approaches for the reasons elaborated in the Section 5.5 below. The candidate OMPs (CMPs) presented here and the OMP eventually selected are therefore model-free, increasing or decreasing the TAC in response to the magnitude of recent trends in CPUE and survey estimates for both species. Furthermore, because of concerns related to the then current low level estimated for the *M. paradoxus* biomass, a minimum estimated rate of increase is required for this species before its contribution to the TAC might increase. The details of the associated computations are set out in Appendix 5.I. The OMP includes a number of free ‘control’ parameters, the values of which can be adjusted to tune the performance of the OMP to achieve the desired balance in terms of the projected risks and rewards.

5.3.4 Objectives for the fishery

The objectives that were identified for this fishery are essentially threefold.

1) Improve catch rates quickly in the short-to-medium term: standardised catch rates for offshore trawlers had decreased appreciably since the turn of the century (Figure 5.3). Given an increasing fuel price, it would become increasingly difficult for this fishery to operate profitably unless catch rates improved substantially.

2) Increase the *M. paradoxus* biomass level back to the MSYL over 20 years: this component of the hake resource was estimated to be at an unacceptably low level in 2006, so that both to reduce biological risk and taking cognisance of international norms, it needed to achieve substantial recovery in the medium to long term.

3) After likely large initial cuts to achieve (1), secure greater TAC stability over time.

5.3.5 Performance statistics

The following performance statistics, related to the objectives above, were computed for the CMPs tested. Projections were conducted over 20 years.

5.3.5.1 *Utilisation-related*

- Average catch: $\frac{1}{20}\sum C_y$ (for both species combined and also for each species separately).

- Annual species-combined catch: C_{2007}, C_{2008}, C_{2009} (note that C_{2006} was fixed by the TAC decision already made in 2005, and simulations assumed that this catch would be landed).

5.3.5.2 *Resource status-related*

- B^{sp}_{2027}/K^{sp} and $B^{sp}_{2027}/B^{sp}_{2007}$: for each species, the expected spawning biomass at the end of the projection period, relative to pristine and to the then current (2007) level;

- $CPUE_{2016}/CPUE_{2003-2005}$: the expected change in species combined offshore trawl CPUE in the next ten years compared with the average over three then recent years data for the offshore trawl fleet. (An average was used because of suspicions that low values in 2005 might to some extent reflect an appreciable downward fluctuation in catchability more than abundance.)

5.3.5.3 TAC variability

- The average annual variation (AAV) in catch: $AAV = \frac{1}{21}\sum_{y=2007}^{2027}\left|C_y - C_{y-1}\right| / C_{y-1}$

In addition, time trajectories (both worm plots and probability envelopes) were plotted for certain outputs from the projections, such as C_y and B_y^{sp} .

5.3.6 Robustness tests

The RS of OMs for the South African *M. paradoxus* and *M. capensis* resources (Chapter 4) was considered to reflect the current 'best' representation of the actual dynamics for these two resources and the associated major uncertainties. There were, however, some further uncertainties (in the data as well as in some of the assumptions made in the RS) that needed to be taken into account when testing the performance of CMPs. The performance of each CMP was thus also assessed using a number of robustness tests to further ensure that the final choice of an OMP was robust to a full range of uncertainties related to both resource dynamics and future data. A series of robustness tests was developed from discussions in the DWG. The full list of robustness tests considered is given in Table 5.2. These include scenarios with different assumptions concerning discards and past catch series, biological information (including natural mortality, recruitment, maturity-at-age), changes in carrying capacity, current status of the resources and future data.

In the process of development of the revised OMP, first the resource was projected forward under a constant catch for a fixed period of time for each of the 28 different robustness tests initially identified (Rademeyer and Butterworth 2006b). Performance statistics were compared, and it was agreed by the DWG given pressures of time to discontinue tests for a subset of the original 28 that provided results very similar to those of the RS. Further along in the development process, six robustness tests were identified as being either ones of immediate interest related to RS selection, or which had suggested appreciable sensitivity in previous tests. These were the following.

1. 'SR1': The assumed standard deviation σ_R of variability about the stock-recruitment curve is fixed to 0.25 throughout (i.e. the estimates of recruitment strength for more recent cohorts are not shrunk further towards the stock-recruitment function expectation) in the assessment scenarios considered for the RS. This sensitivity was originally included in the RS; however, further data showed that the large recent recruitments suggested by such computations were less plausible.

2. 'Decr in *K*': In the RS, below average estimated recruitment for *M. capensis* throughout most of the 1990s and the early 2000s suggests a possible systematic deviation below the stock-recruitment curve (see Figure 4.8 in Chapter 4). To better reflect this reduced *M. capensis* recruitment (and continue this into the future), the carrying capacity for *M. capensis* is reduced by 20% from 1992 onwards.

3. 'A1b — disc1': Discarding for both inshore and offshore trawl fleets is modelled by increasing commercial selectivity by 0.2 for ages 1 and 2 for catches of both *M. capensis* and *M. paradoxus*. Thus, the amount of catch discarded is not an input, but computed within the assessment from the fishing mortality estimated for the offshore and inshore trawlers to be able to take their recorded landings. The loss of fish (to discarding as well as to 'theft' by predators) from longlines is also included by doubling the fishing mortality from this fleet. All discarding components are assumed to occur from the beginning of the fishery to 2006 but are not carried through to the projections. This robustness test was included as an extreme case to see if the OMP would react positively to a decrease in discarding in the future, by increasing catches compared with the RS.

4. 'A7b — Ricker forced': Instead of the Beverton-Holt stock-recruit relationship used in the RS, the stock-recruit relationship is of the Ricker form; this could reflect the possibility that cannibalism plays an appreciable role in the dynamics. Furthermore, the stock-recruit curve for each species is constrained so that maximum recruitment

occurs when the spawning biomass is at 45% of the pristine level to avoid the possibility of estimated values corresponding to extreme values of MSYL.

5. ‘B7 — fut σ_R=0.4’: In conjunction with increased variability for the stock-recruitment fluctuations in the past, future variability is also increased (to σ_R=0.4, compared with 0.25 for the RS). Although the assessments yield the lesser value, this is low compared with levels of, and variability typical for, other groundfish, and may reflect ‘smearing out’ of real fluctuations through inadequate methods to estimate catches-at-age (e.g. aggregating catches-at-length over sex when somatic growth rates are sex dependent).

6. ‘B8 — decr *K* in future’: The carrying capacity *K* for both species is assumed to decrease linearly by 30%, starting in 2007, to reach the reduced level in 2011. This is to ensure that the OMP adopted is robust to a decrease in carrying capacity that could arise from environmental changes for example.

5.4 Results

For each CMP, 10 replicates of each of the 24 RS cases (i.e. a total of 240 simulations) were projected over a 20-year period into the future. The different replicates represent alternative plausible future ‘states of nature’ that are compatible with the available data. These different replicates vary due to stochastic effects — both recruitment variability and observation error are added to future CPUE and survey abundance indices. Each of the 24 RS cases was equally weighted. Ideally more than 10 replicates per case would have been run, but computing time limitations precluded this; in any case, however, the primary concern was to capture uncertainty among rather than within the cases.

Although a large number of CMPs were investigated during the development of OMP-2007, only five are presented here for illustrative purposes. These CMPs illustrate the two key trade-offs that faced stakeholders in making a final choice:

(a) the extent of recovery sought for the *M. paradoxus* population: higher recovery targets meant lesser anticipated TACs (on average), though also higher CPUEs, in the medium term; and

(b) the limitations placed on the extent of the hake TAC change allowed from one year to the next: for the same level of risk of resource reduction, greater limitations would generally mean lesser TACs on average.

OMP1 is tuned to three different recovery targets for *M. paradoxus* (median final spawning biomass depletions in 2027 of 15%, 20% and 25% of the pristine level — referred to as $\text{OMP1}_{15\%}$, $\text{OMP1}_{20\%}$ and $\text{OMP1}_{25\%}$ respectively). There is a limitation on the maximum allowed inter-annual TAC change for OMP1 of 10%. For OMP6 and OMP7, only the 20% median recovery tuning for *M. paradoxus* is shown. Both these last two CMPs include a fixed three-year phase-down of 7.5% per annum. After the three years, while both the maximum increase and decrease in TAC are fixed to 5% per annum for OMP6, the maximum annual decrease in TAC for OMP7 differs through dependence on the recent average CPUE relative to its 2002–2004 average level (see Equation App.5.I.5). This is so that TAC decrease proportions are kept low unless CPUE falls below some threshold level, following which greater drops (up to 15% in this case) may occur in order to reverse adverse resource abundance trends. Results from a constant catch harvesting strategy (tuned to a 20% median recovery target for *M. paradoxus* across the 240 simulations) are also presented for comparative purposes. The control parameter values for each of these candidate MPs are given in Table App.5.I.1.

Key comparative results for the variety of CMPs considered are shown in Table 5.3 and Figure 5.4 for the RS. Figure 5.5 shows trajectory envelopes of resource abundance, CPUE, catch and TAC change for an application of each of the CMPs when tuned to the 20% median recovery target for *M. paradoxus* for the RS.

For the same *M. paradoxus* recovery tuning, OMP6 and OMP7 result in lower average catches compared to OMP1 (Figure 5.4a), this being the trade-off for providing greater TAC stability (Figure 5.4b). Although under the constant catch strategy comparatively good average catches are obtained, this strategy results in the extinction of the *M. paradoxus* resource in some instances (Figure 5.4d). Furthermore, from the lower 90% probability interval for the *M. paradoxus* spawning biomass, it is clear that, although the median recovery is the same, the risk of the resource falling to an unacceptably low level is much greater when a fixed 5% maximum inter-annual change in TAC is enforced (OMP6) or there is no change at all (constant catch strategy) (Figures 5.4d, 5.5).

Comparative results for an application of $\text{OMP1}_{20\%}$ to a series of robustness tests are shown in Figure 5.6. Because of time constraints, only four of the corresponding 24 RS scenarios were run for those tests that involve changes to assumptions regarding past data and therefore require refitting of the OM. The four scenarios include (see Chapter 4 for more details):

i. using the central of the three assumptions for the timing of historic change by the offshore trawlers from focusing on *M. capensis* alone to concentrate more on *M. paradoxus* (C1), together with
ii. the two alternative constraint sets for natural mortality (M1 and M4), and with
iii. only two of the options for steepness (H1 — steepness is estimated for both species, and H4 — *M. paradoxus* steepness fixed to 0.8 and *M. capensis* steepness fixed to 0.7). However, in the robustness test with a decrease in future carrying capacity (B8 — Decr in *K* in future) for which only future projections are affected, the full 24 scenarios are run.

The four scenarios used for (most of) the robustness tests give a comparatively slightly more optimistic appraisal of the status of the *M. paradoxus* resource than does the full RS. The SR1 robustness test reflects better catches and better *M. paradoxus* recovery than for the RS. Similarly, assuming that the discarding that took place in the past is not continued in the projections (A1b — disc1) results (not surprisingly) in better *M. paradoxus* recovery and future increased catches compared with the RS. With the Ricker stock-recruitment curve (A7b — Ricker), the projected recovery for *M. paradoxus* is good (though note that this reflects in part the lower *K* for Ricker compared with Beverton-Holt fits of OMs); associated expected catches, however, do not increase substantially. As expected, increasing the variability in recruitment from σ_R=0.25 to σ_R=0.4 (σ_R=0.4) results in wider ranges for all statistics; average catches over the projection period for example could drop below 100 000 tons. Assuming a decrease in the *M. capensis* carrying capacity in the past (Decr in *K*) does not affect the combined species or *M. paradoxus* results substantially. The robustness test in which the carrying capacity of both species is decreased in the future (B8 — decr in *K* in future), however, shows an important drop in predicted average catches, and future CPUE does not increase as much as for the RS.

5.5 Discussion

5.5.1 Why select an empirical-based MP?

Age-aggregated model approaches (Fox and Pella-Tomlinson) for model-based CMPs were investigated during the development of OMP-2007. However, they failed to outperform the empirical-based CMPs, because they could not mimic the future CPUE and survey data adequately, seemingly because of age/selectivity effects. Indeed, in many projections, the survey trends are flat because they are dominated by younger fish, whereas the CPUE trends are more sensitive to trends in the numbers of older fish. This leads to features in the time-series of abundance indices that an age-aggregated model cannot reproduce. Although an age-structured production model-based CMP would be able to capture such features, this was not considered as the basis for a OMP because of the practical constraints of the very long computing time required for tests.

An empirical-based CMP that included a recruitment index was also investigated, with the intent that by taking more immediate action in response to indications (from the age distribution of survey catches) of recruitment falling above or below past average levels, target recovery levels would be more closely attained, with catches raised or lowered correspondingly and appropriately. However, it was found that any advantage in principle that use of recruitment estimates in setting TACs would appear to provide is more than offset by the poor precision with which such recruitments can be estimated from survey results.

Furthermore, an empirical-based CMP allowed for an easier acceptance by stake-holders because it was more easily understood.

5.5.2 Final OMP selection

The two major focuses in the selection of the final CMP were (1) the recovery target for *M. paradoxus*, which correlated closely with expected levels of increase in CPUE in the medium term and (2) the inter-annual TAC variation constraints. A series of CMPs were initially tuned to median final depletions for *M. paradoxus* in 2027 of 15%, 20% and 25% of the pristine level. The attention was directed mainly at this species as it was estimated to be in a poor state at that time compared with the *M. capensis* resource that was estimated to be above its MSYL. A median recovery target of 20% was selected. The DWG agreed that a median recovery to 15% in 2027 was insufficient from both resource and CPUE standpoints, but that targeting 25% (above the estimated MSYL for this species) might have serious negative economic impacts through large TAC reductions in the short term.

It is evident from the lower 90% probability intervals for the *M. paradoxus* spawning biomass projections (Figure 5.5) that restricting the inter-annual change in TAC to 5% (OMP6) leads to greater biological risk, even given a fixed TAC phase-down for three years. In OMP7, the restriction in TAC changes is also 5%, but there is also the possibility for the TAC to decrease by as much as 15% in one year, if CPUE results are well below the recent average. Although the risks for the *M. paradoxus* resource are similar for OMP7 compared with OMP1, the industry did not feel comfortable with the possibility (despite the small associated estimated probability of occurrence) of such a decrease in the TAC.

5.5.3 'Exceptional circumstances'

The intention in designing any OMP is that it can be used on a routine basis to provide scientific management advice, subject (in South Africa) to regular four-yearly reviews. However, occasionally 'Exceptional Circumstances' can arise which may indicate the need for recommendations to deviate from the outputs from such OMPs, or necessitate bringing the regular review forward. Appendix 5.II is a document agreed by MCM Scientific Working Groups to be used for a number of species to specify the procedures governing the identification of such circumstances, and the resultant actions that may follow.

During the development of OMP-2007, an instance of such Exceptional Circumstances occurred, as a result of which the RS of OMs was revised. The RS that had initially been used for OMP testing was based on data to 2003. A further two years data became available and, although the survey biomass estimates for both species and the CPUE for *M. paradoxus* were within 90% probability intervals predictions (albeit marginally so in some cases), the 2005 CPUE value for *M. capensis* was appreciably outside the range predicted (Figure 5.7). The DWG agreed that an Exceptional Circumstances situation applied, with the original RS deemed to cover an insufficient range of possibilities to be considered as a totally reliable basis for selecting a new OMP. The decision was therefore made to refit the OMs within the RS taking account of these new data before proceeding to the OMP testing and selection phases.

5.5.4 What if the TAC could be disaggregated by species?

Initial OMP trials revealed that the major limitation to finding a suitable procedure that yields higher catches was related to the inability to simultaneously obtain adequate performance in terms of risk to the *M. paradoxus* resource. Furthermore, results reflected a slight drop over time in the utilisation of the *M. capensis* resource (Figure 5.8) — a characteristic whose desirability might be questionable given the relatively healthy status estimated for this resource, but which is difficult to avoid without exposing the *M. paradoxus* resource to greater risk. The reason underlying this problem appears to be that, while a CMP advocates decreasing the *M. paradoxus* catch, this is not achieved in reality, because the F_{ratio} prescription sees a larger component of *M. paradoxus* in the total catch ultimately achieved than was intended.

Within the constraints of the management system assumed thus far, it appears that it is not possible to simultaneously improve catch levels and guard against risk to the *M. paradoxus* resource. It was shown that, if the management could adjust the future F_{ratio} achieved each year by controlling the ratio of *M. paradoxus*:*M. capensis* in the deep-water trawl sector (e.g. by broadly regulating the depths at which fishing takes place), substantially higher catches could be achieved.

5.5.5 The overall process

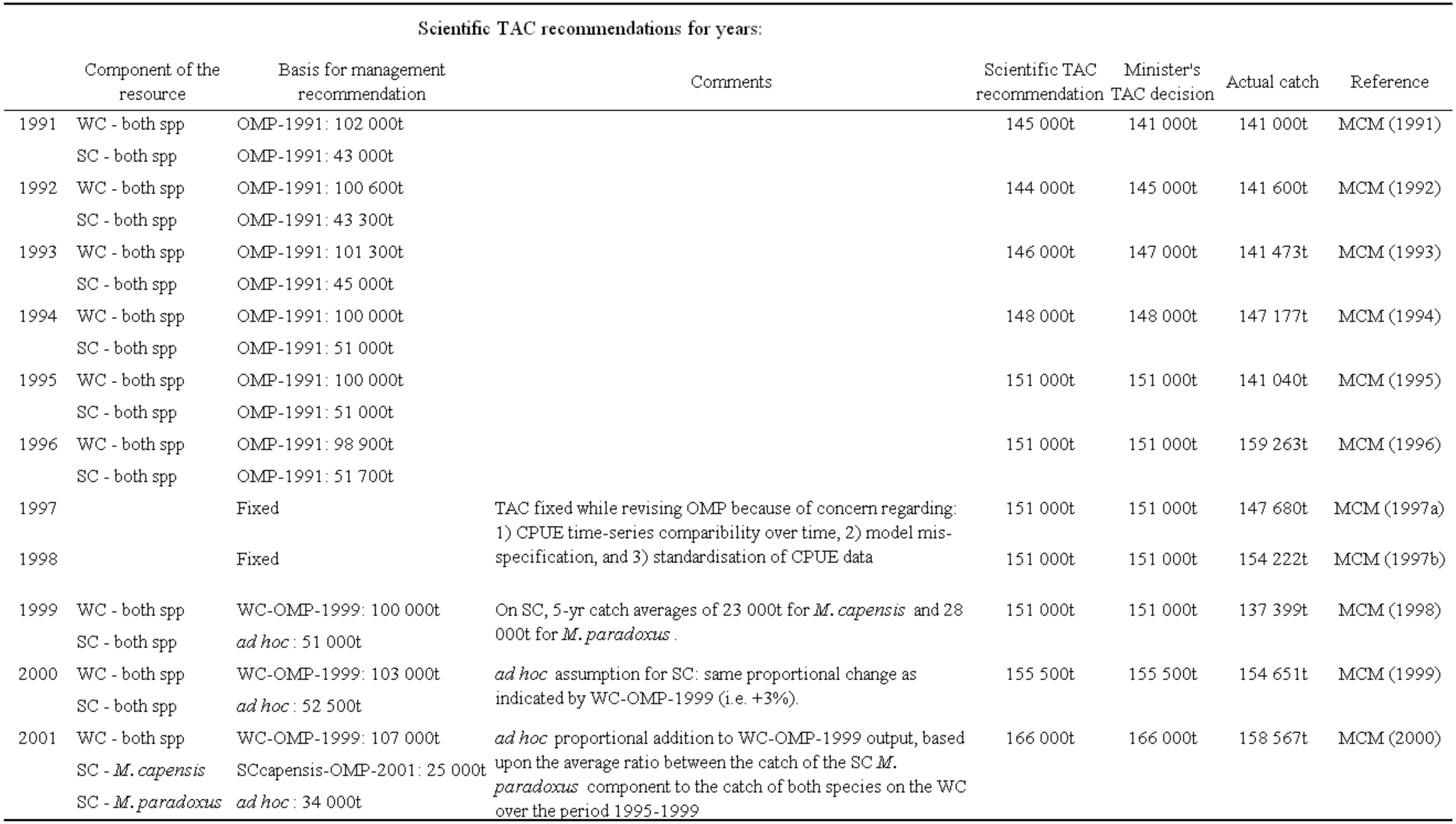
A disappointing aspect of the overall process was the relatively rushed concluding phases that were necessitated to meet the October 2006 deadline for completion with the selection of a single OMP. This required reduction of the extent of robustness testing, in particular, compared to initial plans. These plans had left adequate time between OM finalisation and the final deadline for the OMP selection process for robustness testing to have been more thoroughly addressed. However, the target date for OM finalisation slipped as a joint consequence of the need to refit the OMs, given additional data, and to secure stake-holder buy-in to the results that industry questioned as indicating a better status for *M. capensis* than seemed compatible with their perceptions of a recent appreciable downturn in CPUE.

The process described above led to the recommendation that $OMP1_{20\%}$ be adopted as OMP-2007, the basis for recommending hake TACs over the 2007–2010 period until the next scheduled major review. Application for 2007 saw the TAC reduced from 150 000 tons to 135 000 tons.

5.6 Future Focus

Probably the greatest immediate source of concern in 2006 about this OMP and the OMs that underlay its evaluation and selection related to the indirect methods (species ratio *vs* depth relationships estimated from survey results) used to disaggregate the commercial catches by species. These were planned to be re-evaluated once sufficient data from a recently enhanced observer programme to monitor the species composition of the catch on board trawlers became available.

Table 5.1: TAC recommendations and basis for advice from 1991 to 2007.



			Scientific TAC recommendations for years:				
	Component of the resource	Basis for management recommendation	Comments	Scientific TAC recommendation	Minister's TAC decision	Actual catch	Reference
1991	WC - both spp	OMP-1991: 102 000t		145 000t	141 000t	141 000t	MCM (1991)
	SC - both spp	OMP-1991: 43 000t					
1992	WC - both spp	OMP-1991: 100 600t		144 000t	145 000t	141 600t	MCM (1992)
	SC - both spp	OMP-1991: 43 300t					
1993	WC - both spp	OMP-1991: 101 300t		146 000t	147 000t	141 473t	MCM (1993)
	SC - both spp	OMP-1991: 45 000t					
1994	WC - both spp	OMP-1991: 100 000t		148 000t	148 000t	147 177t	MCM (1994)
	SC - both spp	OMP-1991: 51 000t					
1995	WC - both spp	OMP-1991: 100 000t		151 000t	151 000t	141 040t	MCM (1995)
	SC - both spp	OMP-1991: 51 000t					
1996	WC - both spp	OMP-1991: 98 900t		151 000t	151 000t	159 263t	MCM (1996)
	SC - both spp	OMP-1991: 51 700t					
1997		Fixed	TAC fixed while revising OMP because of concern regarding: 1) CPUE time-series comparibility over time, 2) model mis-specification, and 3) standardisation of CPUE data	151 000t	151 000t	147 680t	MCM (1997a)
1998		Fixed		151 000t	151 000t	154 222t	MCM (1997b)
1999	WC - both spp	WC-OMP-1999: 100 000t	On SC, 5-yr catch averages of 23 000t for *M. capensis* and 28 000t for *M. paradoxus* .	151 000t	151 000t	137 399t	MCM (1998)
	SC - both spp	*ad hoc* : 51 000t					
2000	WC - both spp	WC-OMP-1999: 103 000t	*ad hoc* assumption for SC: same proportional change as indicated by WC-OMP-1999 (i.e. +3%).	155 500t	155 500t	154 651t	MCM (1999)
	SC - both spp	*ad hoc* : 52 500t					
2001	WC - both spp	WC-OMP-1999: 107 000t	*ad hoc* proportional addition to WC-OMP-1999 output, based upon the average ratio between the catch of the SC *M. paradoxus* component to the catch of both species on the WC over the period 1995-1999	166 000t	166 000t	158 567t	MCM (2000)
	SC - *M. capensis*	SCcapensis-OMP-2001: 25 000t					
	SC - *M. paradoxus*	*ad hoc* : 34 000t					

Table 5.1 continued.

Scientific TAC recommendations for years:

	Component of the resource	Basis for management recommendation	Comments	Scientific TAC recommendation	Minister's TAC decision	Actual catch	Reference
2002	WC - both spp	WC-OMP-1999: 110 000t	WC-OMP-1999 recommended 3000t increase, but because of concern on *ad hoc M. paradoxus* SC adjustment, total TAC kept fixed.	166 000t	166 000t	147 358t	MCM (2001)
	SC - *M. capensis*	SCcapensis-OMP-2001: 25 000t					
	SC - *M. paradoxus*	*ad hoc* : 25 000t-35 000t					
2003	WC - both spp	WC-OMP-1999: 108 000t	SC *M. paradoxus* component computed to be between 20 000t and 28 000t based on the difference in sustainable yield between a WC only and WC+SC age-structured model for *M. paradoxus* only. It was decided to phase down over 3 years to the total of 158 00t, given global TAC recommendations from the OMPs were expected to be stable over the next 3 years.	163 000t	164 000t	154 838t	MCM (2002)
	SC - *M. capensis*	SCcapensis-OMP-2001: 25 000t					
	SC - *M. paradoxus*	RY difference: 20 000t- 28 000t					
2004	SC - *M. capensis*	SCcapensis-OMP-2001: 24 000t	WC-OMP-1998 overriden as new data indicated that the then current status of resource was appreciably below that implied by the 1997 assessment. 20-yr RY for SC and WC *M. paradoxus* together with SCcapensis-OMP-2000 output suggested 10 thousand tons decrease needed to stabilise abundance. However, projections indicated that reduction of planned 3 thousand tons would not result in undue harm.	161 000t	161 000t	154 403t	MCM (2003)
	WC - both species	RY: 98 000t					
	SC - *M. paradoxus*	RY difference: 31 000t					
2005	Both coasts and species	Coast-combined, species disaggregated model	Runs of coast-combined, species disaggregated models for both *M. capensis* and *M. paradoxus* indicated that the 'default option' of continuation of the planned 8 000t phase-down would not lead to undue immediate risk.	158 000t	158 000	143 613t	MCM (2004)
2006	Both coasts and species	Coast-combined, species disaggregated model with illustrative control rule	An illustrative control rule was developed to set TACs in simulations after an initial 2-yr period of pre-fixed TAC reductions (of 5 000t, 8000t or 10000t). This suggested that an 8 000t reduction for 2006 was appropriate.	150 000t	150 000t	149 999t	MCM (2005)
2007	Both coasts and species	OMP-2007		135 000t	135 000t	not available	MCM (2006)

Table 5.2: List of robustness tests used.

I. Different assumptions about discards and catch series		
1	A1a – disc1	Discarding by offshore and inshore trawlers modelled as increase in commercial selectivity of 0.2 for ages 1 and 2 for *M. capensis* and *M. paradoxus*, in the past only.
2	A1b – disc2	As A1a above, but loss of fish from longlines also included by doubling *F* from this fleet in the past only.
3	A1c – disc3	As A1a above, but from 1996 onwards, discarding of age 3 as well, in the past only.
4	B3a – disc1	Past and future discarding by offshore and inshore fleets only, as in A1a.
5	B3b – disc2	Past and future discarding by offshore and inshore fleets, as well as longline fleet, as in A1b.
6	B3c – disc3	Past and future discarding by offshore and inshore fleets only, as in A1c.
7	A2 – SC unrep catches	Includes small unreported catches from the south coast offshore fleet from 1917 to 1967.
8	A11 – line catches	Handline catches brought down from 5941t to 2500t in 2003 and from 6888t to 1600t in 2004.
II. Different assumptions about biological information		
9	A5a – M2	Upper bounds on natural mortality of 1.0 and 0.3 $yr^{-1}$for ages 2 and 5/5+ respectively.
10	A5b – M3	Upper bounds on natural mortality estimates of 0.5 yr^{-1} for both ages 2 and 5/5+.
11	A7 – Ricker-like	Ricker-like stock recruitment relationship forced for *M. paradoxus*.
12	A9a – dens dep mat	Proportion of age 3 fish that are mature is densisty dependent.
13	A9b – mat=3	3+ age-at-maturity (instead of 4+).
14	A10a – size-dep spawning	Size-dependent spawning, from age-dependent fecundity index.
14	A10d – mat = 7	7+ age-at-maturity (instead of 4+)
III. Others		
15	A3 – σ_R=0.4	Variability for stock-recruitment fluctuations in the past is increased from σ_R=0.25 in the RS to σ_R=0.4. For the projections, σ_R is kept at 0.25.
16	B7 – fut σ_R=0.4	In conjunction with increased variability for stock-recruitment fluctuations in the past, future variability also increased (σ_R=0.4).
17	A4 – decr K in past	Carrying capacity of both species assumed to have decreased linearly by 30% over the 1980 to 2000 period.
18	A8a – force depletion	Current (2006) spawning biomass of *M. paradoxus* is forced upwards to 40% of pre-exploitation level, while spawning biomass of *M. capensis* forced downwards to 30% of its pre-exploitation level.
19	A8b – force depletion	Current spawning biomass of *M. paradoxus* is forced upwards to 30% of pre-exploitation level.
20	A8c – force depletion	Current spawning biomass of *M. capensis* is forced downwards to 30% of pre-exploitation level.
21	A8d – force depletion	Current spawning biomass of *M. capensis* is forced downwards to 20% of pre-exploitation level.
22	A8e – force depletion	Current spawning biomasses of both species forced to 30% of pre-exploitation levels.
23	A8f – force depletion	Current spawning biomass of *M. capensis* is forced downwards to 20% of pre-exploitation level and the steepness parameter for this species is fixed at 0.7.
24	A12 – diff off sel	Decrease in offshore trawlers selectivity of small *M. paradoxus* fish pre-1978.
25	B4a – cal factor=0.6	Calibration factor between *Africana* with old gear and *Africana* with new gear for *M. capensis* is decreased from 0.8 to 0.6.
26	B4b – cal factor=0.9	Calibration factor between *Africana* with old gear and *Africana* with new gear for *M. capensis* is increased from 0.8 to 0.9.
IV. Changes in the future		
27	B1 – no fut surv	No survey biomass estimates in the future.
28	B2 – CPUE trend	Undetected upward trend in catching efficiency of 2% p.a. in the future.
29	B5a – Fratio decr	F_{ratio} for offshore fleet decreased by 30% in projections to model increase in *M. capensis* catches.
30	B5b – Fratio incr	F_{ratio} for offshore fleet increased by 30% in projections to model decrease in *M. capensis* catches.
31	B6 – ll sel	Increase in selectivity of longline fleet on ages 4 and 5 in the future.
32	B8 – decr K in future	The carrying capacity for both spp assumed to decrease linearly by 30%, starting in 2005, to reach the reduced level in 2009.

Table 5.3: Summary of performance statistics for a series of CMPs (defined in the text; ‘const catch’ = constant catch) for the RS. For each statistic, the median (first row) and 90% probability intervals (second and third rows) are shown. Control parameter values of each candidate were tuned to yield the values shown in bold.

		$OMP1_{15\%}$	$OMP1_{20\%}$	$OMP1_{25\%}$	OMP6	OMP7	const catch
Species combined	avTAC	129.52	125.19	120.78	122.93	123.89	124.50
		113.22	108.82	104.80	103.54	98.43	124.50
		144.51	139.43	134.32	137.93	139.80	124.50
	AAV	5.10	5.03	4.92	4.01	4.10	0.85
		3.35	3.45	3.31	3.34	3.23	0.85
		7.01	6.85	6.73	4.93	5.95	0.85
	$CPUE_{2016}/CPUE_{2003\text{-}05}$	1.53	1.57	1.60	1.53	1.50	1.42
		1.24	1.26	1.30	1.17	1.21	0.88
		1.91	1.95	1.99	1.91	1.91	1.92
M. paradoxus	B_{2027}/K	**0.150**	**0.200**	**0.250**	**0.200**	**0.200**	**0.200**
		0.069	0.121	0.167	0.092	0.111	0.000
		0.259	0.313	0.372	0.325	0.396	0.351
	B_{2027}/B_{2007}	2.13	2.88	3.79	3.03	3.05	2.99
		1.21	1.96	2.54	1.74	1.82	0.00
		3.82	4.86	5.98	5.39	6.68	6.97
M. capensis	B_{2027}/K	0.67	0.70	0.72	0.70	0.72	0.69
		0.56	0.59	0.61	0.56	0.59	0.04
		0.82	0.85	0.87	0.86	0.86	0.87
	B_{2027}/B_{2007}	1.42	1.49	1.54	1.49	1.51	1.45
		1.17	1.22	1.26	1.17	1.24	0.11
		1.70	1.78	1.84	1.78	1.81	1.82

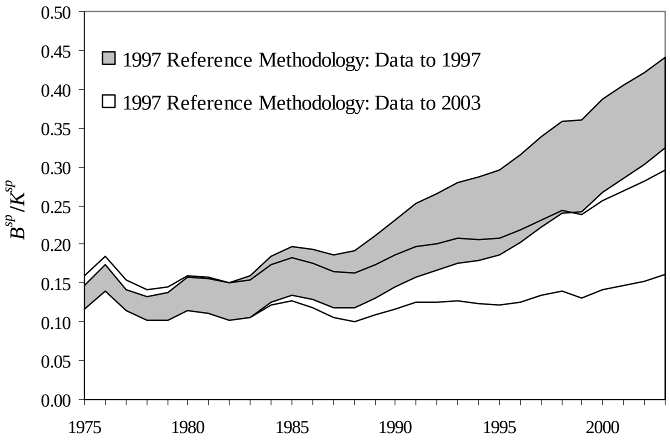


Figure 5.1: 95% probability intervals for the estimated spawning biomass (expressed as a proportion of the pre-exploitation level) for West Coast hake for the 1997 reference case assessment method applied: (i) to the data available at the time of WC-OMP-1999 testing in 1998 and (ii) to the data available in 2003. The projections beyond 1997 for (i) assume the subsequent catches actually made.

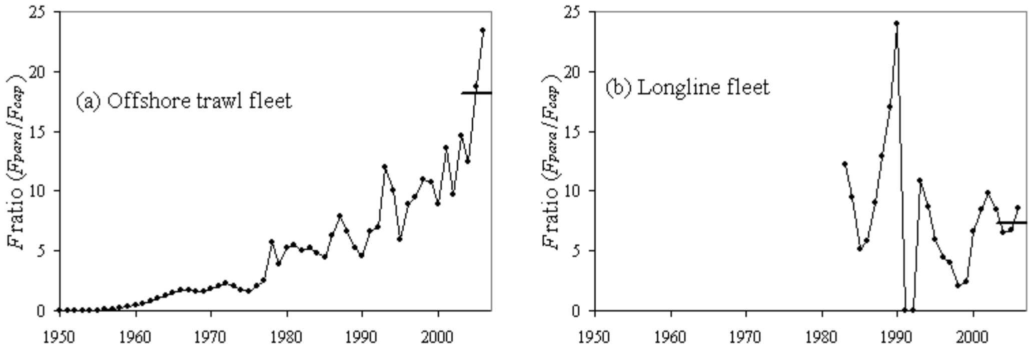


Figure 5.2: Trends in past F_{ratio} ($F_{\text{para}}/F_{\text{cap}}$) for the (a) offshore trawl and (b) longline fleet for the baseline assessment, from Chapter 4. The average over the period 2004–2006 is also shown by the short horizontal line.

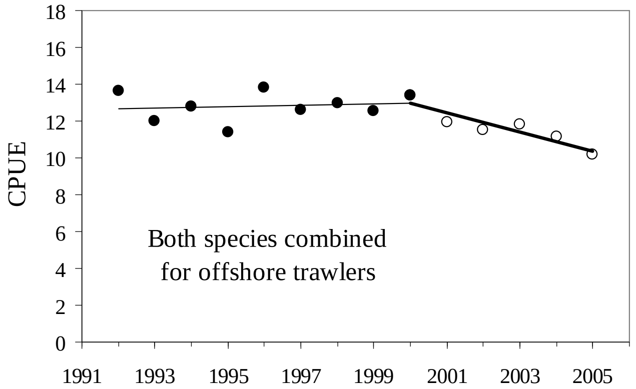


Figure 5.3: Species-combined GLM-standardised CPUE for offshore trawlers. The lines show two linear regressions: 1992–1999 and 2000–2005.

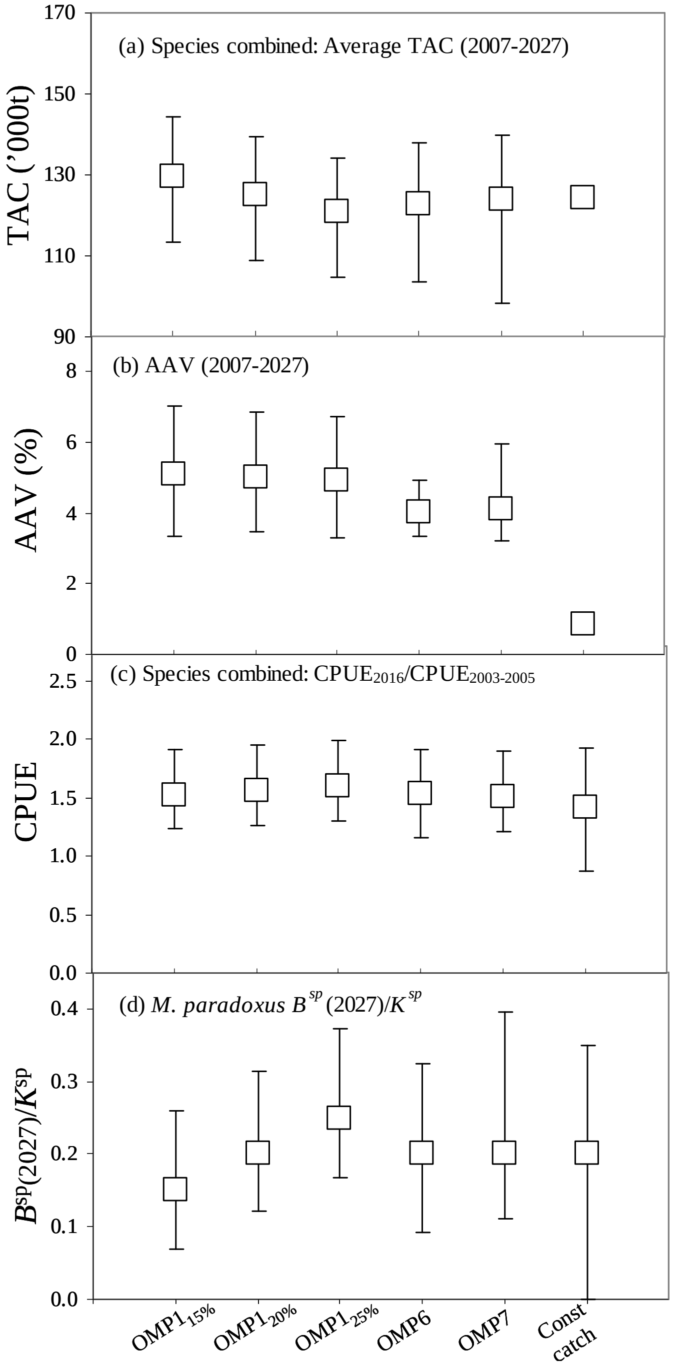
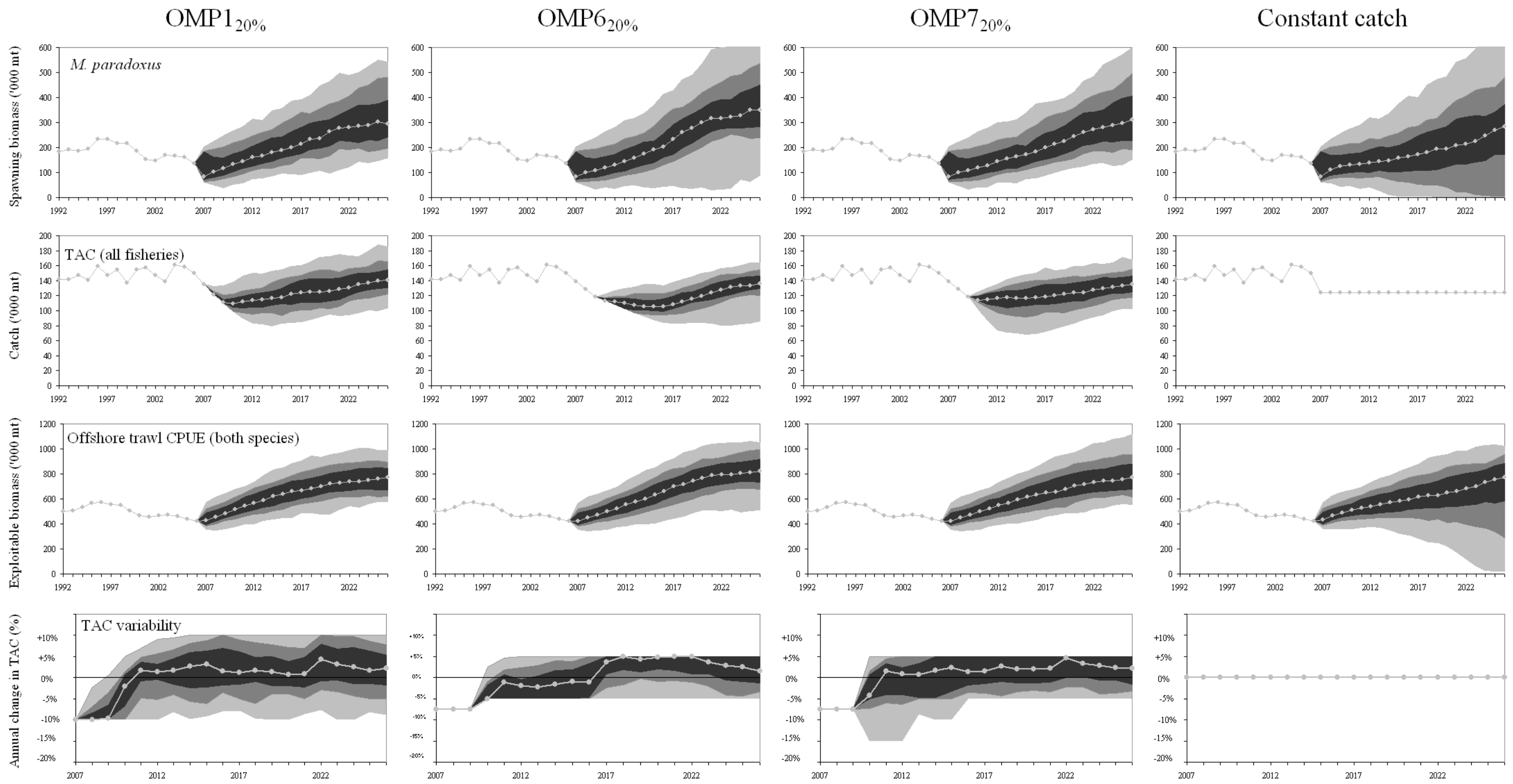


Figure 5.4: Graphical summary of performance statistics for a set of CMPs for the RS. Each panel shows medians together with 90% probability intervals.

Figure 5.5: Trajectories of *M. paradoxus* resource abundance, CPUE, catch and variation in catch for an application of OMP1$_{20\%}$, OMP6$_{20\%}$, OMP7$_{20\%}$ and the constant catch strategy to the RS. In each panel, the median, 50%, 75% and 90% probability intervals are shown. Units for species-combined CPUE are those of the exploitable biomass to which it corresponds. For pre-2007, the average spawning biomass and species combined CPUE trajectories of the RS and the actual species-disaggregated CPUE (divided by the estimated catchability *q*) and total catch are also shown.



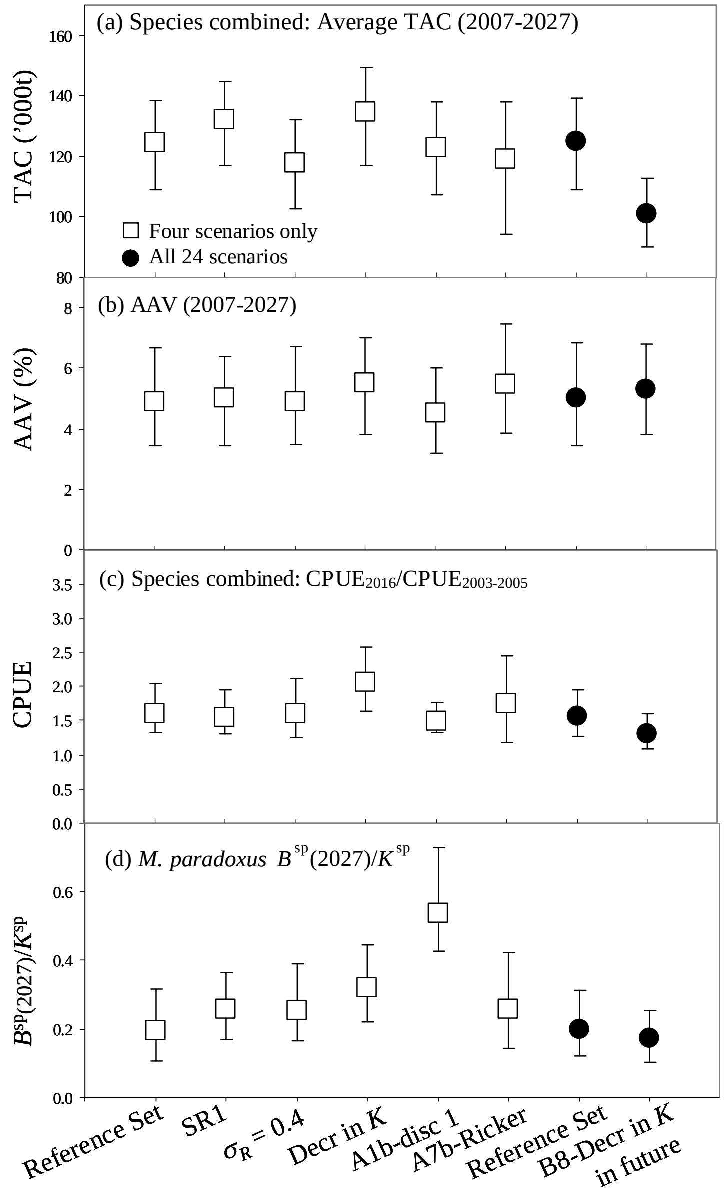


Figure 5.6: Graphical summary of performance statistics for candidate $\mathrm{OMP1}_{20\%}$ for the RS and a series of robustness tests. Each panel shows medians together with 90% probability intervals. The ratios associated with the estimates of K^{sp} are for the K^{sp} in 2006, i.e. in the case of the 'Decr in *K*' test, including the 20% decrease, and in the case of test B8 before the future decrease in carrying capacity.

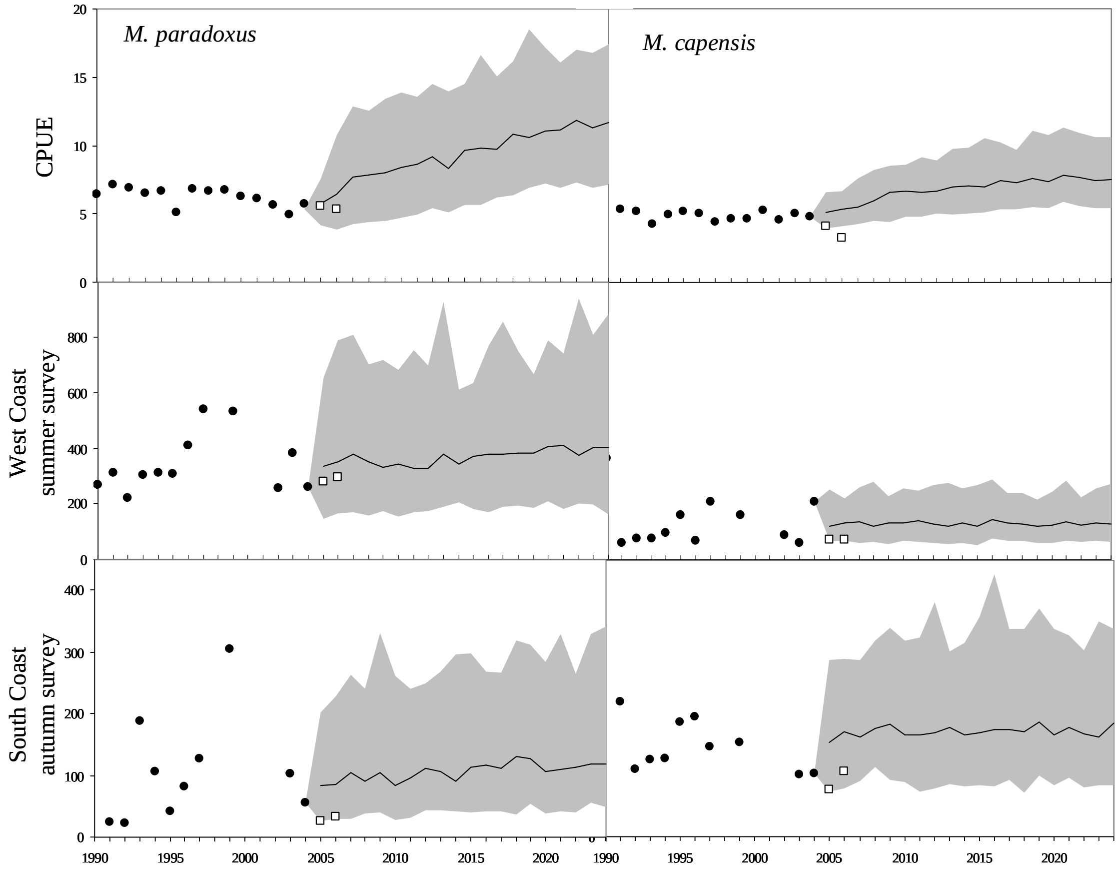


Figure 5.7: Projections under the original RS (fitted to data up to 2003 — solid circles) compared with results given for two further years' resource abundance index data in addition. The open squares show the added data points. The lines are projected medians under the original RS for an illustrative CMP, and the shaded areas the corresponding 90% probability intervals (including the uncertainty associated with observation error).

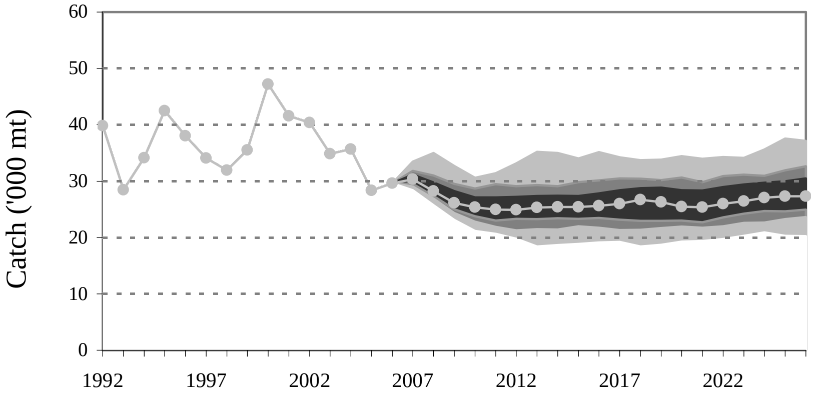


Figure 5.8: Projected catch of *M. capensis* under $OMP1_{20\%}$.

APPENDIX 5.I

OMP-2007 specifications

The formula for computing the TAC recommendation is as follows:

$$TAC_y = C_y^{para} + C_y^{cap} \qquad \text{(App.5.I.1)}$$

with

$$C_y^{spp} = C_{y-1}^{*spp}\left[1+\lambda_y\left(s_y^{spp} - target^{spp}\right)\right] \qquad \text{if } y \leq 2006+Y \text{ and}$$

$$C_y^{spp} = C_{y-1}^{*spp}\left[1+\lambda_y\left(s_y^{spp}\right)\right] \qquad \text{if } y > 2006+Y \qquad \text{(App.5.I.2)}$$

where

TAC_y is the total TAC recommended for year *y*,

C_y^{spp} is the intended species-specific TAC for year *y* (*spp* = *cap* or *para*),

C_{y-1}^{*spp} is the achieved catch[9] of species *spp* in year *y*-1,

λ_y is a year-dependent tuning parameter,

Y is a tuning parameter,

$target^{spp}$ is the target rate of increase for species *spp* and,

s_y^{spp} is a measure of the immediate past trend in the abundance indices for species *spp* as available to use for calculations for year *y*.

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[9] Implemented by applying the species ratio of the catch in year *y*-2 to the TAC for year *y*-1, as the species ratio for year *y*-1 would not yet be known by the time at which a recommendation for the TAC for year *y* would be required.

This trend measure is computed as follows from the species-disaggregated GLM-CPUE ($I_y^{CPUE,spp}$), West Coast summer survey ($I_y^{surv1,spp}$) and South Coast autumn survey ($I_y^{surv2,spp}$) indices:

- linearly regress $\ln I_y^{CPUE,spp}$ *vs* year *y*' for $y' = y - p - 1$ to $y' = y - 2$, to yield a regression slope value $s_y^{CPUE,spp}$, and
- linearly regress $\ln I_y^{surv1,spp}$ and $\ln I_y^{surv2,spp}$ *vs* year *y*' for $y' = y - p$ to $y' = y - 1$, to yield two regression slope values $s_y^{surv1,spp}$ and $s_y^{surv2,spp}$

where *p* is the length of the periods considered for these regressions. Note that the reason the trend for surveys is calculated for a period moved one year later than for CPUE is that by the time of year that the TAC recommendation would be computed for the following year, survey results for the current year would be known, but not CPUE as fishing for the year would not yet have been completed. Note also that surveys carried out using the old gear are rendered comparable to those carried out using the new gear by multiplying them by a species specific calibration factor (0.95 for *M. paradoxus* and 0.8 for *M. capensis*).

Then a weighted average of the slopes is taken to provide a composite value:

$$s_y^{spp} = \left(\frac{s_y^{CPUE,spp}}{2} + \frac{s_y^{surv1,spp}}{4} + \frac{s_y^{surv2,spp}}{4} \right) \qquad \text{(App.5.I.3)}$$

The function for the year-dependent tuning parameter, λ_y, which is a measure of how responsive the candidate OMP is to change in trend, is shown in Figure App.5.I.1:

If $y < 2006 + y_{join}$: $$\lambda_y = \begin{cases} \left(\frac{\delta_3 - \delta_1}{y_{join}} \right)(y - 2006) + \delta_1 & \text{if } s_y > 0 \\ \left(\frac{\delta_3 - \delta_2}{y_{join}} \right)(y - 2006) + \delta_2 & \text{if } s_y \le 0 \end{cases} \qquad \text{(App.5.I.4)}$$

If $y \geq 2006 + y_{join}$: $\lambda_y = \delta_3$.

TAC change constraints

The TAC recommendation when summed over the two species is constrained to increase by no more than α% from year to year, i.e.:

If $TAC_y > (1+\alpha)*TAC_{y-1}$ then $TAC_y = (1+\alpha)*TAC_{y-1}$

The maximum decrease allowed for the TAC in year *y* ($D_y^{\max}$) depends on the recent average CPUE as at year *y* (I_y) expressed relative to its 2002-2004 average level, the underlying rationale being that TAC decrease proportions are kept low unless CPUE falls below some threshold level, following which greater drops are allowed to attempt to reverse adverse resource abundance trends (see Figure App.5.I.2):

$$D_y^{\max} = \begin{cases} D_1 & \text{if } I_y > L_1 \\ D_1 + \dfrac{(D_2 - D_1)}{(L_1 - L_2)^2}(L_1 - I_y)^2 & \text{if } L_1 \geq I_y \geq L_2 \\ D_2 & \text{if } I_y < L_2 \end{cases} \qquad \text{(App.5.I.5)}$$

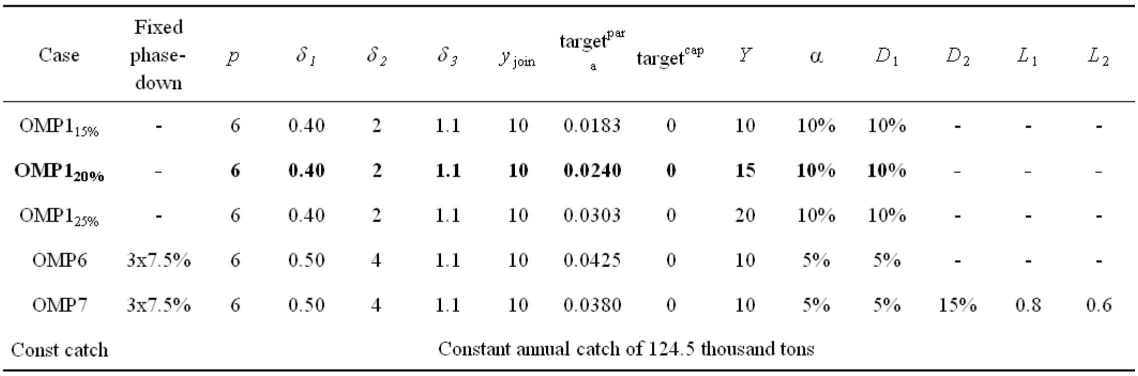
where

D_1, D_2, L_1 and L_2 are constants, and $I_y = \dfrac{\sum_{i=y-2}^{y-1} CPUE_i \Big/ 2}{\sum_{i=2002}^{2004} CPUE_i \Big/ 3}$.

This maximum decrease is computed for both species and the maximum of the two is applied when computing the TAC.

The control parameter values for each of the CMPs referred to in the main text are given in Table App.5.I.1.

Table App.5.I.1: Control parameters for each CMP which is referenced in the main text. The selected OMP-2007 is shown in bold. 'Fixed phase-down' indicates an initial period of a certain number of years over which the TAC is reduced by a certain percentage irrespective of the values of further monitoring data becoming available during that period.



Case	Fixed phase-down	p	δ_1	δ_2	δ_3	y_{join}	$\text{target}_a^{\text{par}}$	$\text{target}^{\text{cap}}$	Y	α	D_1	D_2	L_1	L_2
OMP$1_{15\%}$	-	6	0.40	2	1.1	10	0.0183	0	10	10%	10%	-	-	-
OMP$1_{20\%}$	-	**6**	**0.40**	**2**	**1.1**	**10**	**0.0240**	**0**	**15**	**10%**	**10%**	-	-	-
OMP$1_{25\%}$	-	6	0.40	2	1.1	10	0.0303	0	20	10%	10%	-	-	-
OMP6	3x7.5%	6	0.50	4	1.1	10	0.0425	0	10	5%	5%	-	-	-
OMP7	3x7.5%	6	0.50	4	1.1	10	0.0380	0	10	5%	5%	15%	0.8	0.6
Const catch	Constant annual catch of 124.5 thousand tons													

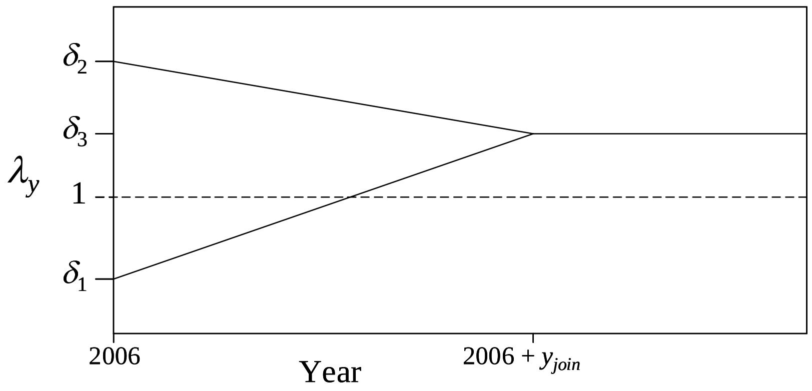


Figure App.5.I.1: Dependence of the catch control law tuning parameter λ_y on year *y*.

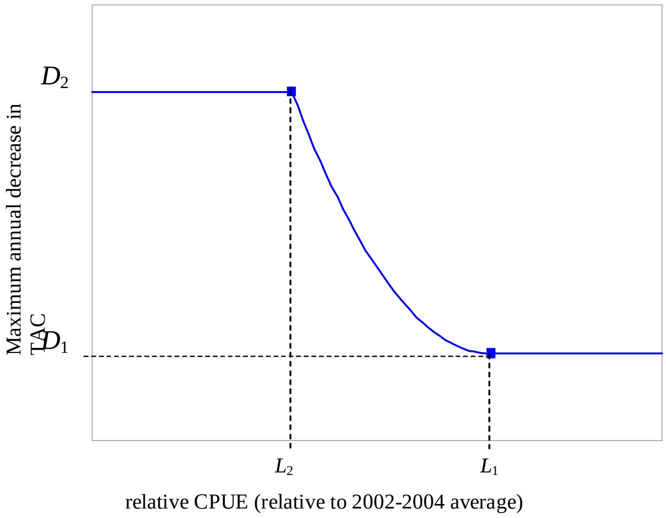


Figure App.5.I.2: Relationship of the maximum annual decrease in TAC to CPUE relative to 2002-2004 average.

APPENDIX 5.II

Procedures for Deviating from OMP Output for the Recommendation for a TAC and for Initiating an OMP Review

5.II.1 Preamble

Currently, scientific recommendations for management controls (e.g. total allowable catch [TAC] or total allowable effort [TAE]) for South Africa's major fisheries are provided by Operational Management Procedures (OMPs). These are pre-agreed formulae for computing these control levels (usually annually), based on pre-agreed resource monitoring data inputs. This combination of formulae and data will have been simulation tested to ensure anticipated performance that is adequately robust given inevitable scientific uncertainties about data and models of the resource dynamics and fishery. (Typically these tests are divided into a core set (or Reference Set) of Operating Models (OMs) for the underlying dynamics, which cover the more plausible scenarios that have quantitatively important implications, and Robustness tests that involve operating models for scenarios considered relatively less plausible or important.)

The intention is that these OMPs be used on a routine basis to provide such scientific management advice, subject to regular four-yearly reviews. However, occasionally 'Exceptional Circumstances' can arise which may indicate the need for recommendations to deviate from the outputs from such OMPs, or necessitate bringing the regular review forward. The purpose of this document is to specify the procedures governing the identification of such circumstances, and the resultant actions that may follow.

This document is constructed as a template that applies generally to OMPs, whatever the fishery to which they apply, but it does also include sections which are fishery specific. Places where entries pertinent to a specific OMP are to be made are indicated by

[ ][10]. These entries, and possible additions to them, require review and finalisation by the relevant MCM Scientific Working Group in parallel with adoption of a new/revised OMP for a specific fishery.

Note that, purely for simplicity of expression, the text that follows is written as if a global TAC were the only management recommendation output by an OMP. However, the provisions following should be understood to apply equally should global effort, either on its own or in conjunction with a global TAC, be the output, and similarly if either or both of such measures are disaggregated by space or time or both.

When an OMP is adopted, the Working Group concerned will ratify a document that contains a complete specification of the formulae used by the OMP to compute recommended management control levels, and of the data to be input. The latter may, as appropriate, contain details concerning pre-processing of such data: for example, the specification of a GLM to standardise a resource abundance index for the effects of covariates other than the year factor related to the abundance trend.

On a number of occasions below, the text requires judgements to be made of whether an effect is ‘appreciable’ (for example, whether an abundance survey result is *appreciably* outside the range predicted in the simulation tests used in selecting the OMP). Such judgements are the province of the Scientific Working Group concerned.

Simulation tests of OMPs assume, at basis, that future resource monitoring data required for input into the OMP will indeed become available as assumed, and that OMP recommendations will be implemented (and in an effective manner). Specific OMPs may include (simulation tested) rules for dealing with the absence of (some) such data, and to indicate adjustments perhaps necessary if implementation differs from the scientific recommendation arising from a previous application of the OMP. To the extent that circumstances arise that are not covered by such rules, and are adjudged by the Working Group to have a likely appreciable impact on the performance of the OMP that would otherwise have been anticipated, the Working Group may consider such an instance of Exceptional Circumstances as conceived in the text following.

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[10] Although this is a general template, the sections in square brackets are hake-specific; different entries would be made in those sections for an OMP for another species

5.II.2 Metarule process

Metarules can be thought of as ‘rules’ that pre-specify what should happen in unlikely, Exceptional Circumstances when application of the TAC generated by the OMP is considered to be highly risky or highly inappropriate. Metarules are not a mechanism for making small adjustments, or ‘tinkering’ with the TAC from the OMP. It is difficult to provide firm definitions of, and to be sure of including all possible, Exceptional Circumstances. Instead, a process for determining whether Exceptional Circumstances exist is described below (see Figure App.5.II.1). The need for invoking a metarule should be evaluated by the MCM [Demersal] Working Group (hereafter indicated by WG), but only provided that appropriate supporting information is presented so that it can be reviewed at a WG meeting.

5.II.2.1 Description of process to determine whether Exceptional Circumstances exist

While the broad circumstances that may invoke the metarule process can be identified, it is not always possible to pre-specify the data that may trigger a metarule. If a WG member or observer, or MCM management, is to propose an Exceptional Circumstances review, then such person(s) must outline in writing the reasons why they consider that Exceptional Circumstances exist, and must either indicate where the data or analyses are to be found supporting the review, or must supply those data or analyses in advance of the WG meeting at which their proposal is to be considered.

Every year the WG will:

- Review population and fishery indicators, and any other relevant data or information on the population, fishery and ecosystem, and conduct a simple routine updated assessment (likely no more than core reference set models used in the OMP testing refitted taking a further year’s data into account)
- On the basis of this, determine whether there is evidence for Exceptional Circumstances for an OMP for another species

Examples of what might constitute an exceptional circumstance in the case of [hake] include, but are not necessarily limited to:

- [Survey estimates of abundance that are appreciably outside the bounds predicted in the OMP testing
- CPUE trends that are appreciably outside the bounds predicted in the OMP testing
- Catch species composition in major components of the fishery or surveys that differ markedly from previous patterns (and so may reflect appreciable changes in selectivity)]

Every two years the WG will:

- Conduct an in-depth stock assessment (more intensive than the annual process above, and in particular including the conduct of a range of sensitivity tests)
- On the basis of the assessment, indicators and any other relevant information, determine whether there is evidence for Exceptional Circumstances

The primary focus for concluding that Exceptional Circumstances exist is if the population assessment/indicator review process provides results appreciably outside the range of simulated population and/or other indicator trajectories considered in OMP evaluations. This includes the core (Reference case or set of) operating models used for these evaluations, and likely also (though subject to discussion) the operating models for the robustness tests for which the OMP was considered to have shown adequate performance. Similarly, if the review process noted regulatory changes likely to effect appreciable modifications to outcomes predicted in terms of the assumptions used for projections in the OMP evaluations (e.g. as a result, perhaps, of size limit changes or closure of areas), or changes to the nature of the data collected for input to the OMP beyond those for which allowance may have been made in those evaluations, this would constitute grounds for concluding that Exceptional Circumstances exist in the context of continued application of the current OMP.

If the WG concludes that there is no or insufficient evidence for Exceptional Circumstances, the WG will:

- Report to the Chief Director: Research, MCM, that Exceptional Circumstances do not exist

If the WG has agreed that Exceptional Circumstances exist, the WG will:

- Determine the severity of the Exceptional Circumstances
- Follow the 'Process for Action' described below

5.II.2.2 Specific issues that will be considered annually (regarding underlying assumptions of the OMs for the OMP testing process)

The following critical aspects of assumptions underlying the OMs for [hake] need to be monitored after OMP implementation. Any appreciable deviation from these underlying assumptions may constitute an exceptional circumstance (i.e. potential metarule invocation) and will require a review, and possible revision, of the OMP:

- [Over recent years species splits of catches from the major fisheries considered in projections are not substantially different from those assumed for the OM projections, or (as appropriate) not outside the bounds for which associated feedback to changes has been incorporated within the OMP
- Selectivities-by-age of the major fisheries do not differ substantially from assumptions made for OM projections
- New CPUE and survey abundance estimates are within the bounds projected by the OMs
- Recruitment levels are within bounds projected by the OMs]

5.II.2.3 Description of process for action

If making a determination that there is evidence of Exceptional Circumstances, the WG will with due promptness:

- Consider the severity of the Exceptional Circumstances (for example, how severely 'out of bounds' are the recent survey results or recruitment estimates)
- Follow the principles for action (see examples below)
- Formulate advice on the action required (this could include an immediate change in TAC, a review of the OMP, the relatively urgent collection of ancillary data, or conduct of analyses to be reviewed at a further WG meeting in the near future)

- Report to the Chief Director: Research, MCM, that Exceptional Circumstances exist and provide advice on the action to take

The Chief Director: Research, MCM, will:

- Consider the advice from the WG
- Decide on the action to take, or recommendations to make to his/her principals

5.III.3 Examples of 'Principles for Action'

If the risk is to the resource, or to dependent or related components of the ecosystem, principles may be:

- The OMP-derived TAC should be an upper bound
- Action should be at least an *x*% decrease in the TAC output by the OMP, depending on severity

If the risk is to socio-economic opportunities within the fishery, principles may be:

- The OMP-derived TAC should be a minimum
- Action should be at least a *y*% increase in the TAC output by the OMP, depending on severity

For certain categories of Exceptional Circumstances, specific metarules may be developed and pre-agreed for implementation should the associated circumstances arise (for example, as has been the case for OMPs for the sardine–anchovy fishery where specific modified TAC algorithms come into play if abundance estimates from surveys fall below pre-specified thresholds). Where such development is possible, it is preferable that it be pursued.

5.II.4 Regular OMP review and revision process

The procedure for regular review and potential revision of the OMP is the process for updating and incorporating new data, new information and knowledge into the management procedure, including the OMs used for testing the procedure. This process should happen on a relatively long time-scale to avoid jeopardising the performance of the OMP, but can be initiated at any time if the WG consider that there is sufficient reason for this, and that the effect of the revision would be substantial. During the revision process, the OMP should still be used to generate TAC recommendations unless a metarule is invoked.

5.II.4.1 Description of Process for Regular Review (see Figure App.5.II.2)

Every year the WG will:

• Consider whether the procedure for metarule process has triggered a review/revision of the OMP. Note that if proposals by a WG member or observer, or MCM management, for an Exceptional Circumstances review include suggestions for an OMP review and possible revision, they must outline in writing the reasons why they consider this necessary, and must either indicate where the data or analyses are to be found supporting their proposed review, or must supply those data or analyses in advance of the WG meeting at which their proposal is to be considered. This includes the possibility of a suggested improvement in the manner in which the OMP calculates catch limitation recommendations; this would need to be motivated by reporting results for this amended OMP when subjected to the same set of trials as were used in the selection of the existing OMP, and arguing that improvements in anticipated performance were evident.

Every two years the WG will:

- Conduct an in-depth stock assessment and review population, fishery and related ecosystem indicators, and any other relevant data or information on the population, fishery and ecosystem
- On the basis of this, determine whether the assessment (or other) results are outside the ranges for which the OMP was tested (note that evaluation for Exceptional Circumstances would be carried out in parallel with this process; see procedures for the

metarule process), and whether this is sufficient to trigger a review/revision of the OMP

- Consider whether the procedure for the metarule process triggered a review/revision of the OMP

Every four years since the last revision of the OMP the WG will:

- Review whether enough has been learnt to appreciably improve/change the operating models (OMs), or to improve the performance of the OMP, or to provide new advice on tuning level (chosen to aim to achieve management objectives)
- On the basis of this, determine whether the new information is sufficient to trigger a review/revision of the OMP In any year, if the WG concludes that there is sufficient new information to trigger a review/revision of the OMP, the WG will:
- Outline the workplan and timeline (e.g. over a period of one year) envisaged for conducting a review
- Report to the Chief Director: Research, MCM, that a review/revision of the OMP is required, giving details of the proposed workplan and timeline
- Advise the Chief Director: Research, MCM, that the OMP can still be applied while the revision process is being completed (unless Exceptional Circumstances have been determined to apply and a metarule invoked) In any year, if the WG concludes that there is no need to commence a review/revision of the OMP, the WG will:
- Report to the Chief Director: Research, MCM, that a review/revision of the OMP is not yet required

The Chief Director: Research, MCM, will:

- Review the report from the WG
- Decide whether to initiate the review/revision process

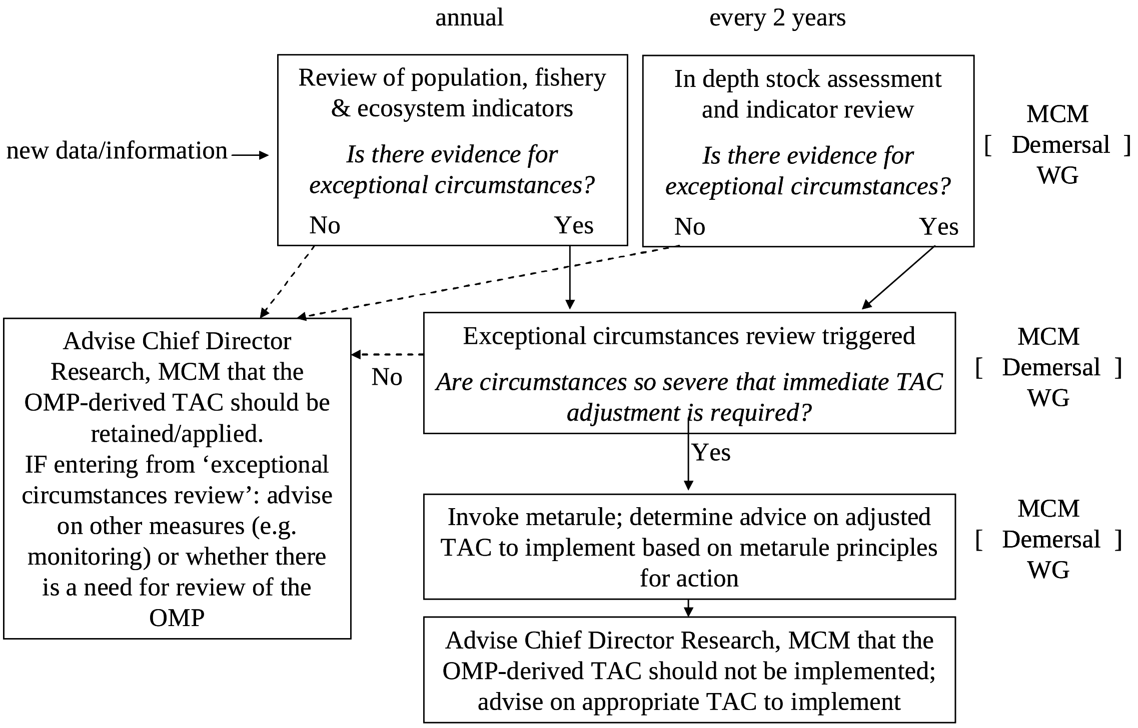


Figure App.5.II.1: Flowchart for metarules process.

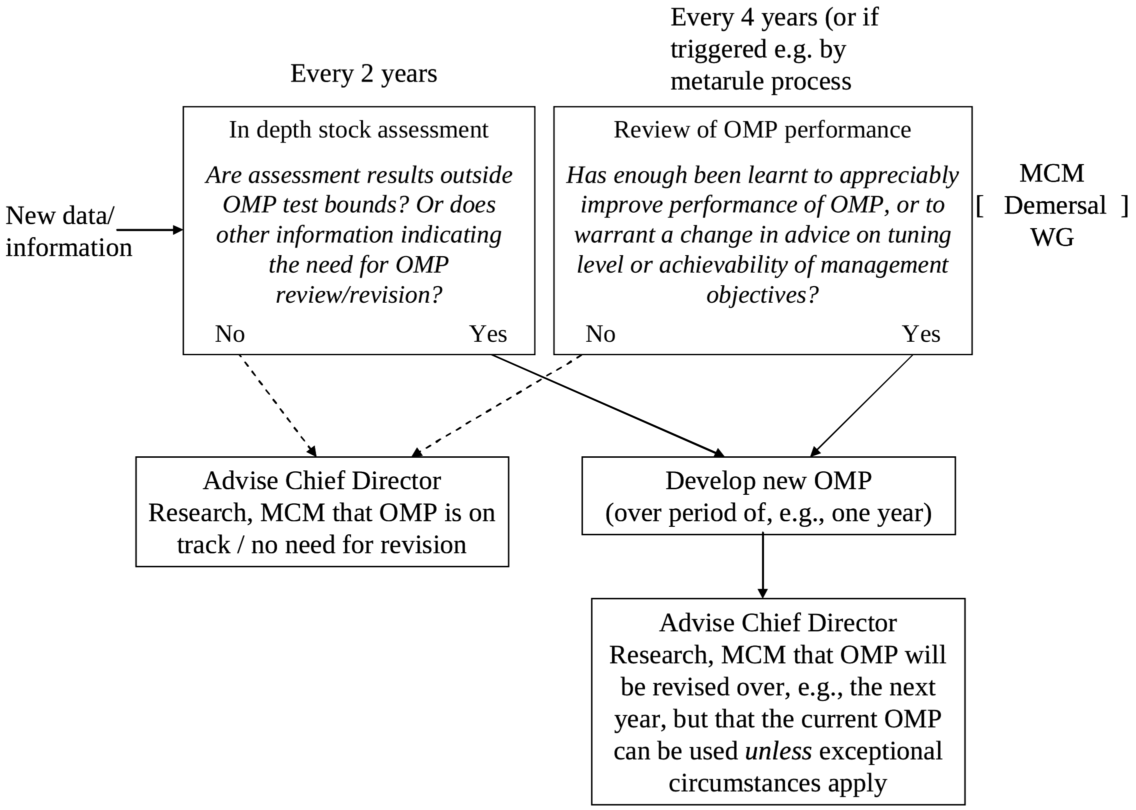


Figure App.5.II.2: Flowchart for regular review and revision process.

Chapter 6

Final remarks and application of OMP-2007

Summary

The TAC recommendations based on OMP-2007 are described for the period 2007-2010. Anecdotal reports of atypical environmental conditions during the January 2008 West Coast survey were the source of further analyses to determine whether this survey should be deemed "non-comparable" to previous surveys and therefore excluded from the TAC computations. Strong scientific evidence could not be provided and the OMP computations for the 2009 TAC did include the 2008 West Coast survey result.

6.1 Introduction

Environmental variability may have important effects on catch rates and research survey sampling (Hofmann and Powell 1998). Quantification of the effects of environmental variability on the shallow-water Cape hake *Merluccius capensis* and the deep-water Cape hake *Merluccius paradoxus* is complicated and remains highly uncertain. During this study concerns were raised that the 2008 environmental conditions and hence hake survey results were anomalous, and hence that this merited further investigation to determine whether or not that year’s survey data, a critical input to the OMP, should be included or not. OMP-2007, described in Chapter 5, had been adopted as the basis for recommending hake TACs over the 2007-2010 period until the next scheduled major review. The 2007 to 2010 recommendations are described below.

6.2 TAC recommendations for the period 2007-2010

6.2.1 2007 and 2008 TAC recommendations

The application of OMP-2007 saw the TAC reduced from 150 000t to 135 000t in 2007. From the simulated projections (see median trajectory in lower left hand panel of Figure 6.5) a further reduction of similar size was anticipated for 2008. Implementation of the OMP formula at the end of 2007 resulted however in a recommended TAC for 2008 of 130 532t, i.e. a reduction of only some 3.3%. The reason for the slightly more positive picture (still within the likely range indicated by the simulated projections) was that the trends in *M. paradoxus* abundance indices were a little better than anticipated.

As advocated in the OMP protocol (see Appendix 5.II), a routine update of the assessment was conducted at the end of 2007, including new commercial (catches and CPUE) and survey (abundance estimates and catches-at-age) data (Rademeyer and Butterworth 2007). Only one scenario of the Reference Set, the one with the highest likelihood, was run. This update did not indicate any major changes from the results obtained a year previously, which would show evidence for "Exceptional Circumstances".

For both 2007 and 2008, the TACs implemented did not differ from the scientific recommendations.

6.2.2 2009 TAC recommendation

Given anecdotal reports that environmental conditions during the January 2008 West Coast survey were atypical, questions were raised in the DWG during 2008 whether the results for that survey were inappropriate for use as input to the OMP. Exceptional Circumstances (see Chapter 5) would be called if sufficient evidence was provided of the "non-comparability" of that survey, i.e. that the conditions in January 2008 on the West Coast were outside the range customary for these surveys in the past, and such as to have an appreciable negative impact on hake catchability.

Assuming that the 2008 West Coast survey results were comparable to those from previous years, the OMP-2007 computations yielded a total 2009 TAC of 118 578 tons, a decrease of 9.14% from the 2008 TAC. What would be the implications of a possible conclusion that these survey results were indeed inappropriate to use? It would have been equivalent to assuming that this survey did not take place, i.e. a "missing data" situation. The document detailing OMP-2007 (Rademeyer and Glazer 2007) specifies the procedure which applies in such circumstances:

"Procedure in event of missing data

CPUE data
Non-availability of data to compute the GLM-standardised CPUE series for each species is not anticipated.

Survey data
a) If at most two of the four survey estimates are not available in a given year, the computations continue as indicated, with the missing data omitted from the regression estimates of slope.
b) If more than two such estimates are missing, or if for more than one survey two years have been missed, computations will continue on the basis in a), but an OMP review will commence immediately. "

Thus in the event that the 2008 West Coast survey had been found by the DWG to have been "non-comparable" to the other surveys, and consequently paragraph a) above applied, the revised output from the OMP in that case would have been a recommended TAC of 123 768 tons.

Preliminary analyses were conducted comparing the environmental data recorded during surveys to determine if any significant difference between the 2008 survey and previous surveys could be found (OLRAC 2008). Although the 2008 results showed some difference to some of the other surveys, these investigations did not yield any conclusive evidence that the environmental conditions prevailing at the time of the January 2008 survey were anomalous when compared to those in previous years, nor that there was any meaningful link between such environmental conditions and the catch rate of hake. Indeed, a potential difference between the environmental conditions during the 2008 and other surveys would have to be linked to the availability of hake before the survey results could be set aside. Further planned analyses could not be completed in time to meet the deadline for the submission of the TAC recommendation for 2009. Furthermore, a survey cannot be discarded without scientifically rigorous and defensible justification, and in circumstances of uncertainty the precautionary approach requires that the lower of alternative TACs apply until such uncertainty might be resolved. The following recommendation was therefore made for the 2009 hake TAC (MCM 2008):

1. *" The **TAC** for 2009 be set in terms of OMP_{2007} at 118 578 tons (i.e. a reduction of 9.1356% from the 2008 level of 130 500 tons).*

[...]
Given the current uncertainty regarding possibly anomalous environmental conditions prevailing at the time of the January 2008 survey and their possible impact on the validity of the abundance estimates for hake from that survey, it is further recommended that:

4. *Current investigations into these conditions be continued with a deadline of 28 February 2009.*
5. *If these investigations provide* ***compelling scientific evidence,*** *that would withstand international scientific peer review, that conditions during the January 2008 survey were anomalous in comparison with previous years* ***and*** *that these conditions lead to a reduction in the catch rates of hake* ***to the extent that*** *this survey under-estimated the biomass of hake, an upward-adjustment to the* ***TAC*** *may be applied in March 2009.*
6. *This upward-adjustment would be of the magnitude of 5 190 tons, bringing the total* ***TAC*** *for the season to 123 768 tons (i.e. a reduction of 5.1586% from the 2008 level), as would be indicated by* OMP_{2007} *if the results of the January 2008 survey was excluded from the calculation of the* ***TAC*** *for 2009."*

Strong evidence of the "non-comparability" of the 2008 January survey estimates was not available for the end of February 2009 deadline, so that the 2009 TAC remained at 118 578 tons.

Work has been underway to investigate the possibility of including environmental data in survey standardisation. The focus needs to be on those environmental parameters that can be linked to hake catchability. Including environmental data in the survey standardisation should not however be confused with some sort of "quality control" on the surveys, in which for example certain environmental conditions (such as "green water") would be avoided in conducting tows. If such avoidance behaviour took place,in the future when it did not in the past, the whole survey series would become non-comparable and another calibration would be needed before the data could be used as input to the OMP.

6.2.3 2010 TAC recommendation

With all survey and CPUE abundance indices larger than for the previous year for both *M. paradoxus* and *M. capensis*, the total 2010 TAC output from OMP-2007 was 119 831 tons, i.e. 1.05% greater than the 2009 TAC.

6.3 Final remarks

At the time of the OMP-2007 development, the hake fishery was in a poor condition with abundance having recently declined, in part as a result of poor incoming recruitment for the two species. After a period of relative stability during the 1990's, the offshore trawler catch rate had declined by about 25% during the 2000's to economically near non-viable levels. Furthermore, separating the species in the analyses revealed that although the abundance of *M. capensis* was still at a reasonable level, *M. paradoxus* had dropped well below the standard target for fisheries, the Maximum Sustainable Yield level. OMP-2007 adopted for hake aimed at an appreciable increase in the abundance of *M. paradoxus*. This recovery plan anticipated *M. paradoxus* to reach the MSY target level after 20 years, while also seeking a 50% increase in catch rates within the following decade.

These gains could not be achieved without short-term pain in terms of catches. Over the four years in which OMP-2007 was in place, the TAC was reduced from 150 thousand tons to a little less than 120 thousand tons. While this required cutbacks in vessels and employment, the benefits in terms of improved catch rates and more healthy resources were already being seen towards the end of the period. Had this recovery plan not been agreed, together with a commitment that it would be implemented, it is doubtful that the MSC certification would have continued, given prevailing international norms for the rate of recovery that should be targeted for depleted resources, such as *M. paradoxus* in this case.

In Figure 6.1, the 2007 to 2010 TACs, the resulting annual TAC variability for that period and the abundance indices used to compute these TACs are plotted on top of the corresponding anticipated trajectories. The actual TAC trajectory happened to be a little better than expected in median terms, primarily because of CPUE and survey abundance indices for *M. paradoxus* which were better on average than anticipated in median terms.

Although the survey abundance indices were well within the projections, the actual CPUE indices, for *M. capensis* in particular, fell outside the values anticipated under OMP-2007 for the RS. Figure 6.2 plots the GLM-standardised CPUE series for the period 2007-2010. The 2009 series shows a different trend in recent years than the other three series, with CPUE falling more rapidly from 2003 than previously thought and for *M. paradoxus* subsequently increasing faster since 2006. Indeed, in 2009 a series of checks were carried out on the hake offshore trawl catch and effort data, which provide the basis of the GLM-standardised CPUE indices (Fairweather *et al.* 2009a). This revealed a problem with data extractions over the immediately preceding years. In revising the CPUE series, it was decided to include catch and effort data for all offshore companies, rather than for select companies only as had been done in the past. This explains in part why the actual *M. capensis* 2010 CPUE series falls well outside the projected bounds. The annual CPUE checks which should be standard during OMP implementation were not as thorough as they should have been, as more attention was focused on *M. paradoxus* and associated results. Although this was not checked during implementation as it should have been, the *M. capensis* CPUE lack of fit would likely not have been seen as an immediate concern because of the estimated healthy condition of *M. capensis* relative to its MSY biomass level.

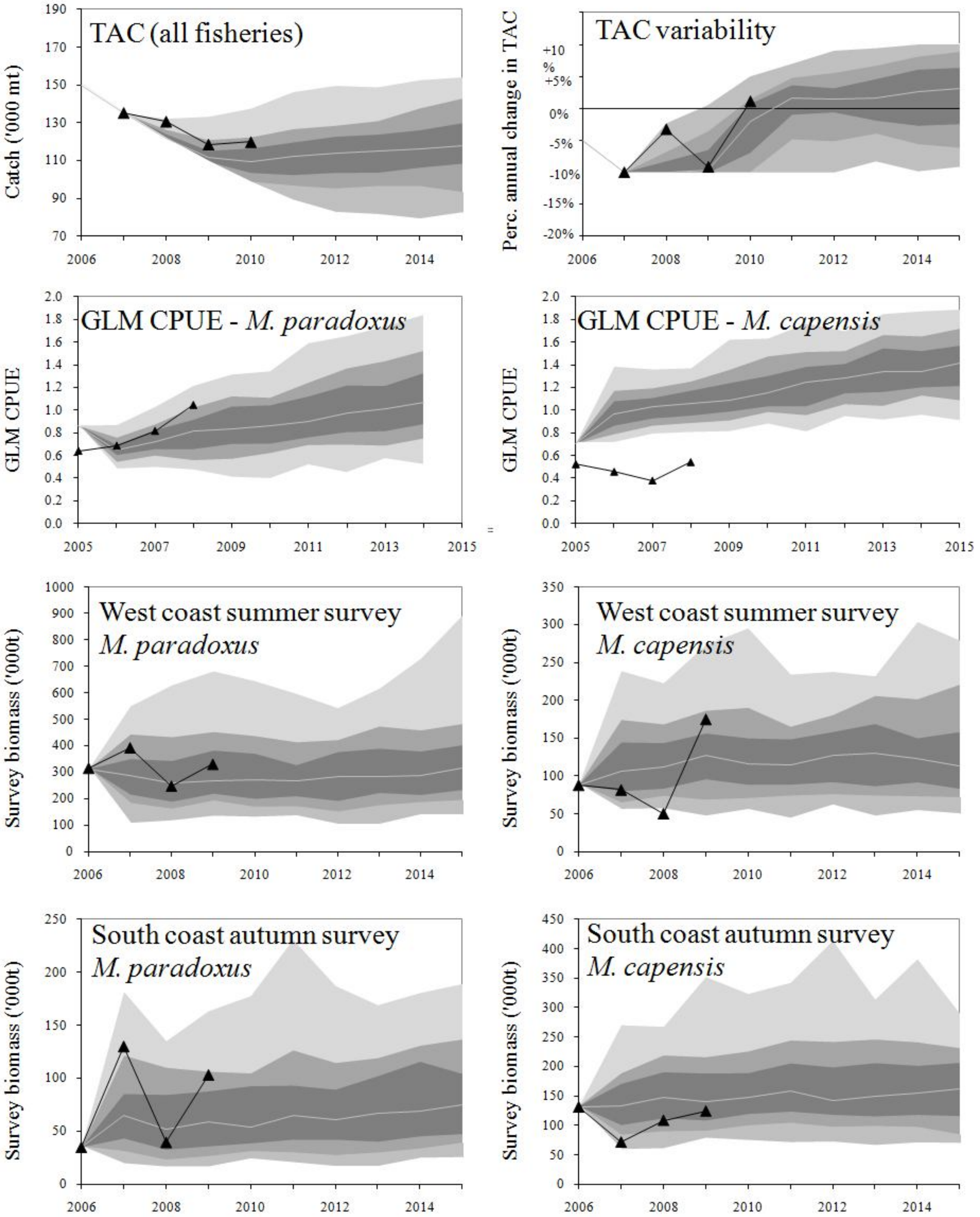


Figure 6.1: Anticipated trajectories (median, 50%, 75% and 90% probability intervals) of TAC, TAC variability, CPUE and survey indices for application of OMP-2007 to the RS. The actual values which eventuated during the period OMP-2007 was applied (2007-2010) are shown as black triangles. The CPUE values have been normalised by their mean over the 1978-2005 period.

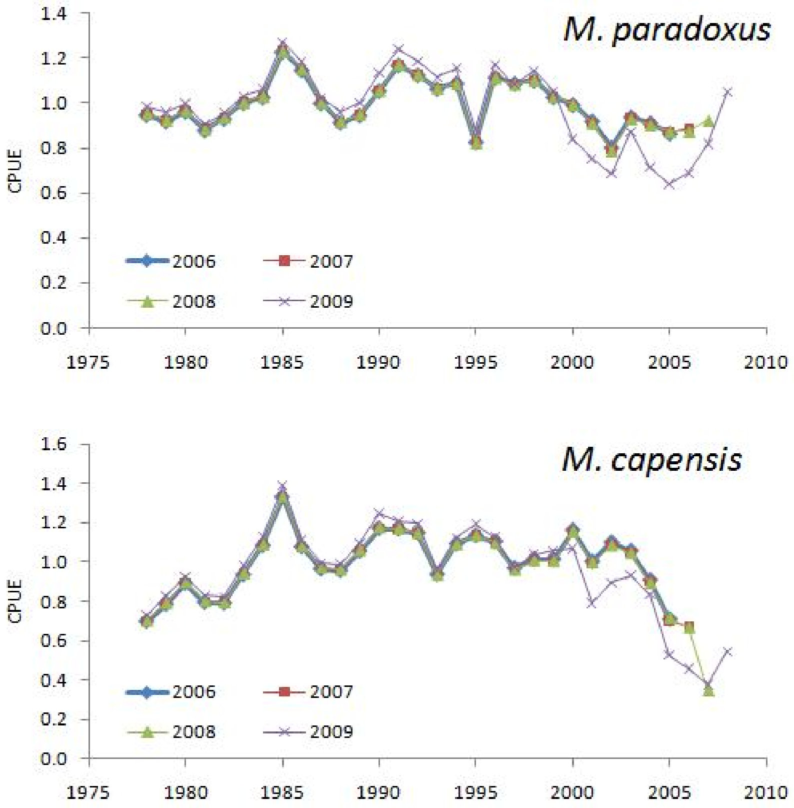


Figure 6.2: GLM-standardised CPUE series for the period 2006-2009. The series have been normalised by their mean over the 1978-2005 period.

SECTION III

Paving the way for OMP-2011

Chapter 7

Why does the current hake assessment indicate the extent of depletion of the *M. paradoxus* population to be high, but that of *M. capensis* to be much less?

Summary

The relatively high extent of depletion estimated for the *M. paradoxus* population is found to be robustly determined, with all five sources of data contributing to the assessment suggesting that both this depletion and recent fishing mortality are relatively high. However these fives sources lead to appreciably different perceptions for the extent of depletion of the *M. capensis* population. The GLM-standardised CPUE series commencing in 1978 is found to be the most influential of the five in leading to present estimates of both a relatively low extent of depletion and fishing mortality for this population. However if there is a trend in bias over time in this index as a measure of abundance, irrespective (almost) of the direction of this bias, the extent of depletion of the *M. capensis* population would be estimated to be notably higher. Research priorities indicated by this analysis include a focus on ageing and sex-differentiation for *M. paradoxus*, and on the possibility that factors responsible for an increase in catching efficiency may have been omitted from the *M. capensis* CPUE GLM standardisation.

7.1 Introduction

Arising from the change in hake assessments from a species-combined to a species-disaggregated form, surprise has been expressed by some at the different statuses estimated for *M. paradoxus* (well below its MSYL) and *M. capensis* (well above its MSYL). Identification of the underlying determinants of these estimates was identified as a high priority issue at the international stock assessment workshop held in December 2008 (Punt and Smith 2008).

This Chapter investigates the reasons underlying the recent estimates of depletion for the two South African hake species reported in assessments around the time OMP-2007 was adopted (Rademeyer and Butterworth 2008) and aims to identify which data source(s) is the primary determinant of these current estimates. This is effected by setting up the assessment model in a form which includes catch data, pre-specifies natural mortality and selectivity (in most cases) at the values estimated for the full assessment, sets the recruitment deviations to zero, and then fits to each data source in turn. These restrictions are necessary as with only single sources of data, it is not possible to estimate as many parameters as for the full assessment.

7.2 Methods

The model used for this analysis is as for the 'New Baseline' assessment described in Rademeyer and Butterworth (2008), except that the model is not fit to the commercial and survey catch-at-length data, as questions had arisen about bias in the growth curves that have been used to incorporate these data. The only two parameters that are estimated for every implementation of these "limited data" assessments are the carrying capacities K^{sp} and the steepness parameters, *h*, for each species.

Two choices for natural mortality have been used, M1 and M2, in both of which *M* is age dependent and for which the following values have been set for ages 2 and 5 with the previous assumptions for age-dependence made to provide the values at other ages:

M1: $M_2 = 0.7$, and $M_5 = 0.35$

M2: $M_2 = 0.4$, and $M_5 = 0.2$

Note that these are not identical to the specifications for the standard OMP-2007 Reference Set of assessments (Chapter 4), where bounds are set on the values of *M* at these ages, rather than the values being fixed. Here the M1 selection is close to the estimates obtained for the best fit amongst the OMP-2007 Reference Set, and the selection made for M2 was primarily intended to provide substantial contrast to M1.

The survey and commercial fishing selectivities have been set to those estimated when all the data sources are used. When the model is fit to catch-at-age data, it is possible to estimate the corresponding selectivities and this has been done in some cases. The deviations about the stock-recruitment curve are set to zero.

The final *M. paradoxus* and *M. capensis* depletions are estimated when each data source is included in turn. Then to investigate the shape of the likelihood profile for these depletions, the model is run including a penalty function (not included in plots of the likelihood profile) that forces the 2008 depletions to specific values chosen across a wide range.

7.3 Results and Discussion

7.3.1 Implications of using only single sources of data

The negative log-likelihood contributions were computed for a series of *M. paradoxus* final depletions and for each data source fitted in turn (Figure 7.1). In most cases, this is shown for the two choices of natural mortality. The *M. paradoxus* depletions estimated when all data sources are included are shown as arrows. When the model is fit to commercial or survey catch-at-age data, the results are also shown when the corresponding selectivities are estimated as well.

Figure 7.2 is similar to the first figure except that the negative log-likelihoods are plotted for a series of *M. capensis* final depletions. Only the first choice for the *M* vector has been investigated in this case, as the computations are time consuming, and the inter-*M*-choice change in pertinent results is not large for *M. paradoxus*.

The results shown in Figures 7.1 and 7.2 are summarised in Table 7.1. It lists the estimated final depletions and the increase in the negative log-likelihood for a specific data source when i) all data sources are included and ii) when the final depletion is forced to 0.4 for *M. paradoxus* and to 0.3 for *M. capensis*.

For *M. paradoxus*, all data sources point towards a high extent of depletion. Although the catch-at-age information (both commercial and survey) seems the most influential in determining the depletion estimate, when the selectivity is estimated these data are not more influential than the others.

Unlike for *M. paradoxus*, the different data sources do not all point in the same direction in terms of final depletion estimates for *M. capensis,* with the surveys in particular pointing to a current biomass well below MSYL while the GLM CPUE (the most influential in terms of the likelihood) pointing towards the opposite direction.

The negative log-likelihood increase of 92.7 (for M1, and 86.6 for M2) for *M. paradoxus* for all data may seem surprisingly large given the lesser values for each data set individually. This is linked to the -lnL for the catch-at-age contributions (the commercial data particularly) increasing substantially because of the selectivities being fixed.

7.3.2 Estimates of *F*

Table 7.2 lists the recent fishing proportions for the two species (reported as averages over the 2004 to 2008 period), while Figure 7.3 plots the annual fishing proportions. These fishing proportions (summed over all fleets) are for the assessment with all data included and for the two choices of *M*; they are also shown for two historical catch series (C1 and C3). The C3 series assumes that the centre point of the historic change from a primarily *M. capensis* to primarily *M. paradoxus* fishery occurred in 1957 rather than 1950 for C1, and hence reflects a greater cumulative catch of *M. capensis.* With the C3 catch option, the fishing proportion is increased slightly in the 1950's and 1960's but this does not have a substantial effect on the overall fishing proportion.

The recent fishing proportion is approximately 10 fold larger for *M. paradoxus* than for *M. capensis*.

Figure 7.4 shows the average catch-at-age proportions for the two species on the West and South coasts. These plots clearly evidence a larger total mortality rate *Z* for *M. paradoxus* than for *M. capensis*. This is not an unambiguous reflection of greater fishing mortality on *M. paradoxus* than on *M. capensis*. It arises in part from the declining selectivity of *M. paradoxus* at older ages, one likely reason for which being that some larger *M.*

paradoxus are located in waters deeper than those in which the fishery operates. However the assessment admits unrestricted estimation of the parameter accounting for this declining selectivity effect, and hence indicates that that effect alone is insufficient to account for the higher *Z* for *M. paradoxus* for which higher fishing mortality than for *M. capensis* must therefore be a contributory factor.

Figure 7.5 shows the average fishing proportion-at-age over the 2004-2008 period for both species, again illustrating the higher recent fishing intensity on *M. paradoxus* compared to *M. capensis*. .

Figure 7.6 plots the spawning biomass per recruit as a function of fishing proportion *F* for the two species. Given that the assessments generally estimate stock-recruitment steepness *h* to be very high, these plots closely reflect the population depletion to be expected as *F* is increased. It is therefore very clear that the existing estimates of depletion are closely related to these estimated fishing proportions.

7.3.3 What would lead to a greater extent of depletion for *M. capensis*

It is clear from Table 7.1 that all data sources point to a low recent (2008) extent of depletion for *M. paradoxus*. The estimate for *M. capensis* is however heavily influenced by the GLM CPUE series. It is possible that the GLM series trend could be biased as an index of abundance as a consequence of undetected changes in fleet efficiency. To investigate the effect of such possible biases in the GLM CPUE series, the assessment has been run including biases in trends for these series for a number of different values for this bias for each species in turn. Figure 7.7 shows the actual GLM CPUE series and as they would appear if adjusted for certain potential positive and negative biases in their overall trend. Figure 7.8 shows how the depletion estimates are affected by these possible biases. The estimated steepness parameters are also shown, as the sudden important large change in depletion for *M. capensis* is caused by a switch from an estimated high steepness to a low steepness. Depletion estimates for *M. paradoxus* are not as affected as those for *M. capensis* by trends in bias in the GLM CPUE series. The existing series for *M. capensis* correspond (almost) to the lowest of the range of possible extents of depletion of the *M. capensis* population; in particular if the bias trend is negative (as would correspond to an undetected increase in efficiency in the catching power of the fleet), the extent of depletion would be estimated to be appreciably higher (e.g. for an undetected increase in efficiency of 2% per year, the depletion estimate for *M. capensis* drops from 0.75 to 0.23).

Figure 7.9 plots the spawning biomass trends for *M. capensis* for a series of trends in bias in the GLM CPUE series, while Figure 7.10 shows how these trends affect estimates of the 2008 ratio of the spawning biomasses of *M. capensis* to *M. paradoxus*. With an undetected increase in efficiency in the *M. capensis* fishery, this ratio drops from 4 towards parity, which some have suggested would be a more realistic appraisal.

As the negative bias in the trend of the *M. capensis* GLM-standardised CPUE trend is increased, the assessment results suddenly switch from a low extent of depletion and high steepness to a high extent of depletion and low steepness. These results beg further explanation. Figure 7.11 shows the -lnL contributions from each data source to the total across the full range of possible steepness values, for the cases with no bias in the *M. capensis* GLM-CPUE series trend and when a trend bias of -0.5% p.a. (a value sufficient to "flip" maximum likelihood results to the low steepness option) is introduced to this CPUE series. For the case with no bias in the trend, preference for the high steepness result is either neutral or strongly indicated for each data source. For the GLM-CPUE series however, the likelihood does also start improving at low steepness. For the case with a negative bias in the trend, the improved likelihood for the GLM-CPUE series for lower steepness becomes much more marked, to the extent that it over-rides the contrary trends in the CAA likelihoods. The result is that the total -lnL becomes multimodal in steepness, with (here) the mode at smaller steepness marginally preferred to that at high steepness.

Thus it is the multi-modality of the likelihood surface that results in the sudden switch in results evident in Figures 7.8 and 7.9. This indicates that use of maximum likelihood estimates alone for operating models may not be adequately capturing the extent of uncertainty about the status of the *M. capensis* population, so that it may be necessary to move towards Bayesian estimation for which posterior distribution would not evidence this rapid flip.

7.4 Conclusions

All five data sources point to a high extent of depletion for *M. paradoxus*. The value itself is driven by the combination of recent catch levels (note that these have on average been some fourfold larger than for those for *M. capensis* over the last five years) and of the high fishing mortality indicated by the rapid fall off in *M. paradoxus* catches with age. In contrast, the different data sources point in different directions with respect to the estimated depletion of the *M. capensis* population, with the GLM-standardised CPUE series that commences in 1978 playing the most influential role in the recent low fishing mortality and extent of depletion estimated for this population.

What aspects of the data merit checking to confirm the correctness or otherwise of these results? For *M. paradoxus*, attention should most likely be focussed on the combination of ageing and sex-differentiation, as changes there could impact the estimation of high fishing mortality that is being drawn from the recent catch-at-age distributions shown in Figure 7.4. For *M. capensis* re-examination of factors that might influence catching efficiency in the GLM-standardisation needs emphasis, particularly as undetected efficiency increases there could markedly change current perceptions of a relatively low extent of depletion of this population. The sensitivity (see Figure 7.8) of the estimate of steepness h for *M. capensis* to possible undetected trends in catching efficiency of the fleet suggests investigating cases where h is fixed at intermediate values in the [0.30; 0.98] range.

It is possible that some of the information on the level of depletion for both species is coming from the structural assumptions of the model. Some of these assumptions have been explored here, such as the constraints on natural mortality and the historic catches level. Other dimensions that could be considered in future work include the shape of the stock-recruitment curve and the assumptions made about the selectivities at larger ages. Overall analyses conducted thus far indicate robust determination of the relatively high extent of depletion estimated for the *M. paradoxus* population.

Table 7.1: For each source of data being fitted and each *M* vector choice, the first column gives the estimated *M. paradoxus* depletion (note that depletion is B^{sp}/K^{sp}, as distinct from extent of depletion which is [1 - B^{sp}/K^{sp}]), and the next two columns give the –lnL increase when all five data sources are included and when the *M. paradoxus* depletion is forced to 0.4. *M. capensis* results are shown similarly, except that the last column compares the –lnL to that when the *M. capensis* depletion is forced to 0.3.

		M. paradoxus			*M. capensis*		
	Fitted to:	a) Estimated *M. paradoxus* depletion	b) Increase in -lnL from a) when all data sources are included	c) Increase in -lnL from a) when 2008 *M. paradoxus* depletion is forced to 0.4	d) Estimated *M. capensis* depletion	e) Increase in -lnL from d) when all data sources are included	f) Increase in -lnL from a) when 2008 *M. capensis* depletion is forced to 0.3
M_2=0.7, M_5=0.35	survey	0.17	1.2	4.6	0.10	2.0	0.5
	historic CPUE	0.28	1.6	3.2	0.54	1.6	0.0
	GLM-CPUE	0.11	1.4	3.4	0.80	1.4	23.8
	survey CAA	0.08	1.2	20.5	0.39	1.4	0.0
	survey CAA (sel est)	0.09	1.6	2.5			
	commercial CAA	0.10	2.2	56.0	0.66	2.2	1.1
	commercial CAA (sel est)	0.10	7.7	3.4			
	all data	0.14	0.0	92.7	0.75	0.0	11.4
M_2=0.4, M_5=0.2	survey	0.14	1.2	6.0			
	historic CPUE	0.26	0.6	16.0			
	GLM-CPUE	0.10	2.7	1.4			
	survey CAA	0.10	0.2	16.0			
	commercial CAA	0.10	5.7	52.9			
	all data	0.11	0.0	86.6			

Table 7.2: Average fishing proportion (summed over all fleets) for the period 2004 to 2008 for the ages at maximum selectivity for *M. paradoxus* and *M. capensis*. This is shown for both choices of M vectors and two historical catch series (C1 and C3). Note that the C3 series assumes that centre point of the historic change from a primarily *M. capensis* to primarily *M. paradoxus* fishery took place in 1957 rather than 1950 for C1, and hence reflects a greater cumulative catch of *M. capensis*.

		M. paradoxus (age = 3)	*M. capensis* (age = 5)
Catch series C1	M_2=0.7, M_5=0.35	0.523	0.054
	M_2=0.4, M_5=0.2	0.540	0.075
Catch series C3	M_2=0.7, M_5=0.35	0.540	0.062
	M_2=0.4, M_5=0.2	0.541	0.067

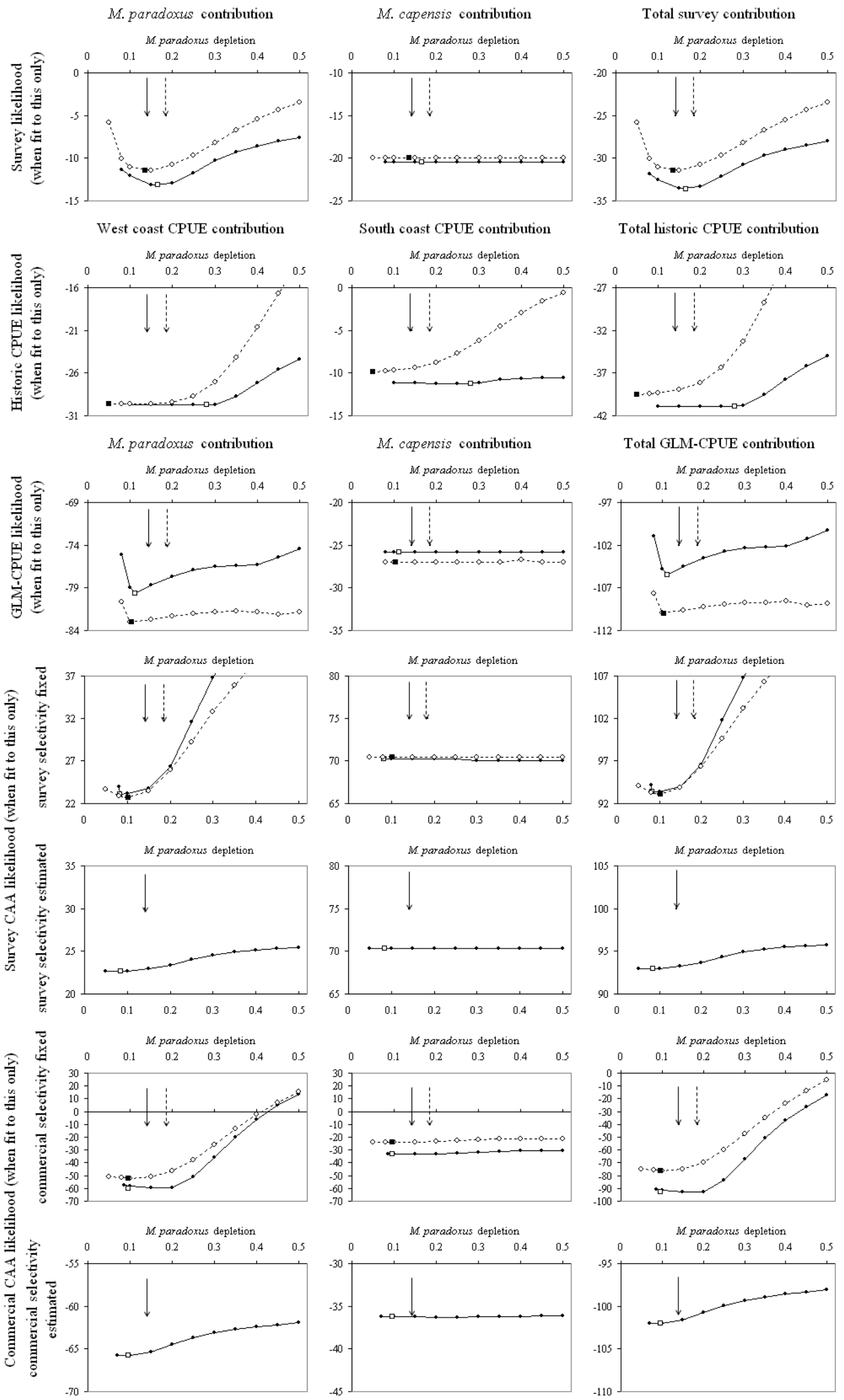


Figure 7.1: -lnL contribution of each data source when fitted on its own for a series of *M. paradoxus* depletions. The full lines represent the first *M* vector choice (M1: "M_2=0.7 and M_{5+}=0.35") while the dashed lines represent the second choice (M2: "M_2=0.4 and M_{5+}=0.2"). The downward arrows show the *M. paradoxus* depletion estimated for the assessment using all five data sources. Note: the vertical axis has been kept within a 15 points range for all cases except for the second last row.

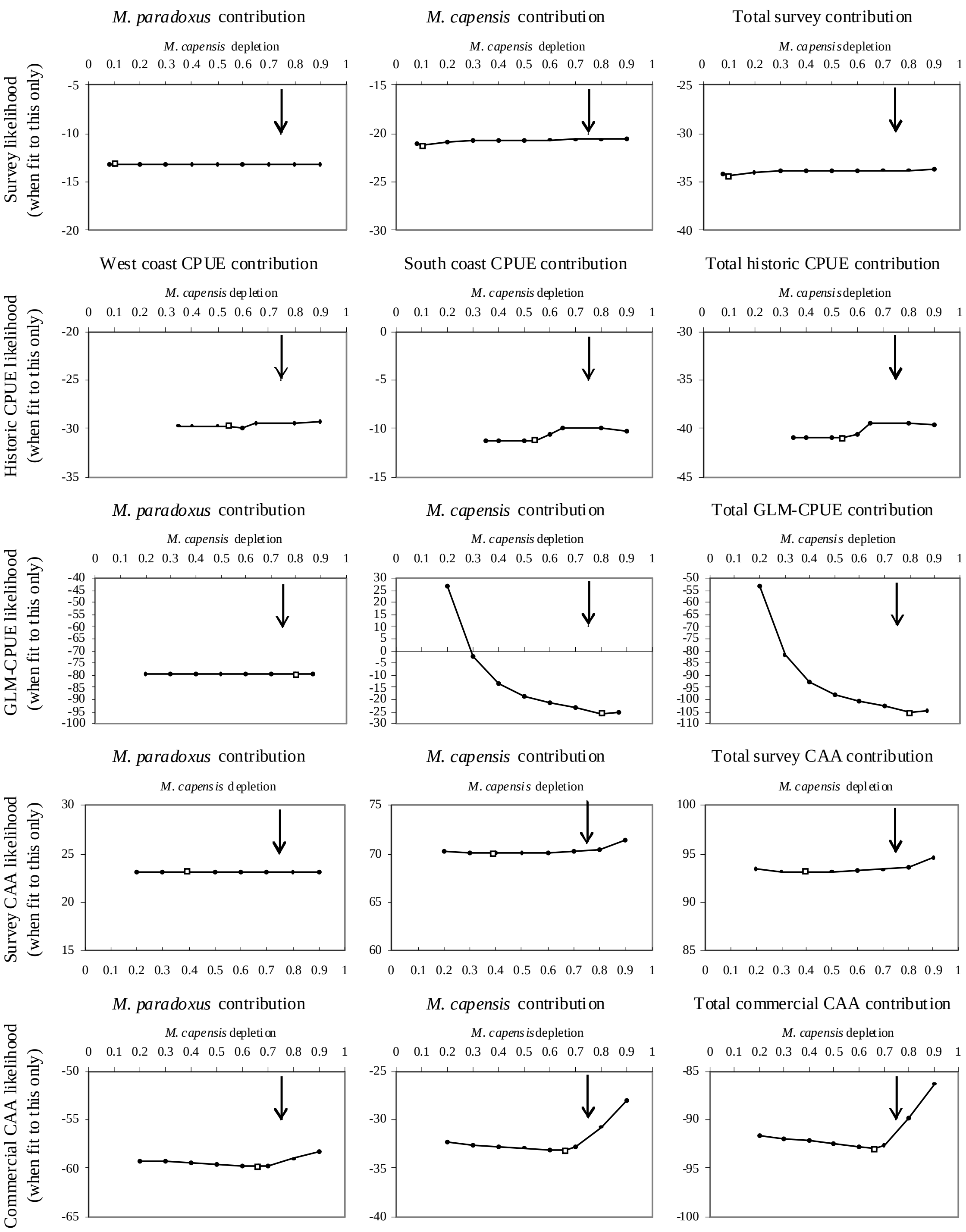


Figure 7.2: -lnL contribution of each data source when fitted on their own for a series of *M. capensis* depletions for the choice of *M* vector M1: "M_2=0.7 and M_{5+}=0.35". The downward arrows show the *M. capensis* depletion estimated for the assessment using all five data sources. Note: the vertical axis has been kept within a 15 points range for all cases except for the middle row.

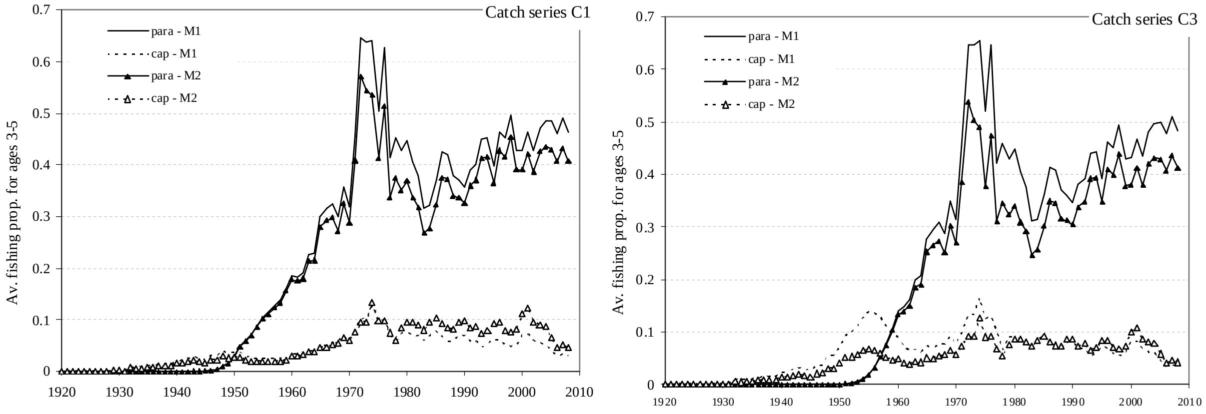


Figure 7.3: Annual fishing proportion (summed over all fleets) averaged over ages 3 to 5 for the assessment with all data, for the two choices of *M* and catch series C1 (left plot) and C3 (right plot).

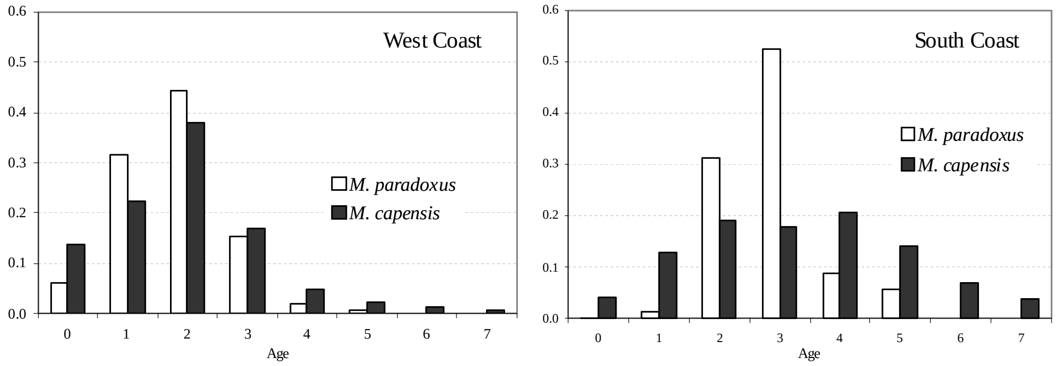


Figure 7.4: Survey catch-at-age proportions (averaged over all the years available).

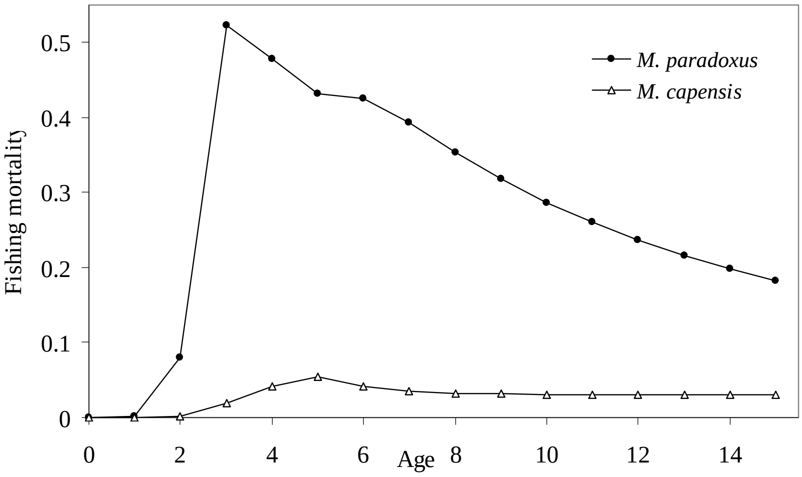


Figure 7.5: Average fishing proportion-at-age (summed over all fleet) for the period 2004 to 2008 for *M. paradoxus* and *M. capensis*, for the assessment with all data sources included, the M1 vector choice for natural mortality and historical catch series C1.

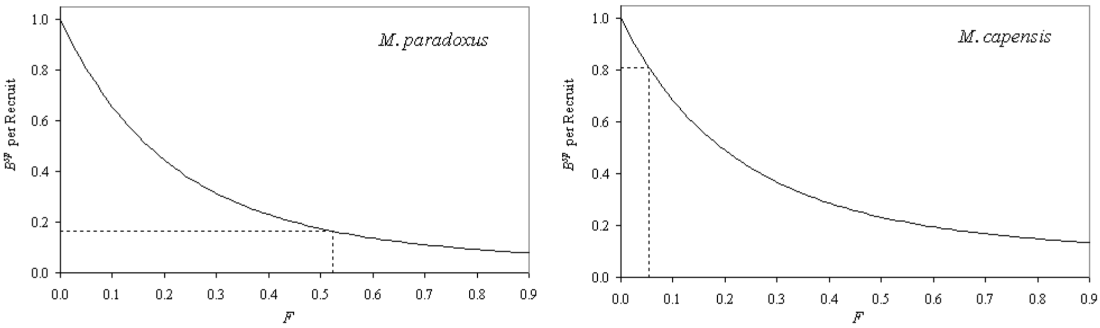


Figure 7.6: Spawning biomass-per-recruit (relative to that for the unexploited population) as a function of the fully selected fishing proportion *F*, for the assessment with all data sources included, the first choice (M1) for the *M* vector, and historical catch series C1. The selectivity used to compute these is the average over all fleets, assuming the same proportion of the catch as was made by each fleet in 2008. The dashed lines show the recent *F* levels (average of 2004 to 2008).

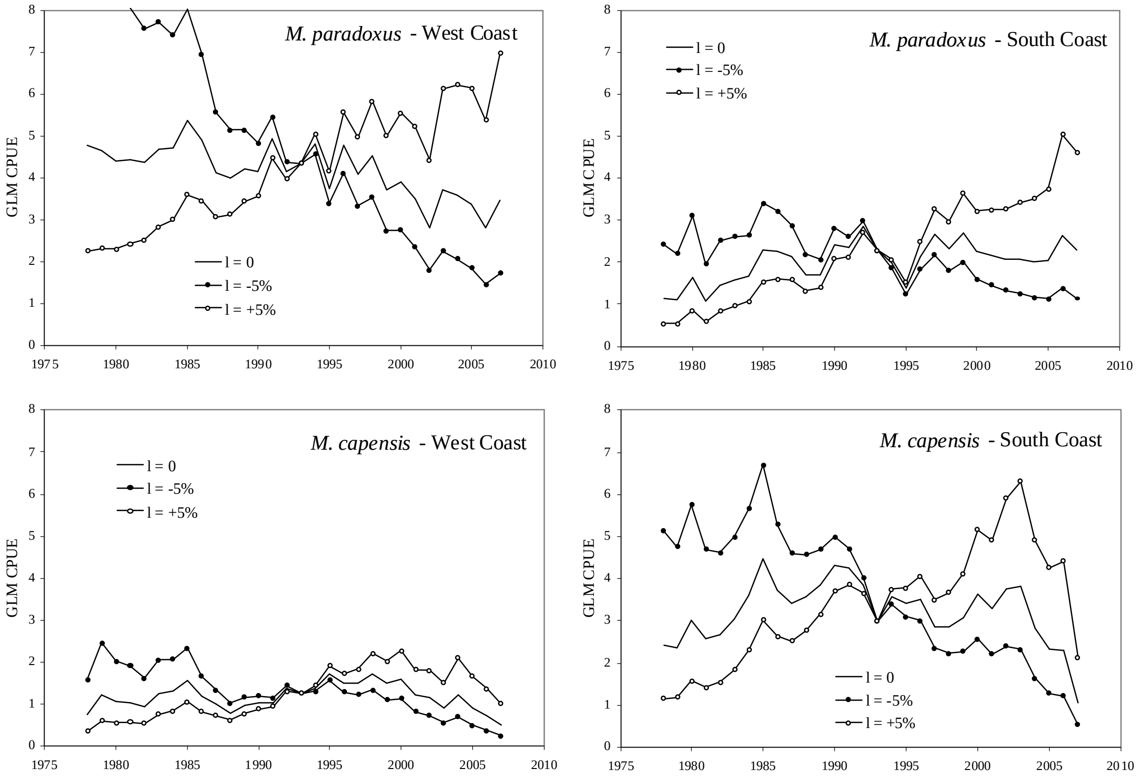


Figure 7.7: West Coast and South Coast *M. paradoxus* and *M. capensis* GLM CPUE series, and with two alternative bias trends added.

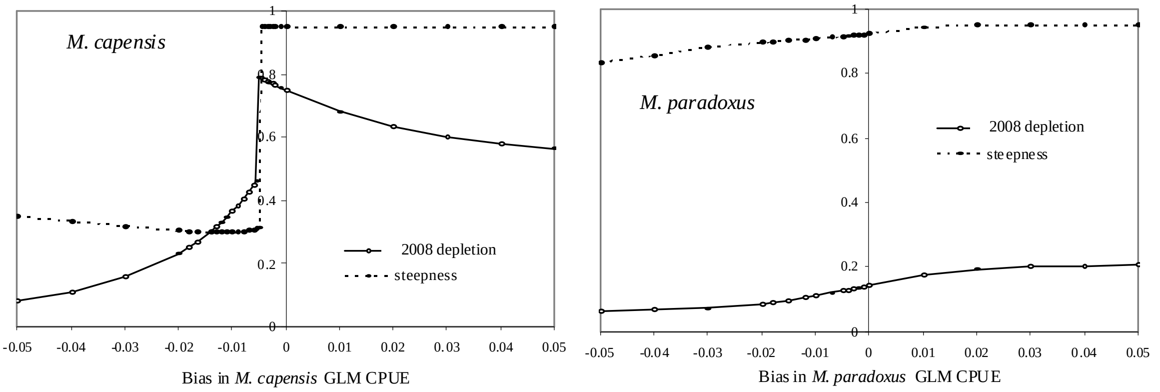


Figure 7.8: Estimated depletion and steepness parameters for *M. capensis* and *M. paradoxus* as a function of a bias trend in the respective GLM CPUE series.

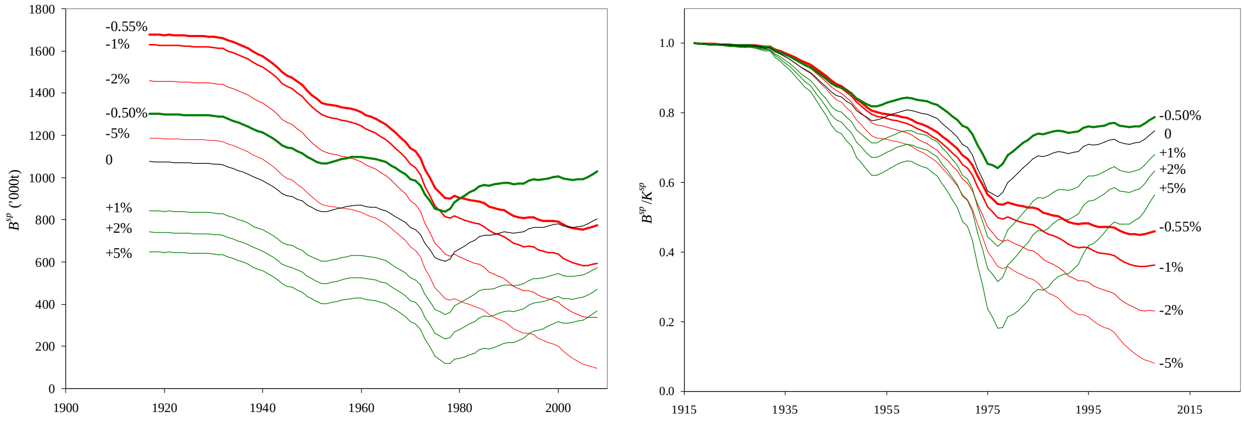


Figure 7.9: *M. capensis* spawning biomass trends for a series of values of a trend in bias in the *M. capensis* GLM CPUE series.

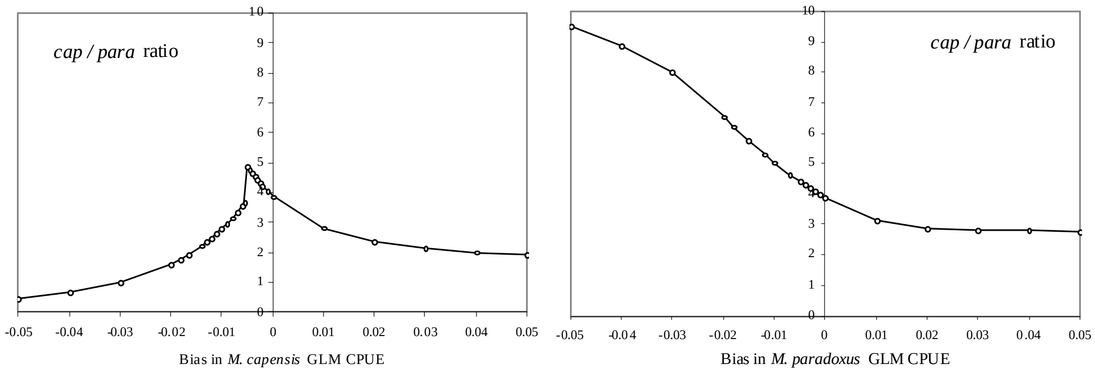


Figure 7.10: Estimated 2008 *M. capensis*/ *M. paradoxus* spawning biomass ratio for a series of values of a trend in bias in the *M. capensis* GLM CPUE series.

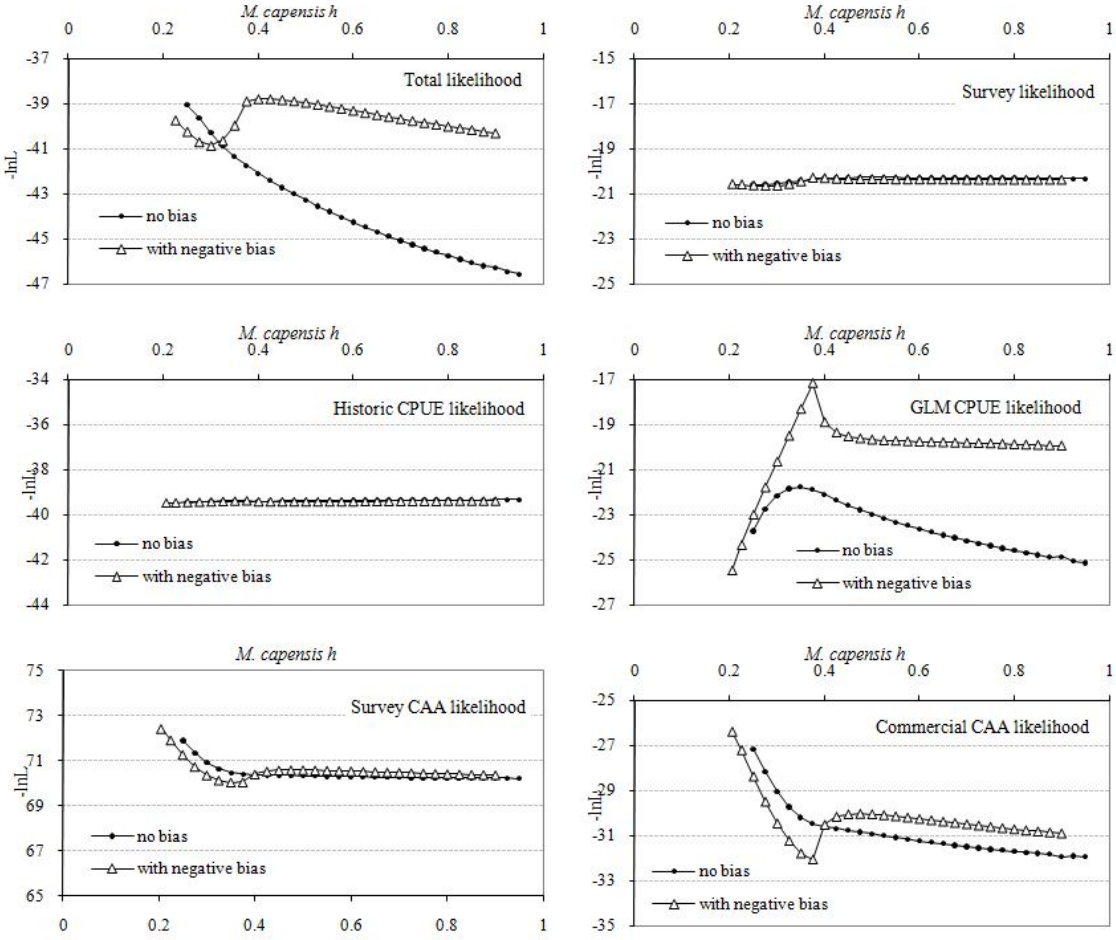


Figure 7.11: -lnL contribution of each data source for a series of steepness values *h* for *M. capensis*, for the assessment with all data sources included, and either no bias or with negative bias in the *M. capensis* GLM CPUE series trend.

Chapter 8

A gender-disaggregated assessment of the South African hake resource, fitting directly to age-length keys: a New Reference Case

Summary

The assessment methodology for the hake resource is refined to include gender-disaggregation, and to fit directly to age data and estimate growth curve parameters internally in the likelihood maximisation process. This approach successfully resolves the conflict between fits to catch-at-age and catch-at-length distributions evident in earlier assessments. The current *M. paradoxus* female spawning biomass is estimated to be at 59% of its MSY level, whereas the corresponding *M. capensis* estimate is well above that level.

8.1 Introduction

In updating the assessment presented in Chapter 4, the first step has been to incorporate catch-at-length information directly when fitting the population model. Indeed, it was discovered that in years for which age-length keys were not available, catches-at-length had been converted to catches-at-age based on averages of age-length keys for other years (a problematic and potentially biased approach). This work resulted in the development of a "New Baseline" assessment in 2008, in which catch-at-length information was used directly in years for which ALK are not available (Rademeyer and Butterworth 2008). However, the "New Baseline" fits to the commercial and survey catches-at-age and catches-at-length data were poor (Figures 8.1 and 8.2), the likely reason for this being a conflict between the catch-at-age and catch-at-length information. For example, for the offshore trawl fleet (West Coast and both coasts), the observed length distribution of the catch is very narrow compared to a relatively wide range of ages observed in the catches-at-age (Figure 8.1).

The Review Panel at the December 2008 International Stock Assessment Workshop (Punt and Smith 2008) made the following recommendation with respect to assessment of the hake resource "A sex-structured population dynamics model should be fit to the conditional age-at-length data (age-length keys) and length-frequency data (by sex when such data are available). The growth curves (and the variation in length-at-age) should be estimated within the assessment." The recommendation arose in large part from the need to resolve this conflict between catch-at-age and catch-at-length data, and growth curves input to the then current 2008 "New Baseline" assessment (Rademeyer and Butterworth 2008).

The reason for the gender-disaggregation is that very clear gender-specific differences in somatic growth exist for both *M. paradoxus* and *M. capensis* (Payne 1989), in fact more so than between species (as evidenced by the growth curve fits discussed below). Routine application of age-length keys to obtain catch-at-age proportions had been conducted without attention to gender-specific differences, but gender-differential growth means that larger sized males are not well represented in the catch. This could confound estimates based on catch-at-age data developed from a gender-aggregated age-length key, which might consequently under-represent the number of older hake present. This in turn could affect estimates of natural mortality as well as distort estimates of year-class strength. The comparatively low variability of previous estimates of the recruitment has been a puzzle and concern, which might be resolved by gender differentiation of the assessments. Furthermore there is a sex-imbalance in certain components of the fishery: for example Geromont *et al.* (1995) estimated a female proportion in the South Coast longline catches as high as 83%.

In the light of these considerations, the assessment of the hake resource was refined to incorporate gender- as well as species-differentiation. Thus in this analysis, the genders are modelled separately. As recommended above, the model is also fit directly to age-length keys (ALKs) and length frequencies (as e.g. in Punt *et al*. 2006), rather than to the age frequency information which multiplying the two would provide. There are three reasons for this:

a) ALKs are not available for all years and surveys or fisheries, so that length distribution data have to be fitted directly in those cases.

b) The fishery selectivity is essentially length- rather than age-specific; the assumption of age-specific selectivities when fitting to age-distribution data will lead to misfitting of length distribution data in these circumstances (e.g. the lower tails of the length distributions of younger fish are not present in catches, but an age-specific selectivity requires them to be).

c) The feature of the data described in b) leads to a bias in the estimation of hake growth curves if estimated directly from hake age data, leading to the lengths at younger ages being positively biased; growth curve parameters need to be estimated internally within the assessment to correct for this bias.

This Chapter reports the results from this refined assessment, which is termed the "new Reference Case" (RC). This assessment forms the basis from which the Operating Models that provide the basis for simulation testing of the revised OMP (OMP-2011) for hake are developed (Chapter 9).

8.2 Data and Methods

Appendix 8.I details the data used in this analysis, while the specifications and equations of the overall model are set out in Appendix 8.II.

8.3 Results and Discussion

Values of components of the negative log likelihood and estimates of management quantities for the new Reference Case are given in Table 8.1, while Figure 8.3 plots the spawning biomass trajectories. The spawning biomass trajectories for *M. paradoxus* and *M.*

capensis show little gender difference, with the current 2010 depletion estimated to be at 15% and 54% for *M. paradoxus* and *M. capensis* respectively. For *M. capensis* the female spawning biomass is estimated to be 12% above its MSY level, whereas the corresponding component of the *M. paradoxus* population is estimated at 59% of that level.

The estimated commercial and survey selectivities are shown in Figures 8.4 and 8.5 respectively. Apart for *M. paradoxus* on the South Coast, the male and female selectivities at length are assumed to be the same and are then converted to gender-specific selectivities at age. Because of selectivity differences between males and females apparent in the South Coast surveys for *M. paradoxus*, gender-specific selectivities are estimated for this species in the South Coast autumn and spring surveys, with the female selectivities (for *M. paradoxus* only) scaled downwards for these two surveys by a common factor across lengths which is estimated in the model fitting procedure. This gender difference is assumed to affect the commercial fleet as well, and the female selectivity for the South Coast offshore trawl fleet (the only fleet assumed to catch *M. paradoxus* on the South Coast) is therefore also scaled downwards by a factor estimated in the model fitting. The female selectivity scaling factors estimated for the South Coast spring and autumn surveys and the offshore trawl fleet are 0.13, 0.27 and 0.10 respectively.

All the commercial selectivities show a decrease for large fish. This decrease is estimated for all fleets apart from the offshore trawl and South Coast handline fleets for *M. capensis*. For the *M. capensis* offshore trawl fleet, the selectivity slope is fixed to 1/3 of the inshore trawl fleet slope estimated, while for the handline fleet, the selectivity slope is taken as the average of the estimated longline and inshore fleet slopes.

A penalty has been added to the -lnL to constrain the survey *q*'s for each species not to exceed 1 (see equation App.8.II.34). This amounts to the assumption that there is no substantial herding effect which is biasing the swept-area estimates of abundance from these trawl surveys, and precludes survey abundance estimates from (on average) exceeding the underlying available biomass. Huse *et al*. (2001) estimated a swept area survey *q* of about 0.8 for Namibian hake by comparing acoustic and swept area data. For the Reference Case, the *M. paradoxus q* for the West Coast summer survey hits the upper boundary of 1 (see Table 8.1).

Figure 8.6 plots the gender-specific growth curves estimated in the model, as well as the estimated length-at-age distributions. The difference between male and female growth curves is estimated to be more important for *M. paradoxus* than for *M. capensis*. *M. capensis* is estimated to grow larger than *M. paradoxus*.

Figure 8.7 plots the estimated stock-recruitment relationships, and the time series of residuals about these relationships for both species. A penalty was added to the -lnL so that the mean of the estimated recruitment residuals is close to zero (see equation App.8.II.43). The reason for this is that fits to the last 30 years for which these residuals could be estimated generally showed averages appreciably below zero for *M. capensis*. If such fits had been taken through to projections, this would have meant that immediate future recruitment for *M. capensis* would have been higher on average than over recent years, thus giving a likely spuriously positive impression of resource production. It was felt more appropriate to force this average level of future production to be similar to that over the past three decades. While the possibility that those decades constitute a regime of generally low *M. capensis* productivity cannot be excluded, the associated effective changes in K are considered better reserved for consideration in robustness tests. The extent of residual variability indicated for Figure 8.7 remains low compared to the norm for populations of similar demersal species (Ricard *et al*. 2011) (the output σ_R values are 0.26 and 0.29 for *M. paradoxus* and *M. capensis* respectively).

Figures 8.8 and 8.9 show the fits to the CPUE and survey abundance series. The fits are reasonable for all series.

The fits to the commercial catch-at-length data are shown in Figure 8.10. The length-at-age distributions are assumed to follow a log-normal distribution rather than a normal distribution, as plots of these data are indicative of skew distributions (see Figures App.8.I.2-4). The fits are averaged over all the years for which data are available and are reasonable for all the data sets. There are however some patterns evident in the bubble plots of residuals which could perhaps be improved by having further periods between which selectivities change.

The fits to the survey gender-aggregated and gender-disaggregated catch-at-age data are shown in Figures 8.11 and 8.12 respectively. These fits are also broadly reasonable. In particular, the problem of the lack of fit evident in the corresponding plots for the 2008 "New Baseline" assessment (Rademeyer and Butterworth 2008) appears to be resolved.

The fit to the ALKs is shown in Figure 8.13. The observed and predicted ALKs are compared aggregated over all ALKs, first summed over ages, which should be exactly equal by construction and then summed over lengths. The ALK likelihood downweighting factor, *w*, (see equation App.8.II.41) was set to 0.01 as fits from earlier runs with w=0.001 indicated an apparent lack of influence (underweighting) of these data.

The maturity-at-age ogive used in the new Reference Case is shown in Figure 8.14. Since resource depletion estimates can be sensitive to the manner in which spawning biomass is defined, Table 8.2 compares the estimated 2009 depletions for this ogive with those for fish of age 3+ and of age 4+ (definitions used for earlier assessments). Results for the ogive lie between those for fish of age 3+ and of age 4+.

Table 8.1: Values of components of the negative log likelihood and estimates of management quantities for the Reference Case. The modified Ricker γ values are given in parentheses next to the *h* values. The survey slopes given are for the West Coast summer and South Coast autumn surveys respectively (the two longest series). Note: MSY and related quantities have been calculated assuming a fishing pattern that is the average over the last five years (2005-2009). The natural mortality values shown in bold are fixed.

-lnL total		-94.5		
CPUE historic		-36.9		
CPUE GLM		-136.4		
Survey		-33.9		
Commercial CAL		-51.3		
Survey CAL (sex-aggr.)		-6.6		
Survey CAL (sex-disaggr.)		20.4		
ALK		124.4		
Recruitment penalty		9.1		
Selectivity smoothing penalty		16.2		
		Both	Males	Females
M. paradoxus	K^{sp}	1363	649	715
	h	1.08	(0.18)	
	B^{sp}_{2009}	208	107	102
	B^{sp}_{2009}/K^{sp}	0.15	0.16	0.14
	B^{sp}_{MSY}			174
	B^{sp}_{MSY}/K^{sp}			0.24
	$B^{sp}_{2009}/B^{sp}_{MSY}$			0.59
	MSY	113		
	M_{2-}	**0.75**		
	M_{5+}	**0.375**		
	survey slopes (cm^{-1})	0.002	0.141	
M. capensis	K^{sp}	516	254	262
	h	1.01	(1.58)	
	B^{sp}_{2009}	279	142	137
	B^{sp}_{2009}/K^{sp}	0.54	0.56	0.52
	B^{sp}_{MSY}			122
	B^{sp}_{MSY}/K^{sp}			0.47
	$B^{sp}_{2009}/B^{sp}_{MSY}$			1.12
	MSY	69		
	M_{2-}	**0.75**		
	M_{5+}	**0.375**		
	survey slopes (cm^{-1})	0.008	0.071	
2009 species ratio B^{sp}		1.34	1.33	1.34

	Both	*paradoxus*	*capensis*
Survey q's:			
WC summer		1.00	0.39
WC winter		0.96	0.53
SC spring		0.37	0.67
SC autumn		0.40	0.82
Additional variance:		0.15	0.11
survey CAL 0's:			
Sex-aggr. data:			
WC summer		0.08	0.14
WC winter		0.08	0.13
SC spring		0.13	0.06
SC autumn		0.11	0.04
Sex-disaggr. data:			
WC summer		0.07	0.11
WC winter		-	-
SC spring		0.07	0.05
SC autumn		0.09	0.05
CPUE 0's:			
WC ICSEAF	0.25		
SC ICSEAF	0.25		
WC GLM		0.15	0.24
SC GLM		0.25	0.19
com CAL 0's:			
WC offshore	0.07		
SC offshore	0.10		
SC inshore	0.07		
WC longline	0.04		
SC longline	0.06		
offshore	0.07		

Table 8.2: Estimated 2009 depletion for the new Reference Case spawning biomass, 3+ biomass and 4+ biomass for *M. paradoxus* and *M. capensis*.

	M. paradoxus	*M. capensis*
B^{sp}_{2009}/K^{sp}	0.15	0.54
B^{3+}_{2009}/K^{sp}	0.18	0.55
B^{4+}_{2009}/K^{sp}	0.13	0.50

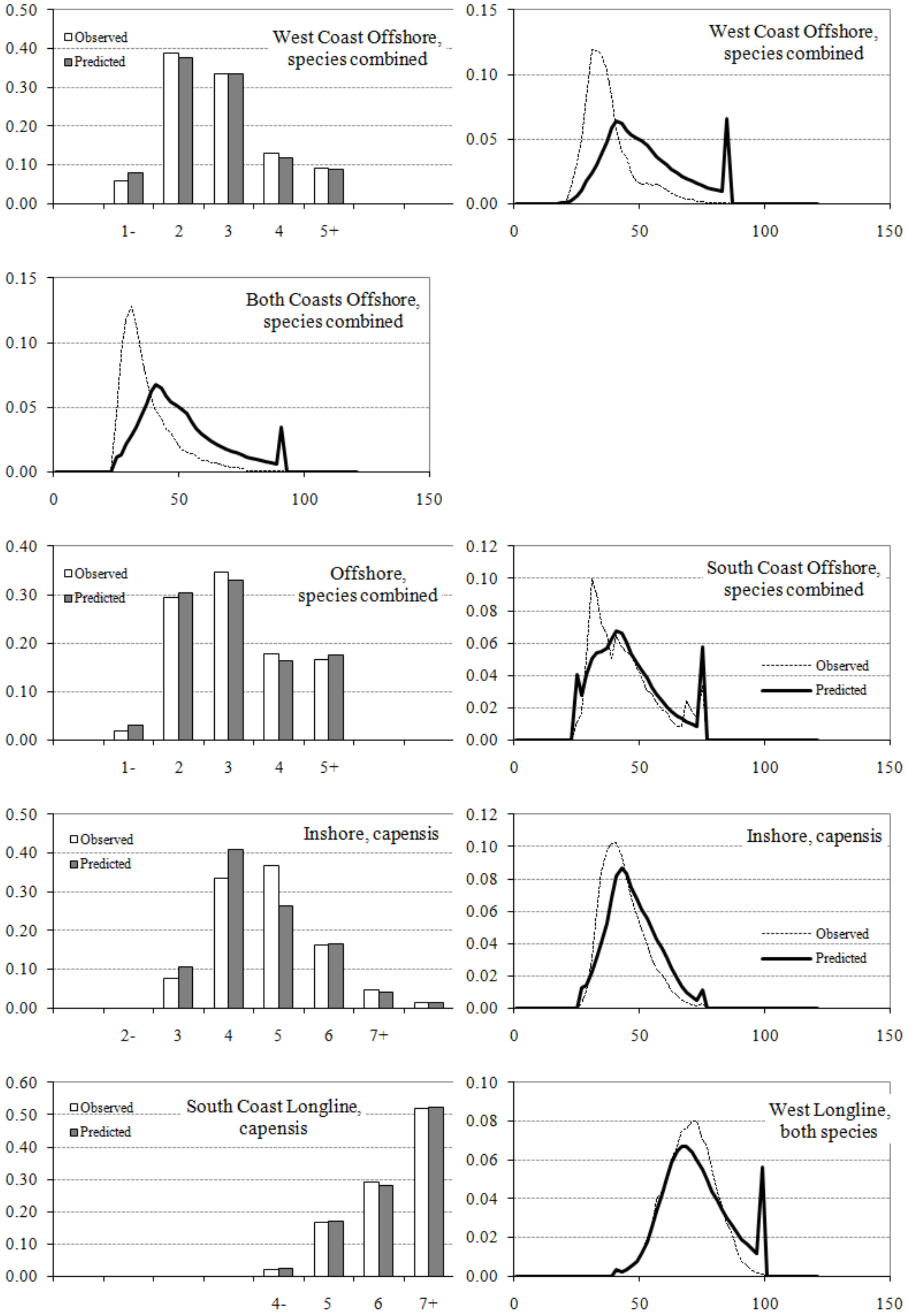
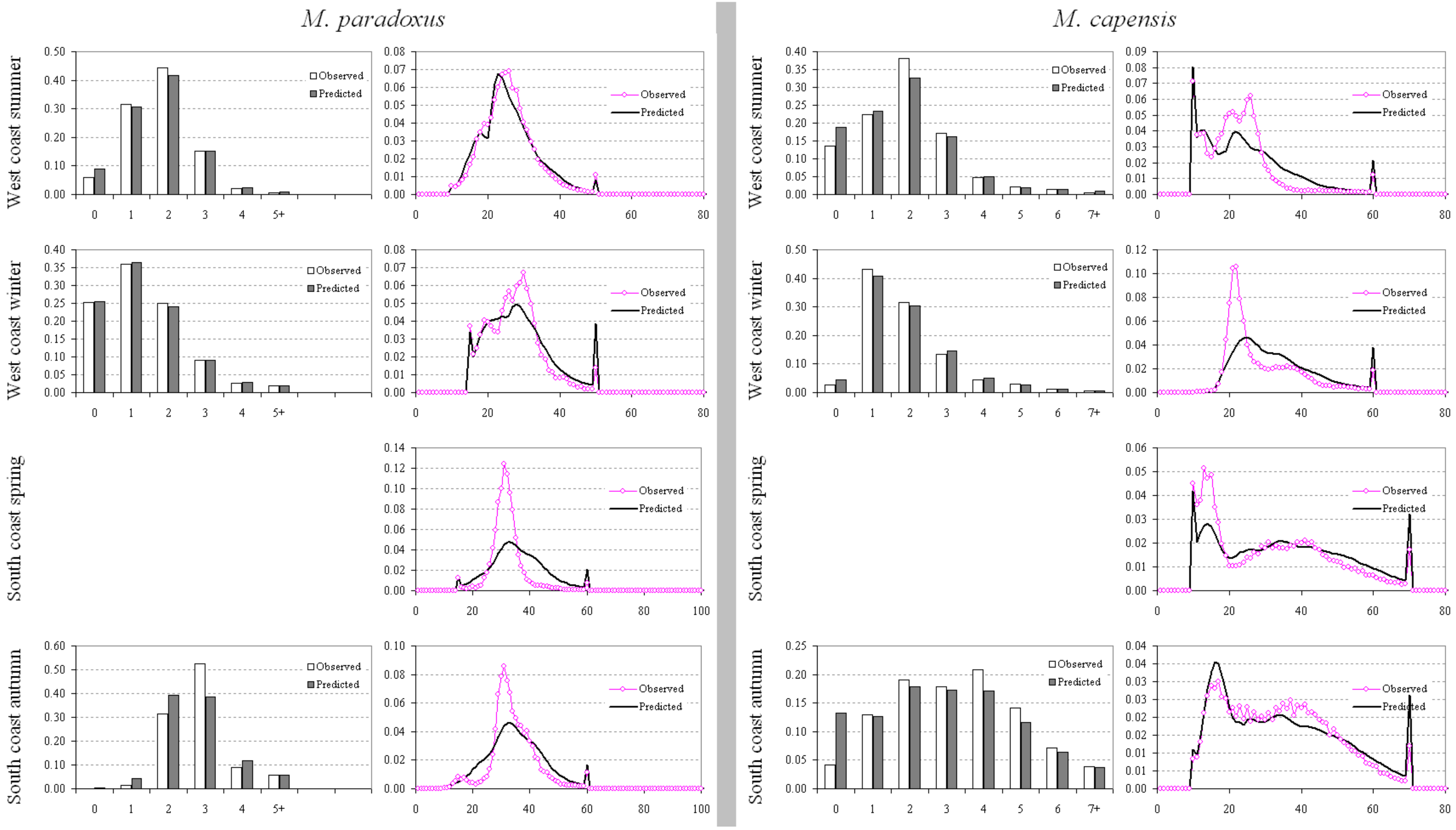


Figure 8.1: Fit to the commercial CAA and CAL data for the "New Baseline" assessment of 2008 (Rademeyer and Butterworth 2008).

Figure 8.2: Fit to survey CAA and CAL for *M. paradoxus* for the "New Baseline" assessment of 2008 (Rademeyer and Butterworth 2008).



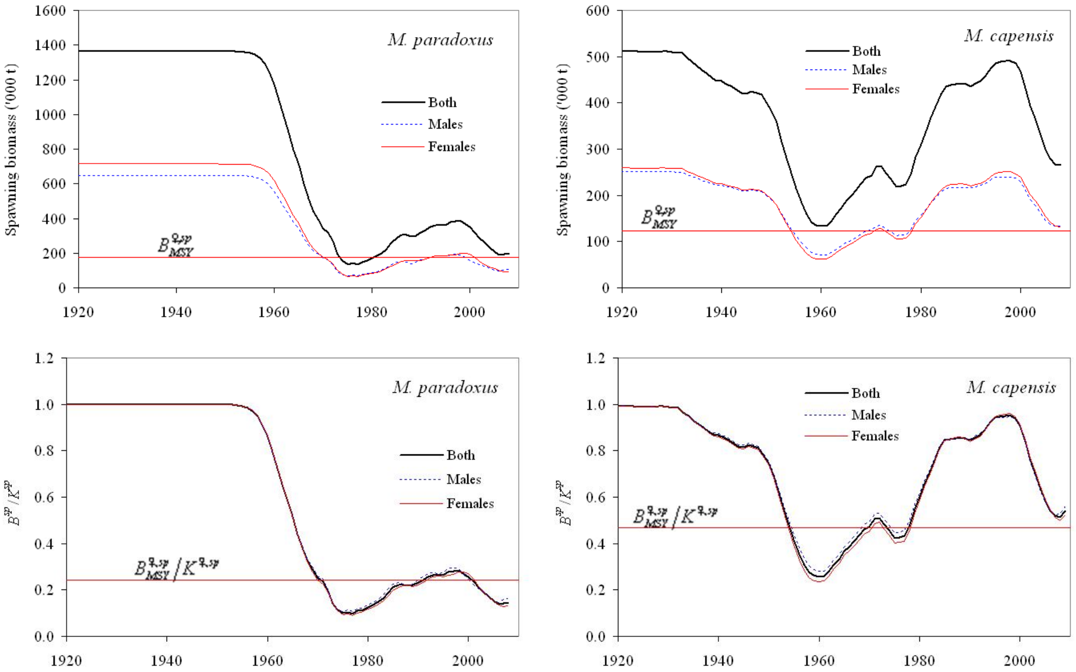


Figure 8.3: Estimated spawning biomass trajectories for *M. paradoxus* and *M. capensis*, both in absolute terms and relative to the pre-exploitation level for the RC.

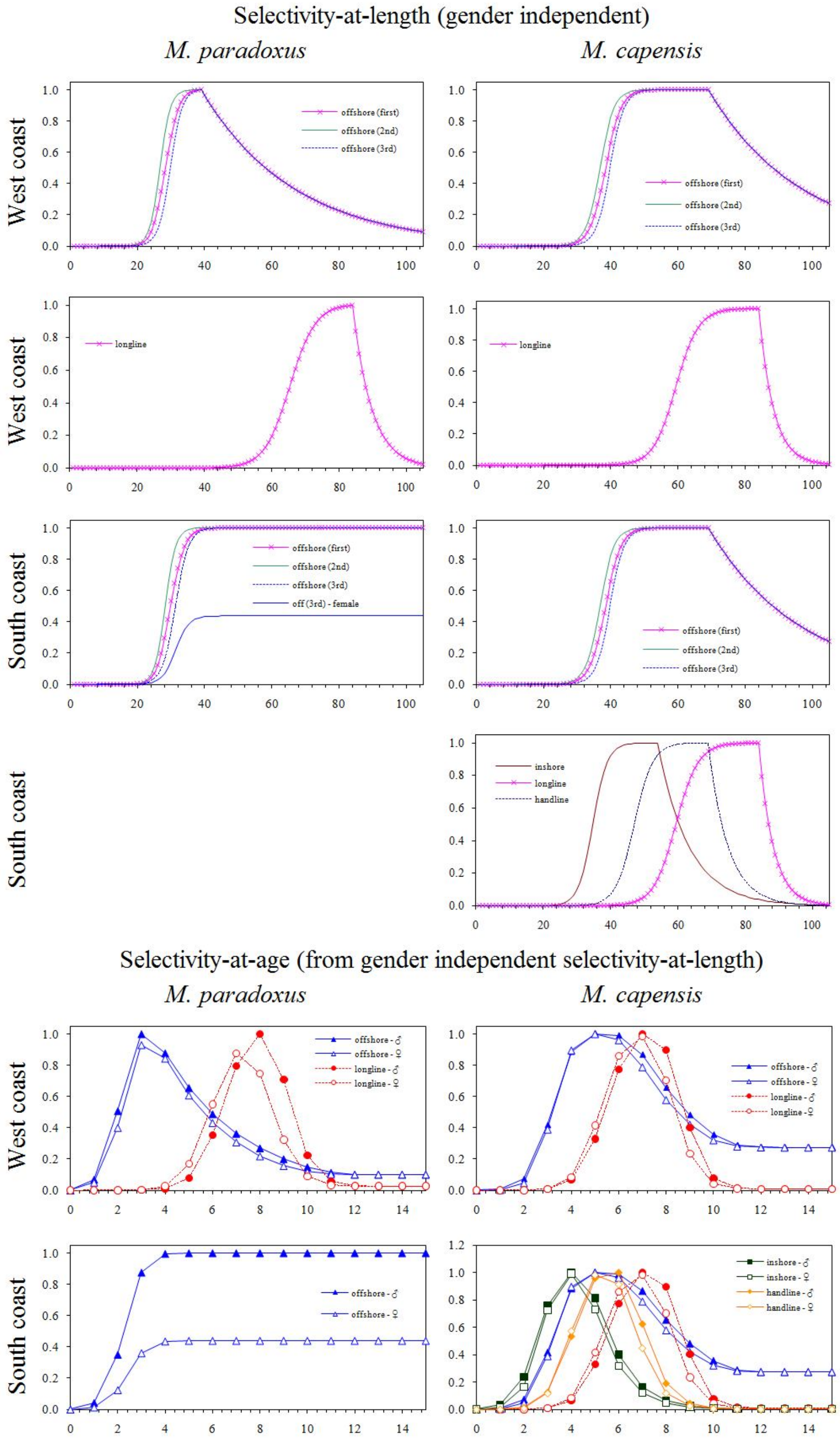
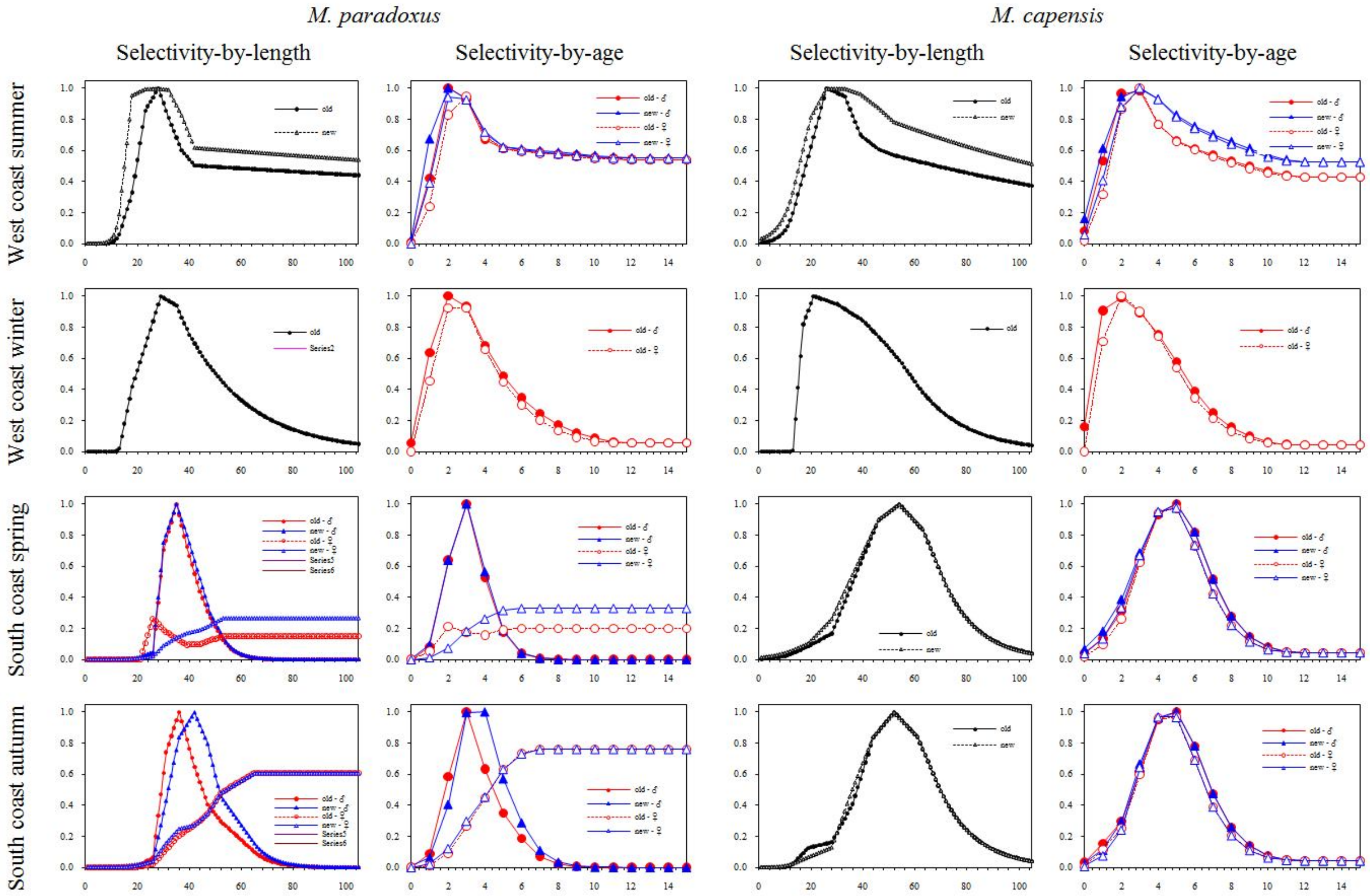


Figure 8.4: Commercial gender-independent selectivities-at-length estimated in the model-fitting and commercial gender-dependent selectivities-at-age that follow from those. Note that because of space constraints, the offshore and longline legends have been omitted for the South Coast *M. capensis* selectivity-at-age plots. The legends for these two fleets are as for those for the West Coast.

Figure 8.5: Survey selectivity-at-length (estimated) for the ‘old’ and ‘new’ *Africana* gear and derived gender-dependent survey selectivity-at-age for each of the four surveys for *M. paradoxus* and *M. capensis*. Note that for the south coast spring and autumn surveys, gender-specific selectivities have been estimated for *M. paradoxus*. For all the other combinations of species and surveys, the selectivities-at-length are gender independent.



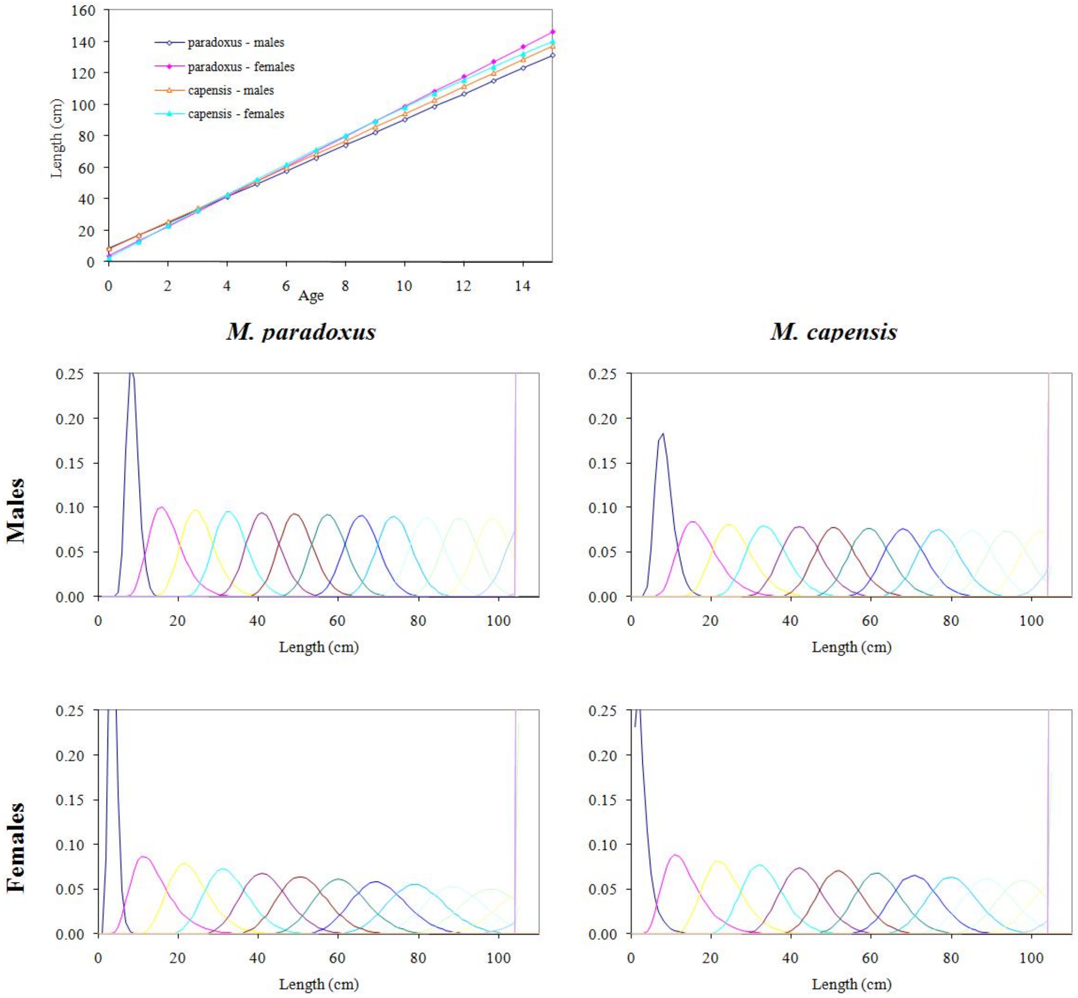


Figure 8.6: Estimated length-at-age relationship and resulting length-at-age distributions for males and females *M. paradoxus* and *M. capensis*. In the lower plots, the distributions, starting from the left, correspond to ages 0, 1, 2, … The 0-year old group has a distribution overlapping zero, which is accumulated into a minus-group of 1 cm length; though such a model for this length distribution is clearly unrealistic, this hardly matters as in implementation the lowest minus-group considered for length is 10 cm, so that any implied structure below that length is ignored.

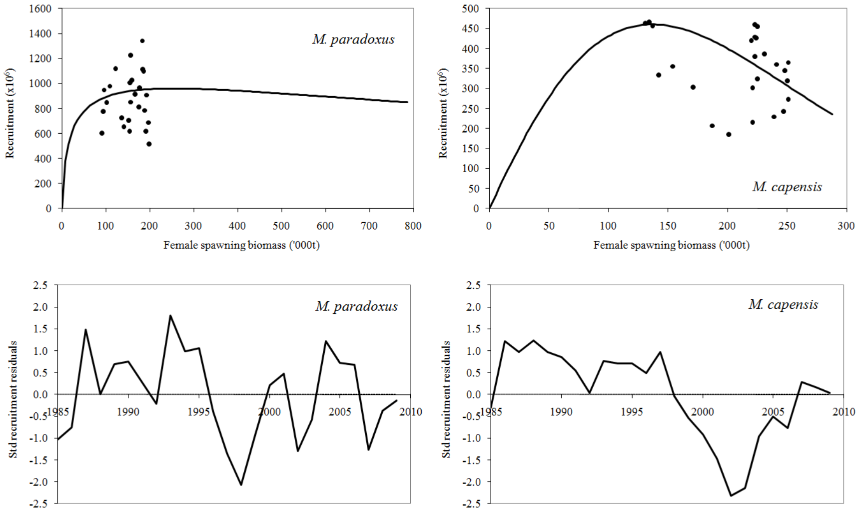


Figure 8.7: Estimated stock-recruitment relationships and time series of standardised stock-recruitment residuals for the RC.

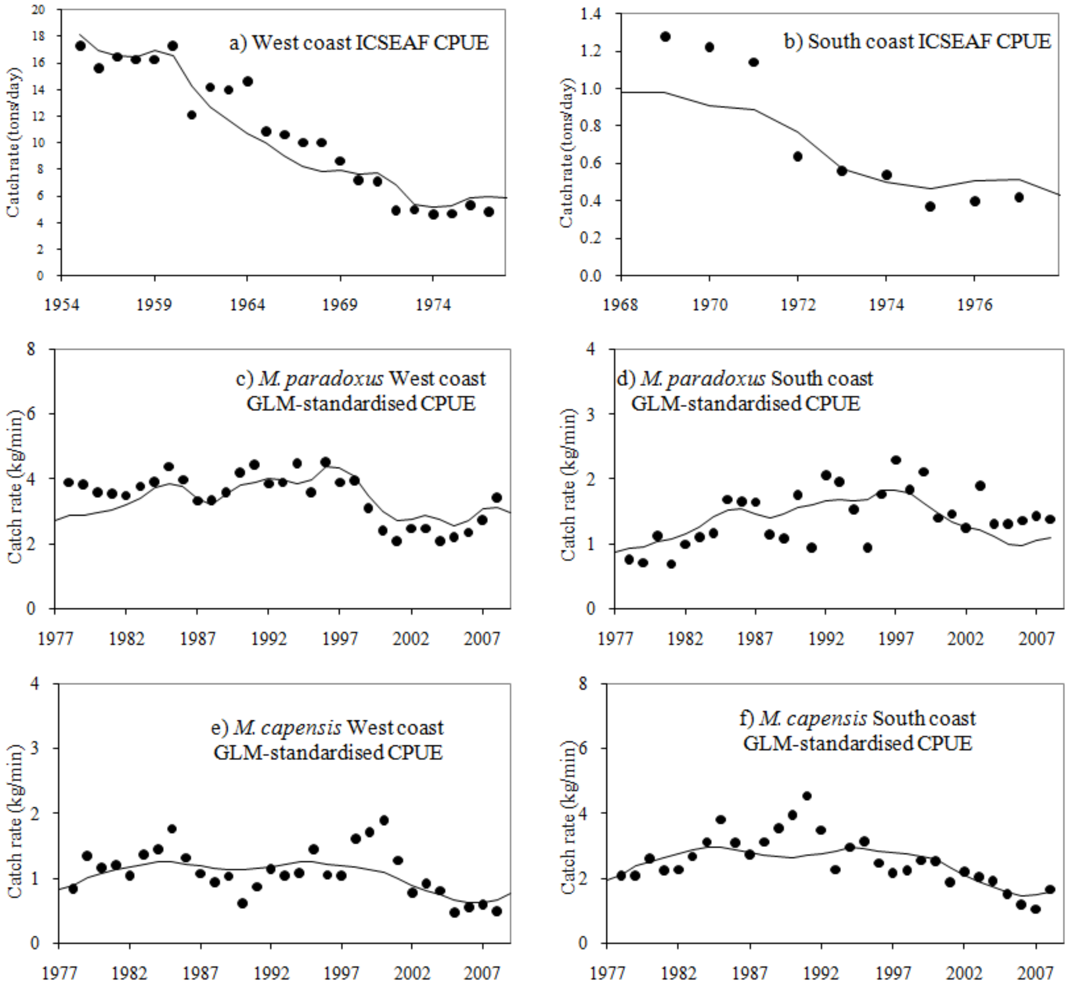


Figure 8.8: Fit of the RC to the CPUE data.

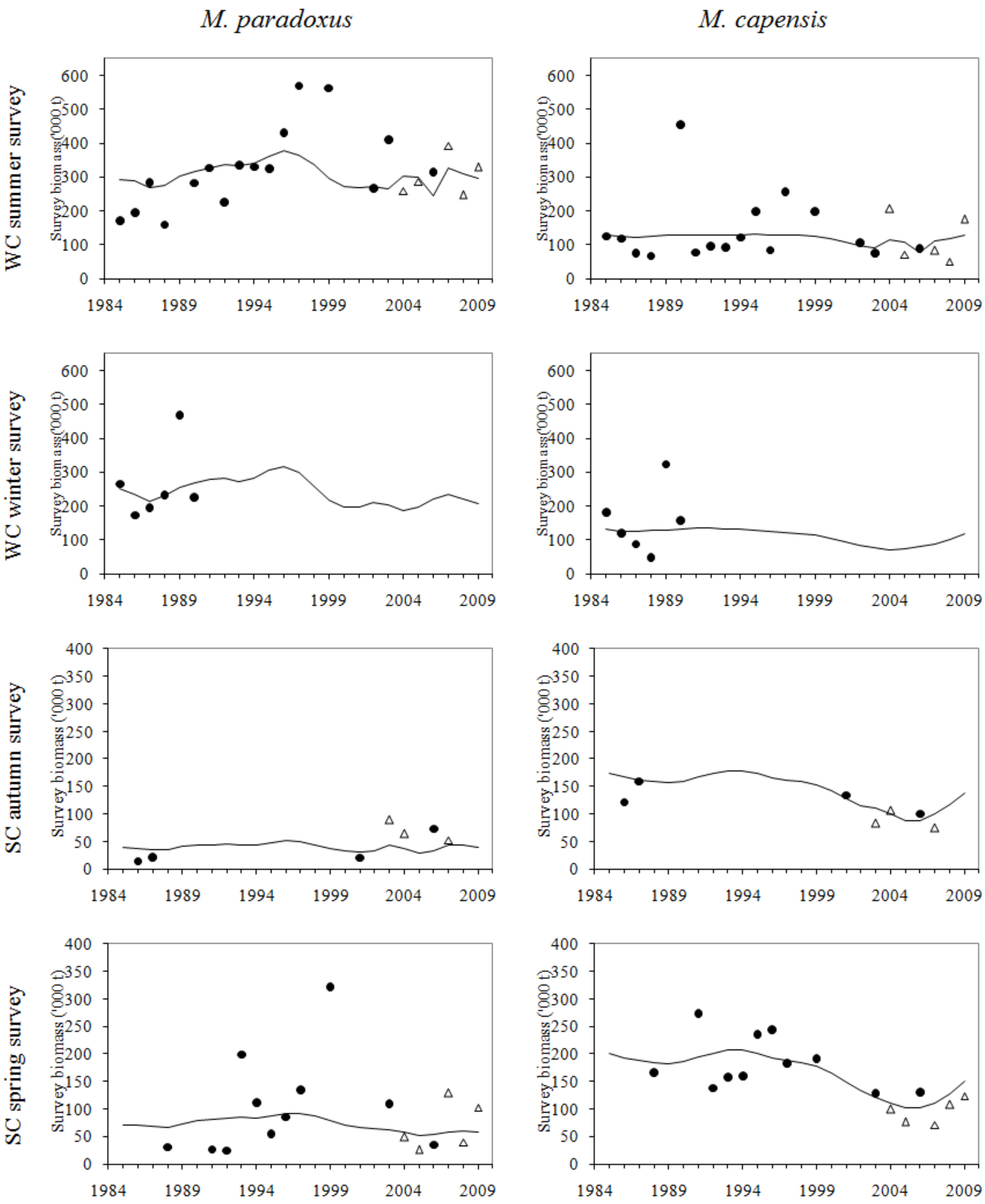


Figure 8.9: Fit of the RC to the survey abundance indices. The triangles represent surveys that have been conducted with the new gear on the *Africana*. These are rescaled by the calibration factor for the species concerned to make them comparable to the other survey results.

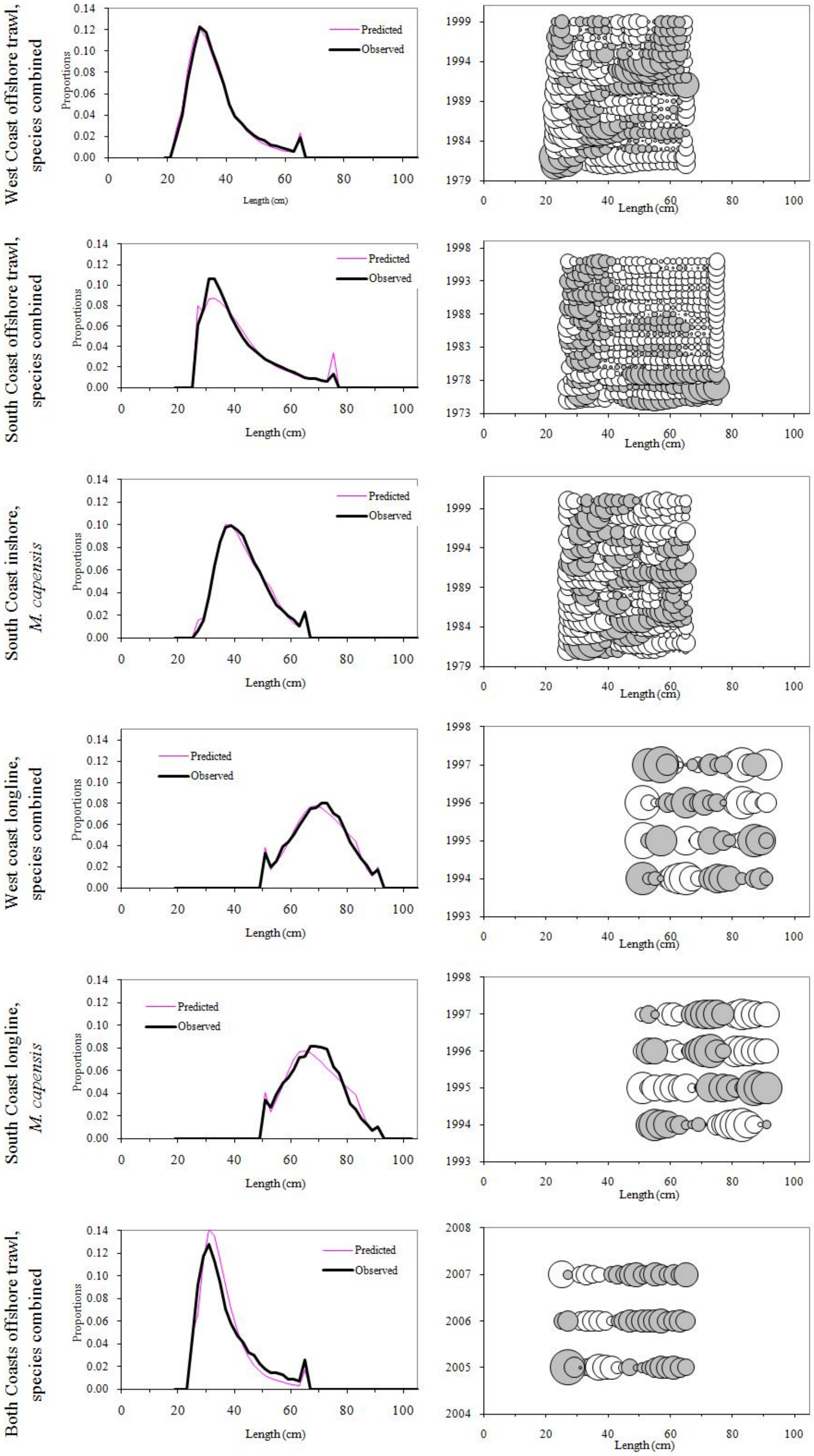


Figure 8.10: Fit of the RC to the commercial proportion-at-length data, aggregated over years for which data are available for the plots on the left.

Figure 8.11: Fit of the RC to the survey gender-aggregated surveys proportion-at-length data (in some plots, aggregated over years for which data are available).

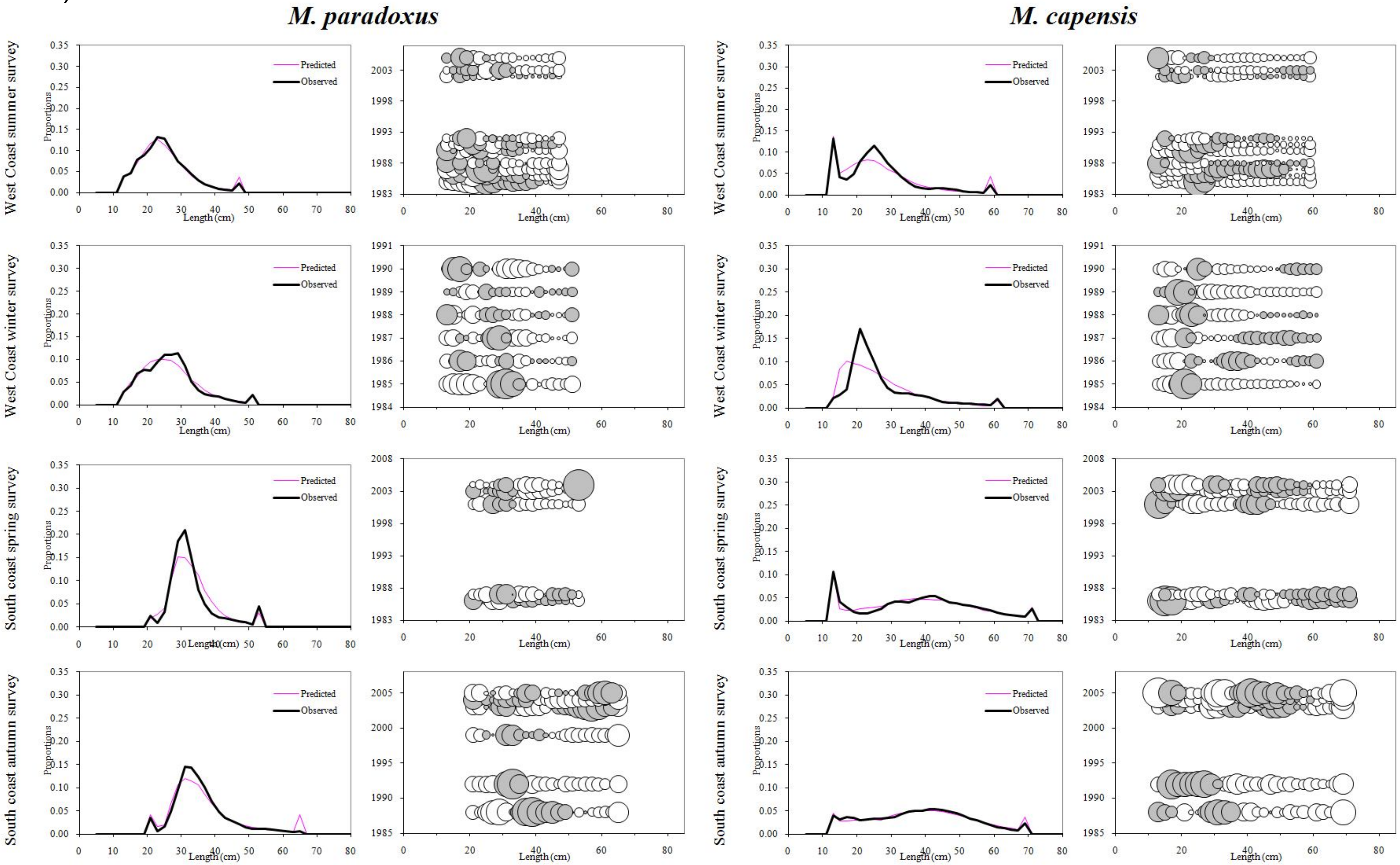


Figure 8.12a: Fit of the RC to the west coast summer survey gender- disaggregated proportion-at-length data (in some plots, aggregated over years for which data are available).

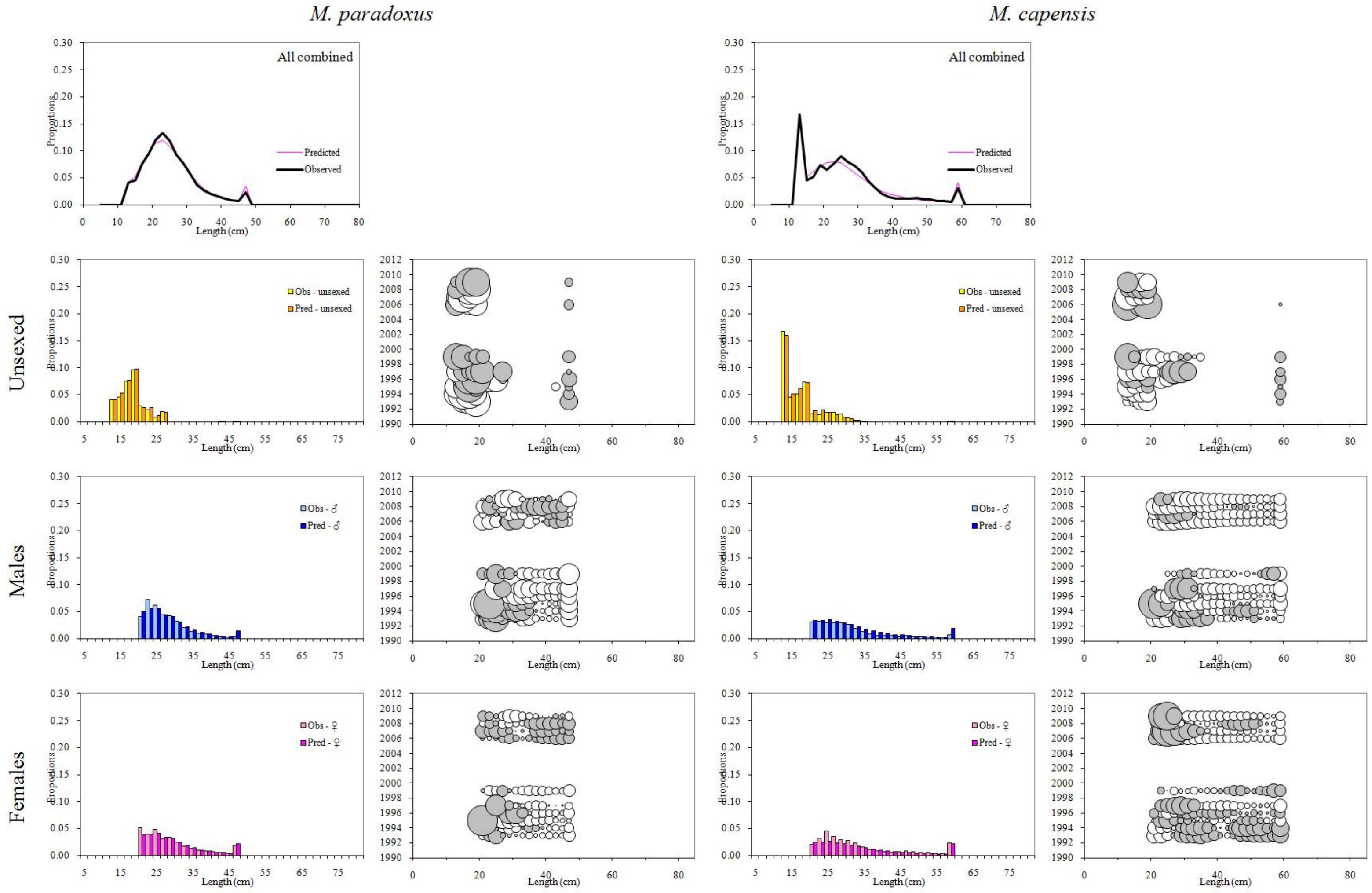


Figure 8.12b: Fit of the RC to the south coast spring survey gender- disaggregated proportion-at-length data (in some plots, aggregated over years for which data are available).

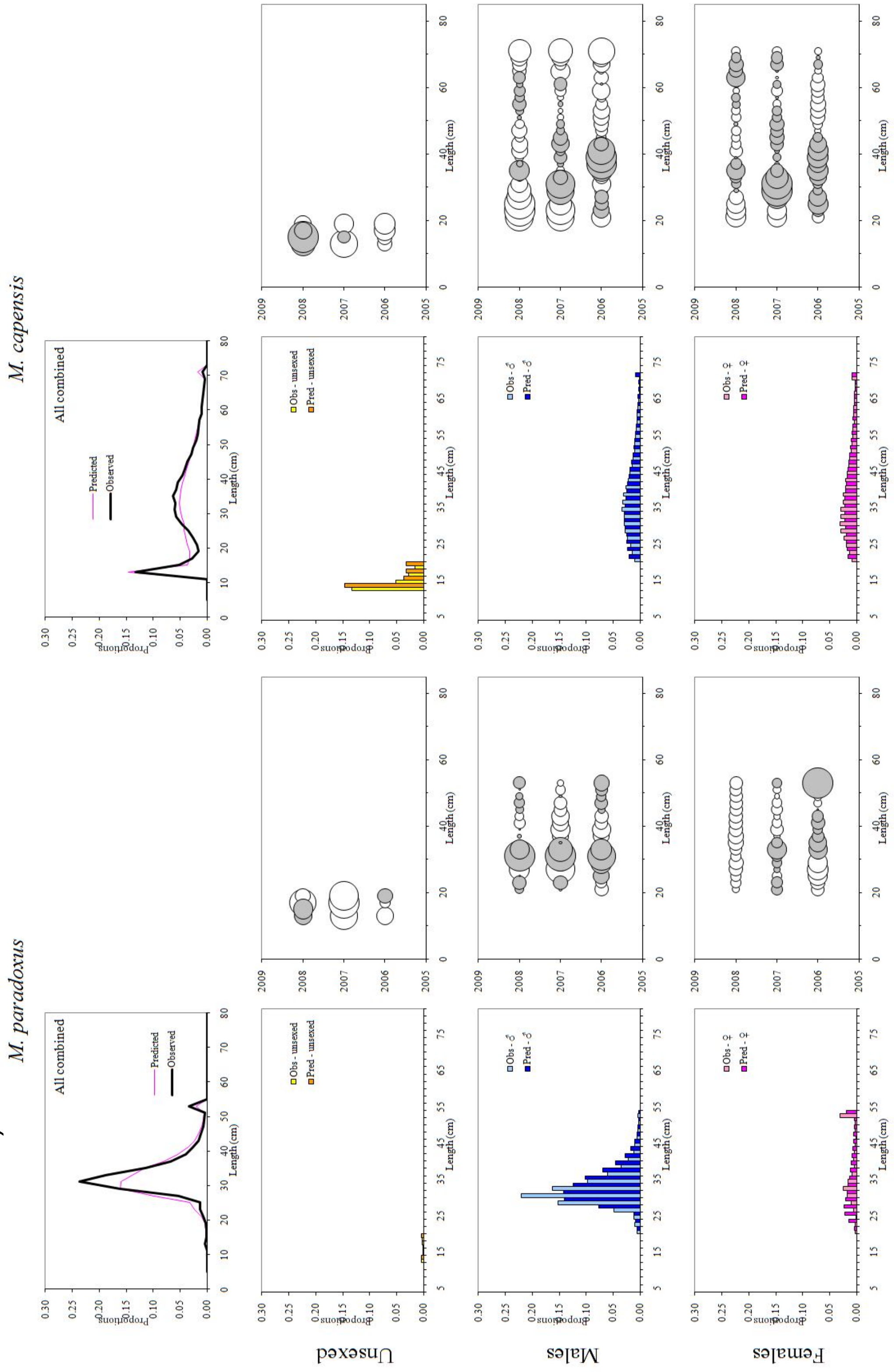


Figure 8.12c: Fit of the RC to the south coast autumn survey gender- disaggregated proportion-at-length data (in some plots, aggregated over years for which data are available).

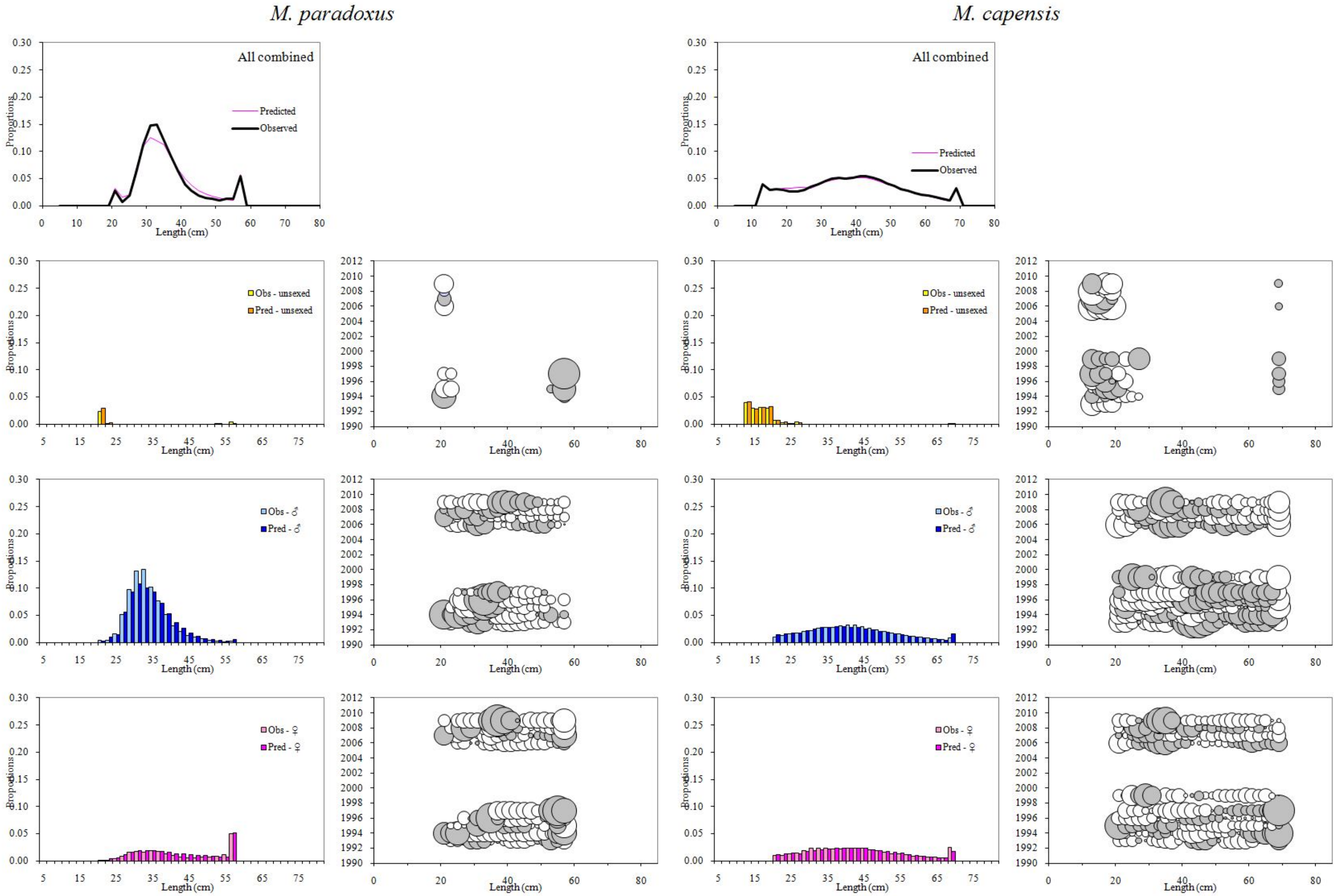
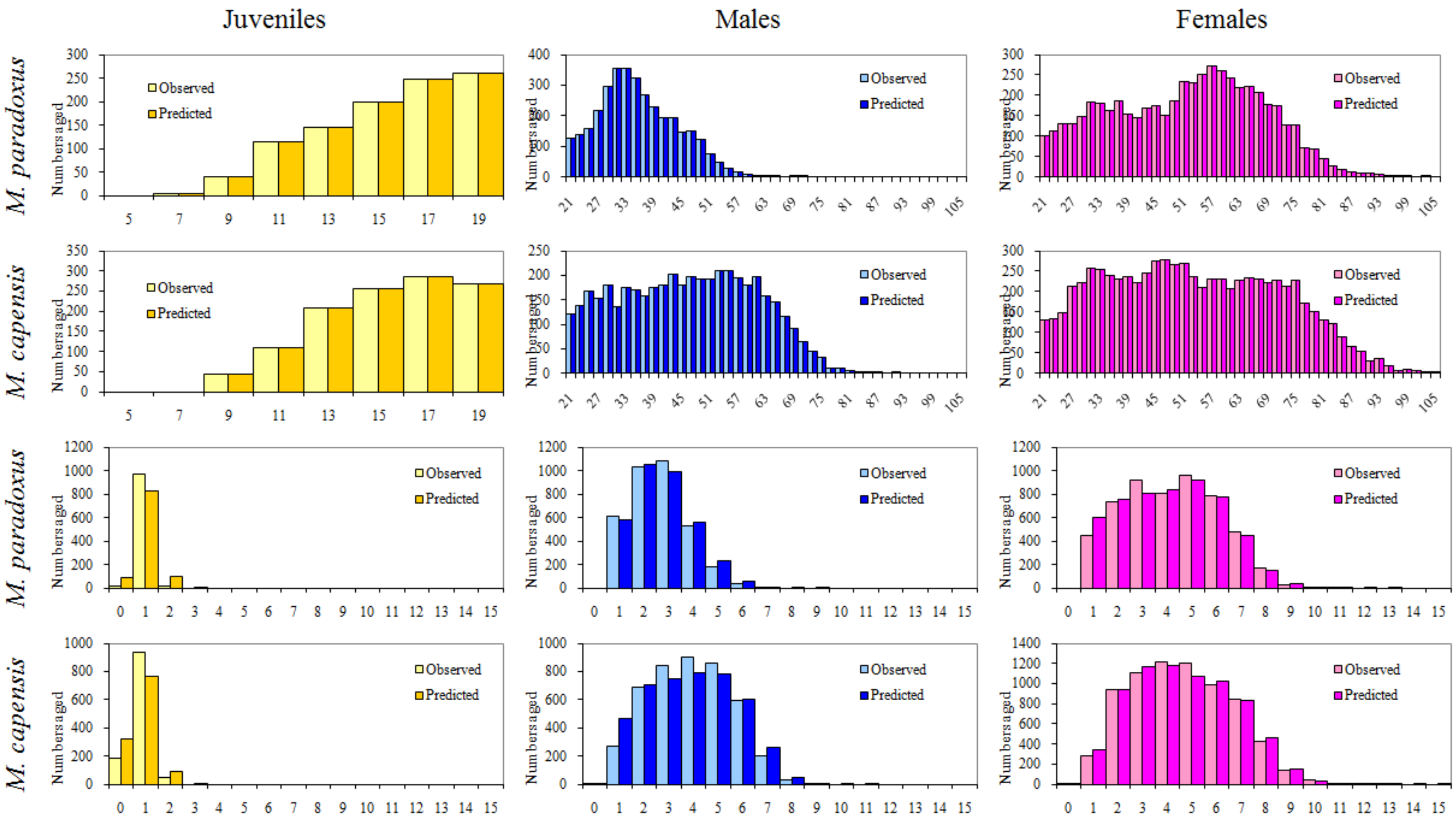


Figure 8.13: Fit of the RC to the ALKs, aggregated over all ALKs. The first two rows are summed over ages (so that model estimate and observation should be exactly equal by construction) and second two rows summed over lengths.



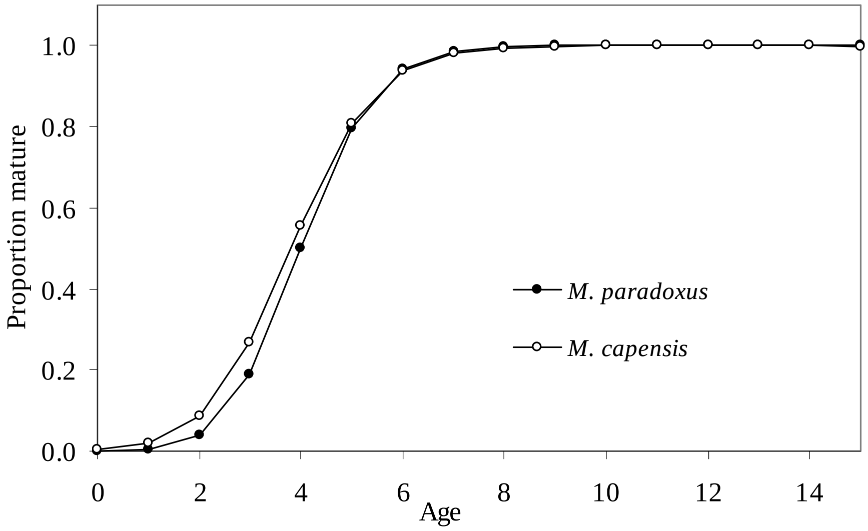


Figure 8.14: Maturity-at-age used in the new Reference Case for *M. paradoxus* and *M. capensis* (Fairweather and Leslie 2008)

Figure 8.15a: Observed vs predicted mean age-at-length for *M. paradoxus* males and females for the west coast summer surveys

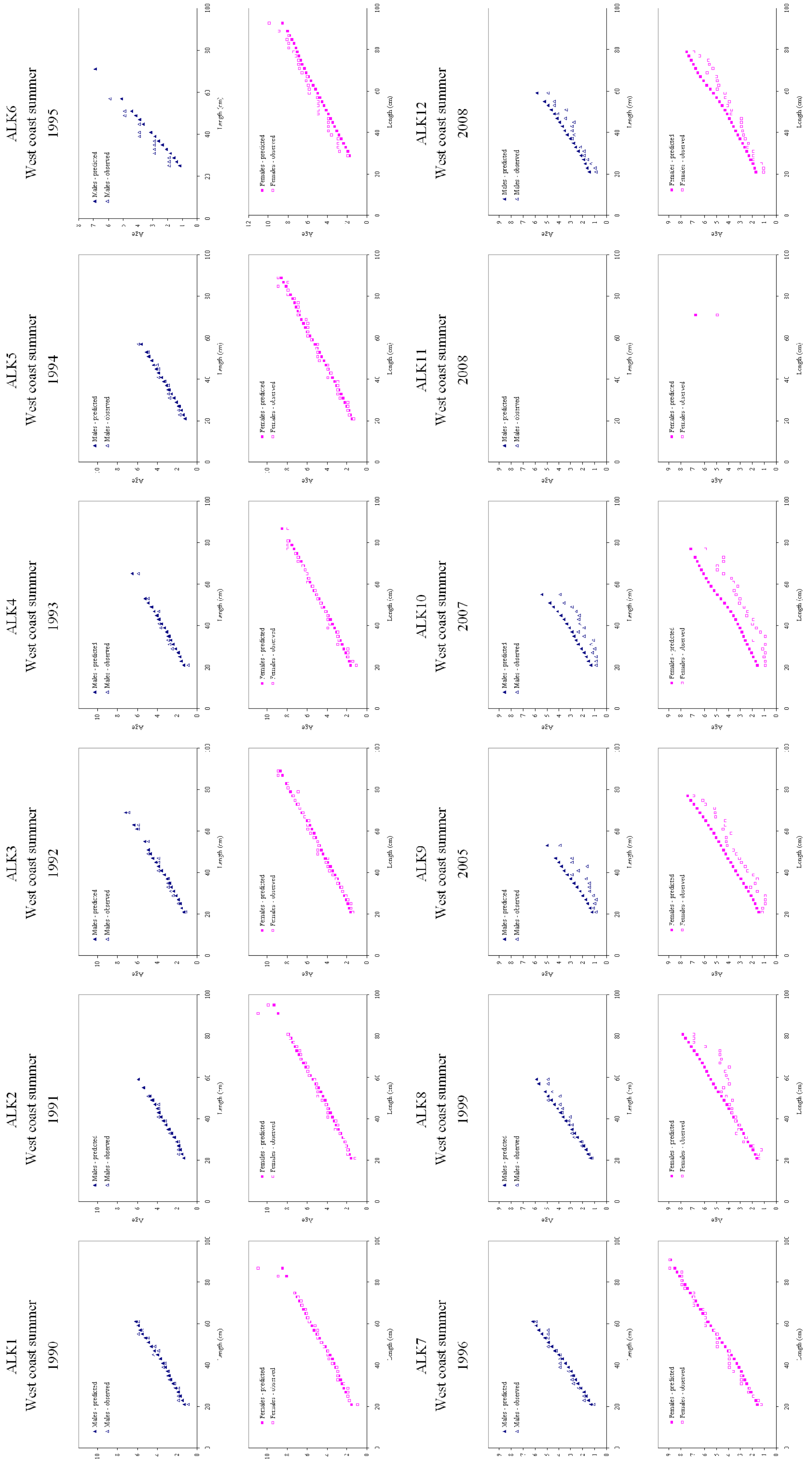


Figure 8.15b: Observed vs predicted mean age-at-length for *M. paradoxus* males and females for the West Coast winter, South Coast spring and South Coast autumn surveys.

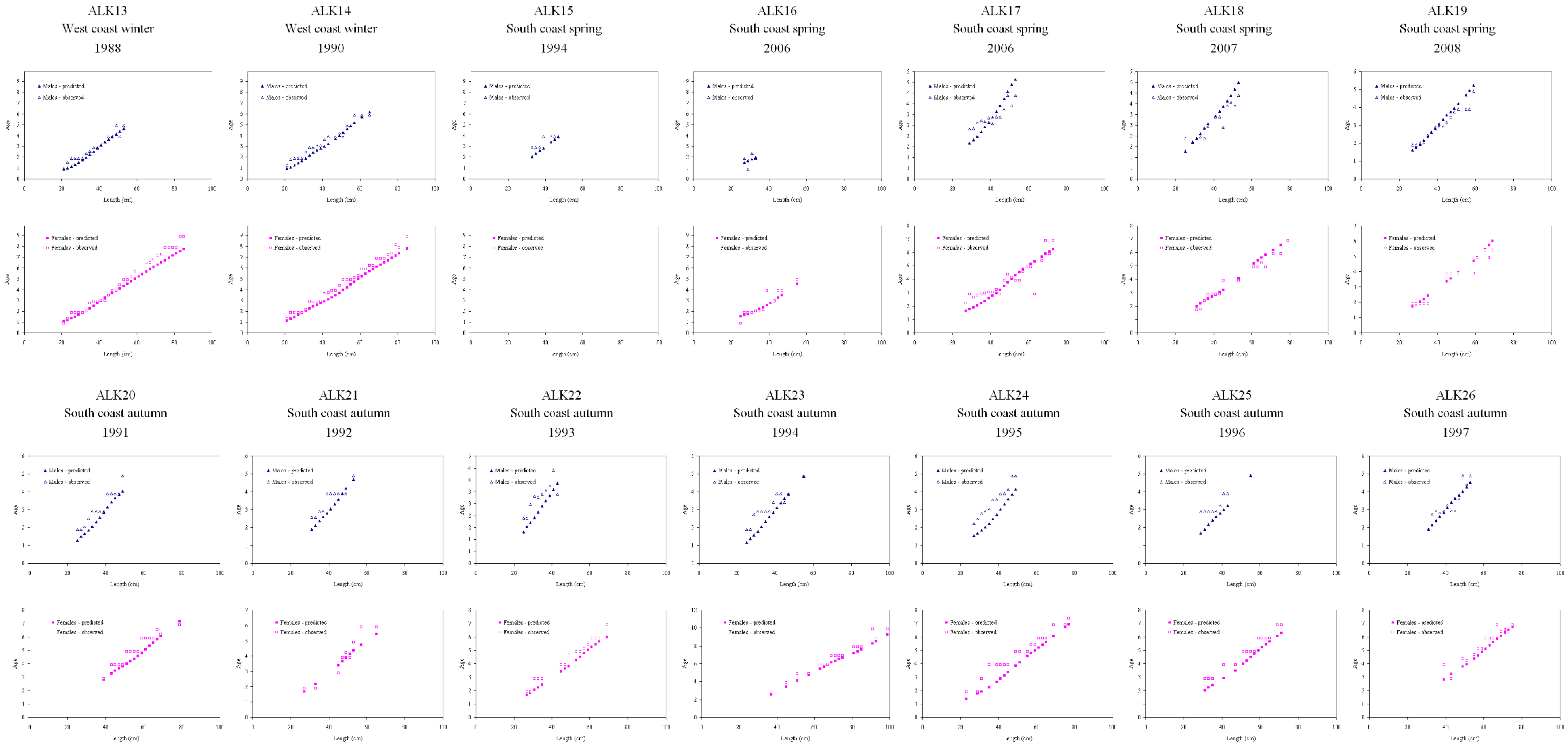
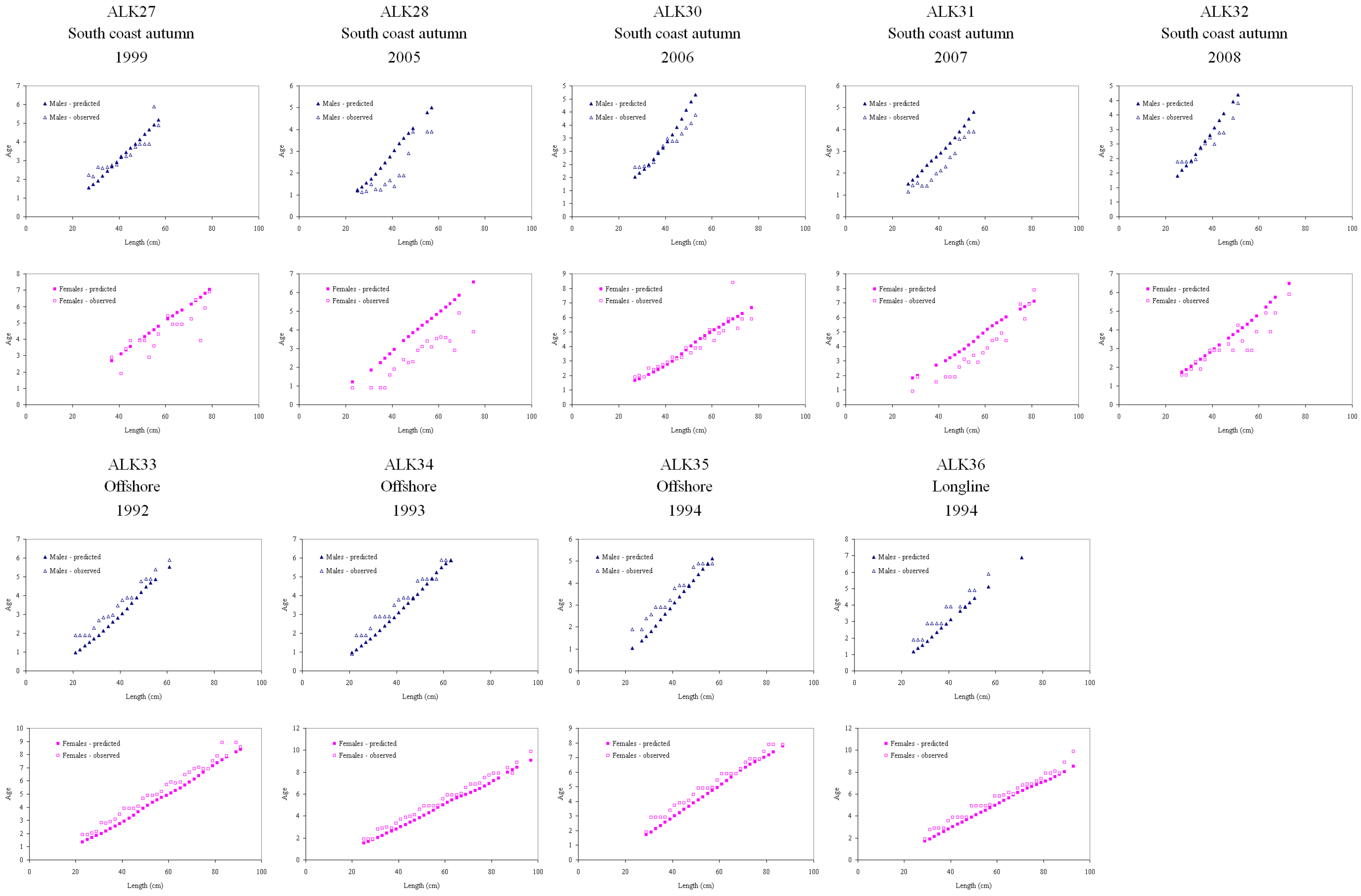


Figure 8.15c: Observed vs predicted mean age-at-length for *M. paradoxus* males and females for the South Coast autumn surveys, offshore commercial trawl and commercial longline.



ALK27
South coast autumn
1999

ALK28
South coast autumn
2005

ALK30
South coast autumn
2006

ALK31
South coast autumn
2007

ALK32
South coast autumn
2008

ALK33
Offshore
1992

ALK34
Offshore
1993

ALK35
Offshore
1994

ALK36
Longline
1994

Figure 8.16a: Observed vs predicted mean age-at-length for *M. capensis* males and females for the West Coast summer surveys.

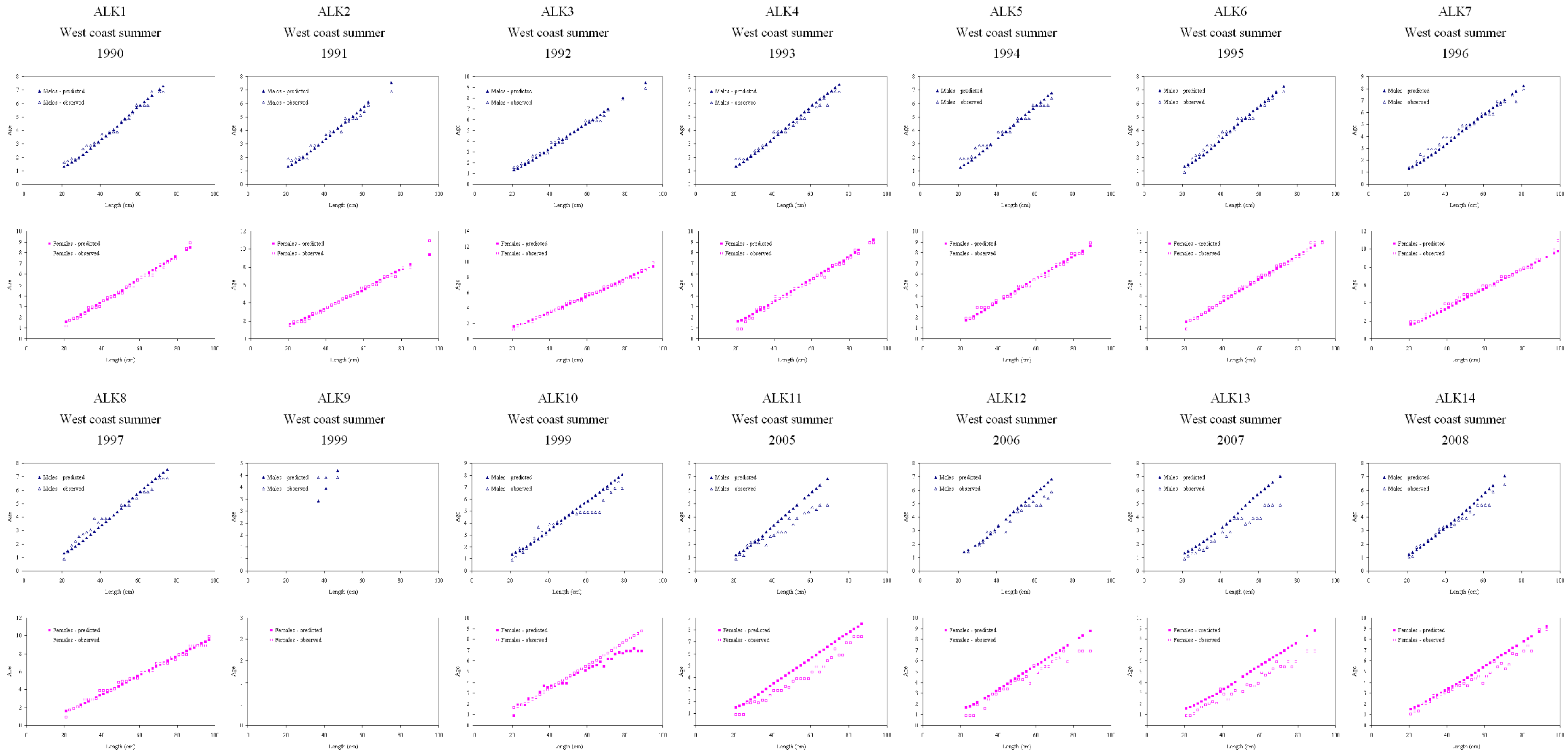


Figure 8.16b: Observed vs predicted mean age-at-length for *M. capensis* males and females for the West Coast winter, South Coast spring and South Coast autumn surveys.

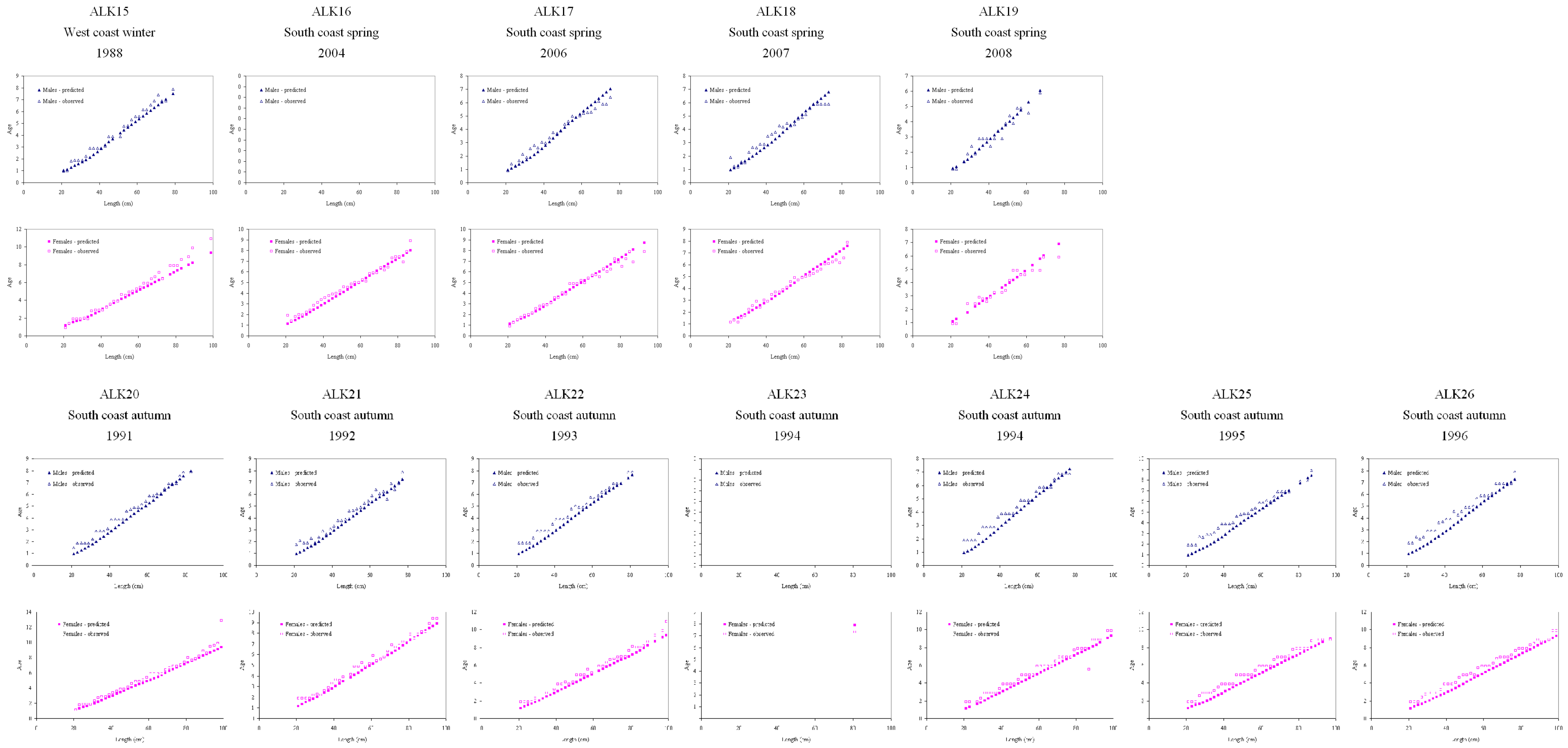
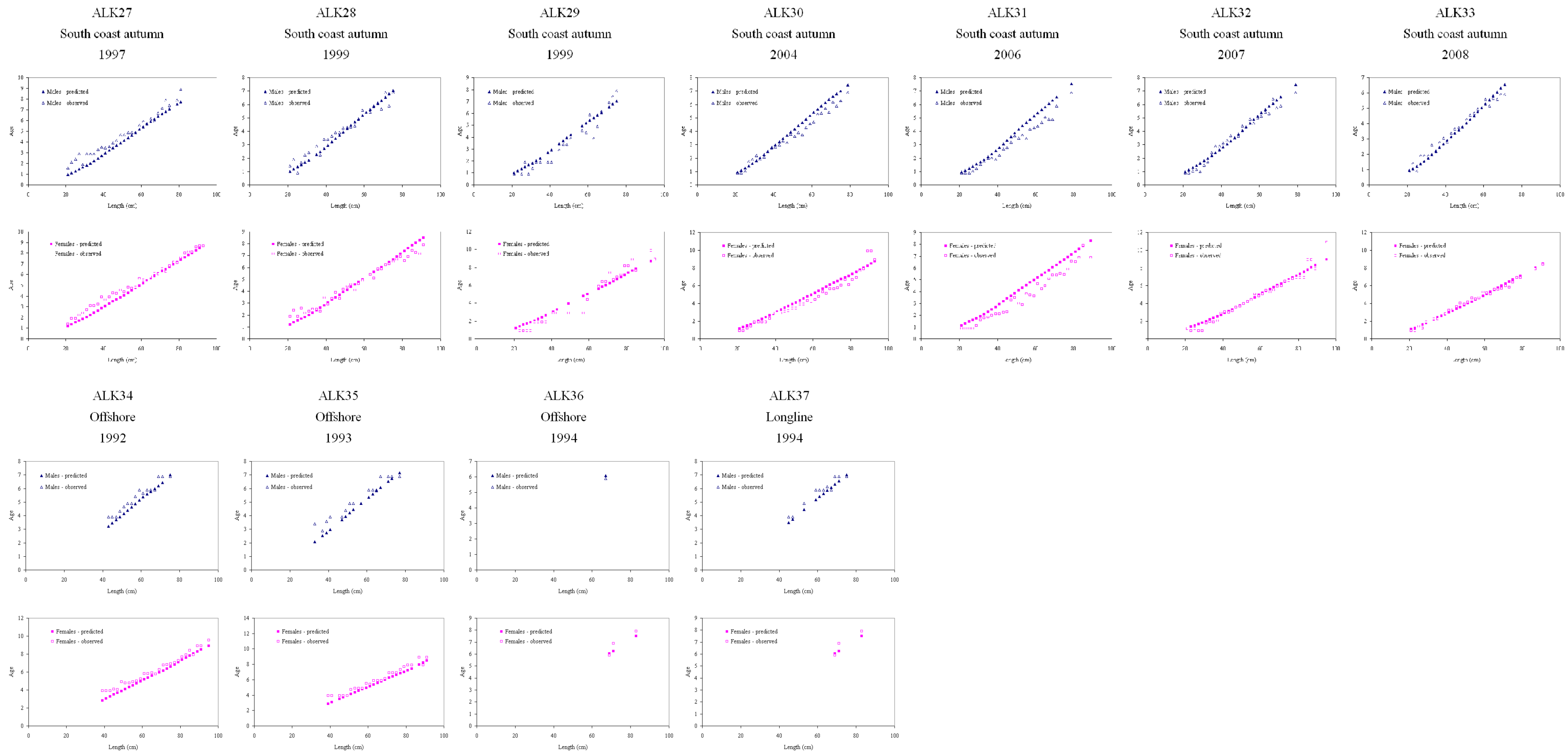


Figure 8.16c: Observed vs predicted mean age-at-length for *M. capensis* males and females for the South Coast autumn surveys, offshore commercial trawl and commercial longline.



APPENDIX 8.I

The data utilized

8.I.1 Annual catches

The species-split of the catches is carried out external to the model as described in Section 4.2.1. The size-based species proportion-by-depth relationships for the West and South coasts which are used, from 1978 onwards, to split by species the offshore trawl fleet catches have been updated by Gaylard and Bergh (2009) from research survey data. Furthermore, for the New Reference Case, the logistic function assumed for the proportion of *M. capensis* caught for the period 1917-1977 has it center at 1958 (P_1), with P_2=1.5.

The total catch in 2009 is assumed equal to the TAC for that year (118 600 tons); it is split between the different fleets and species assuming the same proportions as in 2008. The reported or assumed/estimated catches by fleet and species are given in Table App.8.I.1 and plotted in Figure App.8.I.1.

8.I.2 Abundance indices

Six CPUE time-series are available for assessing the status of the resource (Table App.8.I.2): a CPUE series for each of the South and West coasts developed by the International Commission for South East Atlantic Fisheries (ICSEAF 1989) and a GLM-standardised CPUE series for each coast, for each of *M. paradoxus* and *M. capensis* (Table App.8.I.2) from the offshore trawl fleet (Glazer and Butterworth 2009). The two historical CPUE series cannot be disaggregated by species, as there are no effort-by-depth data available for this pre-1978 period. The GLM standardized CPUE indices are species-specific (the catch data utilised being based on the Gaylard and Bergh (2009) algorithm).

Research surveys have been conducted on board the FRS *Africana* from 1986 in spring and/or autumn on the South Coast and from 1985 in summer and/or winter on the West Coast, and provide fully species-specific information. Since 2003, new fishing gear has occasionally been used on the *Africana*, for which a calibration factor is available. Survey biomass estimates and their estimated (sampling) standard errors are listed in Tables App.8.I.3-4 (Fairweather 2009). Only surveys extending to the deepest depth (500m) which is normally included in the survey design are considered for reasons of comparability.

The surveys conducted on the West Coast in 2000 and 2001 by the *Nansen* research vessel have not been used in this analysis. As no calibration experiments were conducted at the time, these would have to be considered as a separate series and with only two data points would hardly be informative.

8.I.3 Length frequencies

Survey length frequencies are available disaggregated by species and in some years disaggregated by gender (Table App.8.I.5) (Fairweather *et al.* 2009b).

Sex-aggregated proportions-at-length for each survey stratum ($p_{yl}^{surv,i}$) are provided in 1cm length classes (Fairweather *et al.* 2009b). In some instances, the proportions of males and females for a particular survey stratum and length class are available ($q_{yl}^{g,surv,i}$, where $\sum_{g} q_{yl}^{g,surv,i} = 1$). These are converted to survey specific (i.e. aggregated over all strata for a particular cruise) proportions-at-lengths for males (*g*=1), females (*g*=2) and unsexed (*g*=0) (with $\sum_{g=0}^{2} p_{yl}^{g,surv,i} = 1$) as follows:

The proportions-at-length are grouped into 2cm length classes.

a. For all length classes < 21 cm, the proportions-at-length are assumed to be unsexed;

b. For length classes > 20 cm:

- If there is no sex-information for either of the two 1 cm length classes to group (i.e. $\sum_g q_{yl}^{g,surv,i} = 0$ and $\sum_g q_{y,l+1}^{g,surv,i} = 0$), then the proportion for the resulting 2 cm length class is assumed to be unsexed:

$$p_{yL}^{g,surv,i} = \begin{cases} p_{yl}^{surv,i} + p_{y,l+1}^{surv,i} & \text{for } g = 0 \\ 0 & \text{for } g = 1/2 \end{cases} \qquad \text{(App.8.I.1)}$$

- If there is sex-information for one of the two 1 cm length classes to group (i.e. if $\sum_g q_{yl}^{g,surv,i} = 1$ or $\sum_g q_{y,l+1}^{g,surv,i} = 1$), then the sex-information from the one length class is used for both:

$$p_{yL}^{g,surv,i} = \begin{cases} 0 & \text{for } g = 0 \\ q_{yl}^{g,surv,i}\left(p_{yl}^{surv,i} + p_{y,l+1}^{surv,i}\right) & \text{for } g = 1/2 \end{cases} \qquad \text{(App.8.I.2)}$$

- If there is sex-information for both of the two 1 cm length classes to group (i.e. if $\sum_g q_{yl}^{g,surv,i} = 1$ and $\sum_g q_{y,l+1}^{g,surv,i} = 1$), then the sex-information is used directly:

$$p_{yL}^{g,surv,i} = \begin{cases} 0 & \text{for } g = 0 \\ q_{yl}^{g,surv,i} p_{yl}^{surv,i} + q_{y,l+1}^{g,surv,i} p_{y,l+1}^{surv,i} & \text{for } g = 1/2 \end{cases} \qquad \text{(App.8.I.3)}$$

c. The strata proportions-at-length are weighted by the estimated total number in the stratum concerned to obtain a survey specific gender-disaggregated proportions-at-length ($p_{yl}^{g,surv}$). The estimated total number in each stratum is calculated as:

$$N_y^{surv,i} = B_y^{surv,i} \big/ \overline{W}_y^{surv,i} \qquad \text{(App.8.I.4)}$$

where

$B_y^{surv,i}$ is the survey biomass estimate for stratum *i* in survey *surv*, and

$\overline{W}_y^{surv,i}$ is the mean weight of fish for stratum *i* in survey *surv*, with

$$\overline{W}_y^{surv,i} = \sum_l \left(p_{yl}^{surv,i} \alpha l^{\beta}\right) \qquad \text{(App.8.I.5)}$$

d. For each 2 cm length class, if the unsexed proportion is less than 20% of the total proportion in that length class, the sexed proportion is used to split the unsexed proportion into males and females.

The survey length frequencies available are plotted in Figures App.8.I.2-3.

Length frequency information from the commercial catch is not available by species, the reason being that it is often based on cleaned (headed and gutted) fish, which cannot be easily identified by species. As a result it is not possible to disaggregate the commercial length frequencies by species. Commercial catches-at-length for the offshore and for the inshore and longline fleets are shown in Tables App.8.II.10-12. The South Coast inshore and longline fleet catches are assumed to consist of *M. capensis* only.

8.I.4 Age-Length Keys

Table App.8.I.6 lists the age-length keys available. Data from animals with frills on gills (FOG) have been discarded (<3% of the total). All aged animals less or equal to 20cm in length are assumed to be juveniles, i.e. of unknown gender. The few unsexed data from animals greater than 20cm have been discarded (<1% of the total), as well as the outliers, defined as the data points lying outside the mean ± 3s.d. for each age (mean and s.d. calculated across all years and surveys). Three ALKs for *M. paradoxus* have been totally ignored in the model fitting as they seemed completely inconsistent with the other ALKs: i) 1997 West Coast summer survey, ii) 2004 West Coast summer and iii) 2006 West Coast summer. The data for these three sets are shown in Figure App.I.5.

Most otoliths are read more than once; however only one reading for each otoliths is used in the fitting procedure. Table App.8.I.7 show which reader was selected in the event of more than one reading.

Table App.8.I.1a: Species-disaggregated offshore trawl catches (in thousand tons) of South African hake from the South and West coasts (see text for details), assuming 1958 as the centre year of the shift from a primarily *M. capensis* to a primarily *M. paradoxus.*

	M. paradoxus		*M. capensis*			*M. paradoxus*		*M. capensis*			*M. paradoxus*		*M. capensis*	
Year	WC	SC	WC	SC	Year	WC	SC	WC	SC	Year	WC	SC	WC	SC
1917	-	-	1.000	-	1948	0.056	-	58.744	-	1979	93.711	2.653	39.811	4.266
1918	-	-	1.100	-	1949	0.107	-	57.293	-	1980	100.723	2.833	32.805	3.628
1919	-	-	1.900	-	1950	0.260	-	71.740	-	1981	90.572	1.208	30.358	4.277
1920	-	-	0.000	-	1951	0.627	-	88.873	-	1982	84.030	4.063	29.319	7.294
1921	-	-	1.300	-	1952	1.201	-	87.599	-	1983	71.628	5.920	22.805	6.596
1922	-	-	1.000	-	1953	2.422	-	91.078	-	1984	82.940	4.689	28.316	6.246
1923	-	-	2.500	-	1954	5.149	-	100.251	-	1985	93.192	10.054	31.878	9.962
1924	-	-	1.500	-	1955	10.343	-	105.057	-	1986	105.097	9.974	28.708	5.991
1925	-	-	1.900	-	1956	18.540	-	99.660	-	1987	95.954	9.495	21.571	6.189
1926	-	-	1.400	-	1957	32.241	-	94.159	-	1988	83.910	7.184	22.672	7.332
1927	-	-	0.800	-	1958	49.136	-	81.564	-	1989	84.719	6.919	22.541	11.993
1928	-	-	2.600	-	1959	72.535	-	73.465	-	1990	89.976	11.636	13.660	11.155
1929	-	-	3.800	-	1960	95.147	-	64.753	-	1991	92.787	9.604	13.663	12.470
1930	-	-	4.400	-	1961	98.478	-	50.222	-	1992	89.638	19.260	13.649	7.202
1931	-	-	2.800	-	1962	103.768	-	43.832	-	1993	107.370	11.143	10.694	3.117
1932	-	-	14.300	-	1963	123.055	-	46.445	-	1994	112.355	7.842	11.512	3.210
1933	-	-	11.100	-	1964	119.837	-	42.463	-	1995	104.842	4.486	16.055	2.664
1934	-	-	13.800	-	1965	151.211	-	51.789	-	1996	119.889	10.467	9.286	2.822
1935	-	-	15.000	-	1966	145.914	-	49.086	-	1997	108.917	12.902	8.237	2.934
1936	-	-	17.700	-	1967	132.530	5.391	44.170	8.795	1998	115.290	11.165	12.363	2.988
1937	-	-	20.200	-	1968	107.834	10.619	35.766	17.289	1999	90.030	12.749	13.731	2.597
1938	-	-	21.100	-	1969	124.056	14.442	41.044	23.489	2000	91.366	8.777	26.336	4.753
1939	-	-	20.000	-	1970	107.108	9.035	35.392	14.688	2001	98.164	8.213	19.433	7.944
1940	-	-	28.600	-	1971	151.855	11.472	50.145	18.644	2002	95.122	13.629	9.809	4.955
1941	-	-	30.600	-	1972	183.394	17.789	60.539	28.907	2003	95.062	20.503	10.314	4.530
1942	0.001	-	34.499	-	1973	118.629	27.566	39.153	44.790	2004	86.340	28.805	11.891	5.965
1943	0.001	-	37.899	-	1974	92.480	34.613	30.520	56.240	2005	88.722	24.374	6.545	4.872
1944	0.002	-	34.098	-	1975	67.381	25.703	22.236	41.760	2006	84.951	19.923	8.547	4.705
1945	0.004	-	29.196	-	1976	108.192	19.785	35.702	32.145	2007	96.426	14.899	12.444	2.345
1946	0.010	-	40.390	-	1977	76.939	14.086	25.389	22.886	2008	92.445	13.861	6.930	3.646
1947	0.020	-	41.380	-	1978	103.665	3.830	23.847	3.755	2009	85.357	12.798	6.399	3.366

Table App.8.II.1b: Inshore trawl catches of South African hake (assumed to be *M. capensis* exclusively) from the South Coast.

Year	*M. capensis*	Year	*M. capensis*	Year	*M. capensis*
1960	1.000	1977	3.500	1994	9.569
1961	1.308	1978	4.931	1995	10.630
1962	1.615	1979	6.093	1996	11.062
1963	1.923	1980	9.121	1997	8.834
1964	2.231	1981	9.400	1998	8.283
1965	2.538	1982	8.089	1999	8.595
1966	2.846	1983	7.672	2000	10.906
1967	3.154	1984	9.035	2001	11.836
1968	3.462	1985	9.203	2002	9.581
1969	3.769	1986	8.724	2003	9.883
1970	4.077	1987	8.607	2004	10.004
1971	4.385	1988	8.417	2005	7.881
1972	4.692	1989	10.038	2006	5.524
1973	5.000	1990	10.012	2007	6.350
1974	10.056	1991	8.206	2008	5.496
1975	6.372	1992	9.252	2009	5.075
1976	5.740	1993	8.870		

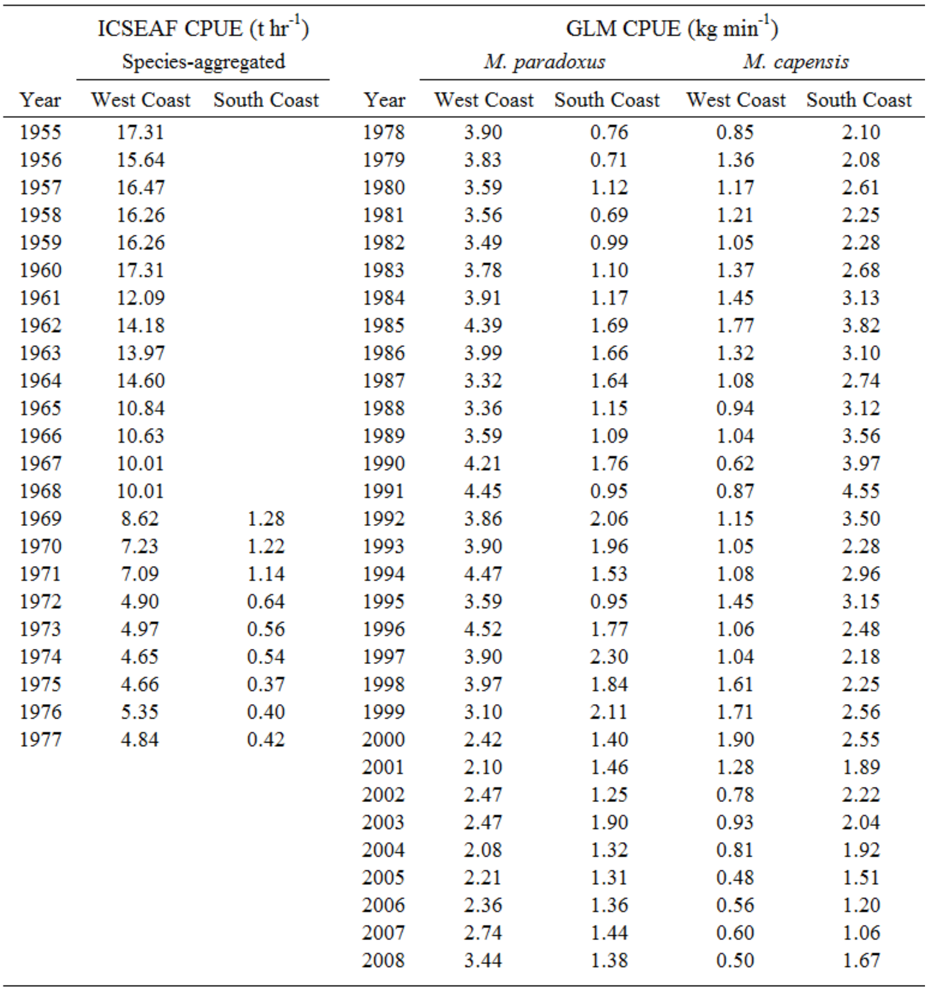
Table App.8.II.1c: Species-disaggregated longline trawl catches of South African hake from the South and West coasts.

	M. para	*M. capensis*	
Year	WC	WC	SC
1983	0.161	0.069	-
1984	0.256	0.110	0.016
1985	0.817	0.350	0.292
1986	0.965	0.413	0.302
1987	2.500	1.071	0.353
1988	3.628	1.555	0.331
1989	0.203	0.087	0.032
1990	0.270	0.116	-
1991	-	-	3.000
1992	-	-	1.500
1993	-	-	-
1994	1.130	0.484	0.626
1995	0.670	0.287	0.650
1996	1.676	0.718	1.828
1997	1.806	0.774	1.872
1998	0.647	0.277	1.471
1999	1.963	0.841	4.144
2000	3.456	1.481	2.077
2001	2.793	1.197	1.688
2002	4.772	2.045	3.945
2003	4.668	2.000	4.878
2004	3.758	1.611	4.429
2005	4.172	1.788	4.559
2006	3.592	1.539	4.032
2007	3.151	1.350	3.834
2008	2.170	0.930	2.740
2009	2.004	0.859	2.530

Table App.8.II.1d: Handline catches of South African hake (assumed to be *M. capensis* exclusively) from the South Coast.

Year	*M. capensis*
1985	0.065
1986	0.084
1987	0.096
1988	0.071
1989	0.137
1990	0.348
1991	1.270
1992	1.099
1993	0.278
1994	0.449
1995	0.756
1996	1.515
1997	1.404
1998	1.738
1999	2.749
2000	5.500
2001	7.300
2002	3.500
2003	3.000
2004	1.600
2005	0.700
2006	0.400
2007	0.400
2008	0.231
2009	0.213

Table App.8.I.2: South and West Coast historic (ICSEAF 1989) and GLM standardized CPUE data (GLM3 of Glazer and Butterworth 2009) for *M. paradoxus* and *M. capensis*. The historic CPUE series are for *M. capensis* and *M. paradoxus* combined.



	ICSEAF CPUE (t hr^{-1})			GLM CPUE (kg min^{-1})			
	Species-aggregated			*M. paradoxus*		*M. capensis*	
Year	West Coast	South Coast	Year	West Coast	South Coast	West Coast	South Coast
1955	17.31		1978	3.90	0.76	0.85	2.10
1956	15.64		1979	3.83	0.71	1.36	2.08
1957	16.47		1980	3.59	1.12	1.17	2.61
1958	16.26		1981	3.56	0.69	1.21	2.25
1959	16.26		1982	3.49	0.99	1.05	2.28
1960	17.31		1983	3.78	1.10	1.37	2.68
1961	12.09		1984	3.91	1.17	1.45	3.13
1962	14.18		1985	4.39	1.69	1.77	3.82
1963	13.97		1986	3.99	1.66	1.32	3.10
1964	14.60		1987	3.32	1.64	1.08	2.74
1965	10.84		1988	3.36	1.15	0.94	3.12
1966	10.63		1989	3.59	1.09	1.04	3.56
1967	10.01		1990	4.21	1.76	0.62	3.97
1968	10.01		1991	4.45	0.95	0.87	4.55
1969	8.62	1.28	1992	3.86	2.06	1.15	3.50
1970	7.23	1.22	1993	3.90	1.96	1.05	2.28
1971	7.09	1.14	1994	4.47	1.53	1.08	2.96
1972	4.90	0.64	1995	3.59	0.95	1.45	3.15
1973	4.97	0.56	1996	4.52	1.77	1.06	2.48
1974	4.65	0.54	1997	3.90	2.30	1.04	2.18
1975	4.66	0.37	1998	3.97	1.84	1.61	2.25
1976	5.35	0.40	1999	3.10	2.11	1.71	2.56
1977	4.84	0.42	2000	2.42	1.40	1.90	2.55
			2001	2.10	1.46	1.28	1.89
			2002	2.47	1.25	0.78	2.22
			2003	2.47	1.90	0.93	2.04
			2004	2.08	1.32	0.81	1.92
			2005	2.21	1.31	0.48	1.51
			2006	2.36	1.36	0.56	1.20
			2007	2.74	1.44	0.60	1.06
			2008	3.44	1.38	0.50	1.67

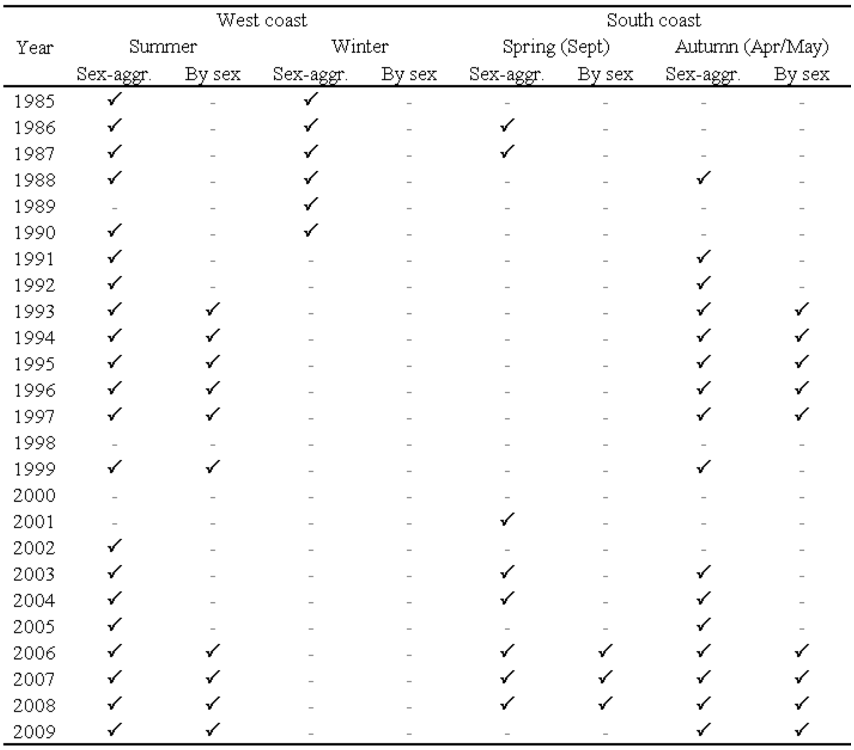
Table App.8.I.3: Survey abundance estimates and associated standard errors in thousand tons for *M. paradoxus* for the depth range 0-500m for the South Coast and for the West Coast. Values in bold are for the surveys conducted by the *Africana* with the new gear.

	West coast				South coast			
Year	Summer		Winter		Spring (Sept)		Autumn (Apr/May)	
	Biomass	(s.e.)	Biomass	(s.e.)	Biomass	(s.e.)	Biomass	(s.e.)
1985	169.959	(36.680)	264.839	(52.949)	-	-	-	-
1986	196.111	(36.358)	172.477	(24.122)	13.758	(3.554)	-	-
1987	284.805	(53.101)	195.482	(44.415)	21.554	(4.605)	-	-
1988	158.758	(27.383)	233.041	(64.003)	-	-	30.316	(11.104)
1989	-	-	468.780	(124.830)	-	-	-	-
1990	282.174	(78.945)	226.862	(46.007)	-	-	-	-
1991	327.020	(82.180)	-	-	-	-	26.638	(10.460)
1992	226.687	(32.990)	-	-	-	-	24.304	(15.195)
1993	334.151	(50.234)	-	-	-	-	198.849	(98.452)
1994	330.270	(58.319)	-	-	-	-	111.469	(34.627)
1995	324.554	(80.357)	-	-	-	-	55.068	(22.380)
1996	430.908	(80.604)	-	-	-	-	85.546	(25.484)
1997	569.957	(108.200)	-	-	-	-	135.192	(51.031)
1998	-	-	-	-	-	-	-	-
1999	562.859	(116.302)	-	-	-	-	321.478	(113.557)
2000	-	-	-	-	-	-	-	-
2001	-	-	-	-	19.929	(9.956)	-	-
2002	267.487	(35.068)	-	-	-	-	-	-
2003	411.177	(69.431)	-	-	**88.442**	(36.051)	108.857	(37.528)
2004	**259.527**	(56.021)	-	-	**63.900**	(17.894)	**48.898**	(20.343)
2005	**286.416**	(39.849)	-	-	-	-	**26.605**	(7.952)
2006	315.310	(49.490)	-	-	72.415	(15.500)	34.799	(8.325)
2007	**392.812**	(70.043)	-	-	**52.287**	(19.231)	**129.646**	(60.661)
2008	**246.542**	(51.973)	-	-	**24.816**	(8.775)	**39.505**	(11.408)
2009	**330.235**	(28.526)	-	-	-	-	**102.834**	(28.670)

Table App.8.I.4: Survey abundance estimates and associated standard errors in thousand tons for *M. capensis* for the depth range 0-500m for the South Coast and for the West Coast. Values in bold are for the surveys conducted by the *Africana* with the new gear.

	West coast				South coast			
Year	Summer		Winter		Spring (Sept)		Autumn (Apr/May)	
	Biomass	(s.e.)	Biomass	(s.e.)	Biomass	(s.e.)	Biomass	(s.e.)
1985	124.647	(22.707)	181.487	(27.476)	-	-	-	-
1986	117.810	(23.636)	119.587	(18.489)	121.197	(16.625)	-	-
1987	75.693	(10.241)	87.391	(11.198)	159.088	(17.233)	-	-
1988	66.725	(10.765)	47.120	(9.568)	-	-	165.939	(21.871)
1989	-	-	323.833	(67.295)	-	-	-	-
1990	455.798	(135.237)	157.800	(23.561)	-	-	-	-
1991	77.357	(14.995)	-	-	-	-	274.298	(44.395)
1992	95.407	(11.744)	-	-	-	-	138.085	(15.357)
1993	92.598	(14.589)	-	-	-	-	158.340	(13.733)
1994	121.257	(35.951)	-	-	-	-	160.555	(23.701)
1995	199.142	(26.812)	-	-	-	-	236.025	(31.840)
1996	83.337	(9.285)	-	-	-	-	244.410	(25.107)
1997	257.293	(46.056)	-	-	-	-	183.087	(18.906)
1998	-	-	-	-	-	-	-	-
1999	198.716	(32.467)	-	-	-	-	191.203	(14.952)
2000	-	-	-	-	-	-	-	-
2001	-	-	-	-	133.793	(20.858)	-	-
2002	106.253	(15.813)	-	-	-	-	-	-
2003	75.960	(13.314)	-	-	**82.928**	(9.010)	128.450	(20.062)
2004	**205.939**	(33.216)	-	-	**106.119**	(15.596)	**99.902**	(12.027)
2005	**70.983**	(13.845)	-	-	-	-	**76.932**	(5.965)
2006	88.420	(22.851)	-	-	99.867	(9.803)	130.900	(14.816)
2007	**82.270**	(11.441)	-	-	**74.615**	(7.383)	**70.940**	(5.615)
2008	**50.877**	(5.355)	-	-	**94.232**	(11.456)	**108.195**	(9.978)
2009	**175.289**	(39.920)	-	-	-	-	**124.004**	(11.808)

Table App.8.I.5: Survey length frequencies available in February 2010.



Year	West coast				South coast			
	Summer		Winter		Spring (Sept)		Autumn (Apr/May)	
	Sex-aggr.	By sex	Sex-aggr.	By sex	Sex-aggr.	By sex	Sex-aggr.	By sex
1985	✓	-	✓	-	-	-	-	-
1986	✓	-	✓	-	✓	-	-	-
1987	✓	-	✓	-	✓	-	-	-
1988	✓	-	✓	-	-	-	✓	-
1989	-	-	✓	-	-	-	-	-
1990	✓	-	✓	-	-	-	-	-
1991	✓	-	-	-	-	-	✓	-
1992	✓	-	-	-	-	-	✓	-
1993	✓	✓	-	-	-	-	✓	✓
1994	✓	✓	-	-	-	-	✓	✓
1995	✓	✓	-	-	-	-	✓	✓
1996	✓	✓	-	-	-	-	✓	✓
1997	✓	✓	-	-	-	-	✓	✓
1998	-	-	-	-	-	-	-	-
1999	✓	✓	-	-	-	-	✓	-
2000	-	-	-	-	-	-	-	-
2001	-	-	-	-	✓	-	-	-
2002	✓	-	-	-	-	-	-	-
2003	✓	-	-	-	✓	-	✓	-
2004	✓	-	-	-	✓	-	✓	-
2005	✓	-	-	-	-	-	✓	-
2006	✓	✓	-	-	✓	✓	✓	✓
2007	✓	✓	-	-	✓	✓	✓	✓
2008	✓	✓	-	-	✓	✓	✓	✓
2009	✓	✓	-	-	-	-	✓	✓

Table App.8.I.6: Species- and sex-disaggregated age and length data available in February 2010 by reader.

		M. paradoxus										*M. capensis*									
	Year	UR	AD	LB	KG	JP	AP	DJ	PM	TA	KB	UR	AD	LB	KG	JP	AP	DJ	PM	TA	KB
West coast summer survey	1990	351										354									
	1991	349										384									
	1992				310	310	44								390	389	33				
	1993				313	311		49				2			353	352		62			
	1994				290	290		4							282	282		6			
	1995					303					303					368					368
	1996	292										365									
	1997	333		334								334									
	1999	268	307	299								319	352	359							
	2004			506																	
	2005			354									340								
	2006		465	468									163								
	2007		557	554									369	372							
	2008		412	409									475	453							
West coast winter survey	1988	471										354									
	1990	303																			
South coast spring survey	1994	10																			
	2004												808	808							
	2006		489	243									512								
	2007		116										441								
	2008		149										127								
South coast autumn survey	1991	109										421									
	1992				40	40	5								329	329	91				
	1993				95	95		23							407	407		40			
	1994				95	69		27				5			390	391		83			
	1995	95										404									
	1996	60										373									
	1997	85										387									
	1999		139	139					140	140	140		266	264					408	406	400
	2004												508								
	2005		194	193																	
	2006		444	358										740							
	2007		215	214									629	626							
	2008		137										643	643							
Offshore commercial	1992				521	521	46								260	260	28				
	1993				645	646		75							115	115		17			
	1994				330	330		38				5									
Longline comm.	1994				314	314		9							131	126		5			

Table App.8.I.7: For each set of age readers, the reader shaded is the one whose otolith readings were used.

M. paradoxus

1	UR		
2	KG	JP	AP/DJ
3	UR	AD	LB
4	AD		
5	JP	KB	

M. capensis

1	UR				
2	KG	JP	AP/DJ		
3	JP	KB			
4	UR	AD	LB		
5	AD	LB	PM	TA	KB
6	PM	TA	KB		
5	LB				

The readers are: Alexia Daniels (AD), Luke Bester (LB), ‘Unknown Reader’ (UR), Kevin Gradie (KG), John Prinsloo (JP), Andy Payne/Dave Japp (AP/DJ), Phoeby Mullins (PM), Teressa Akkers (TA) and Kashif Booley (KB).

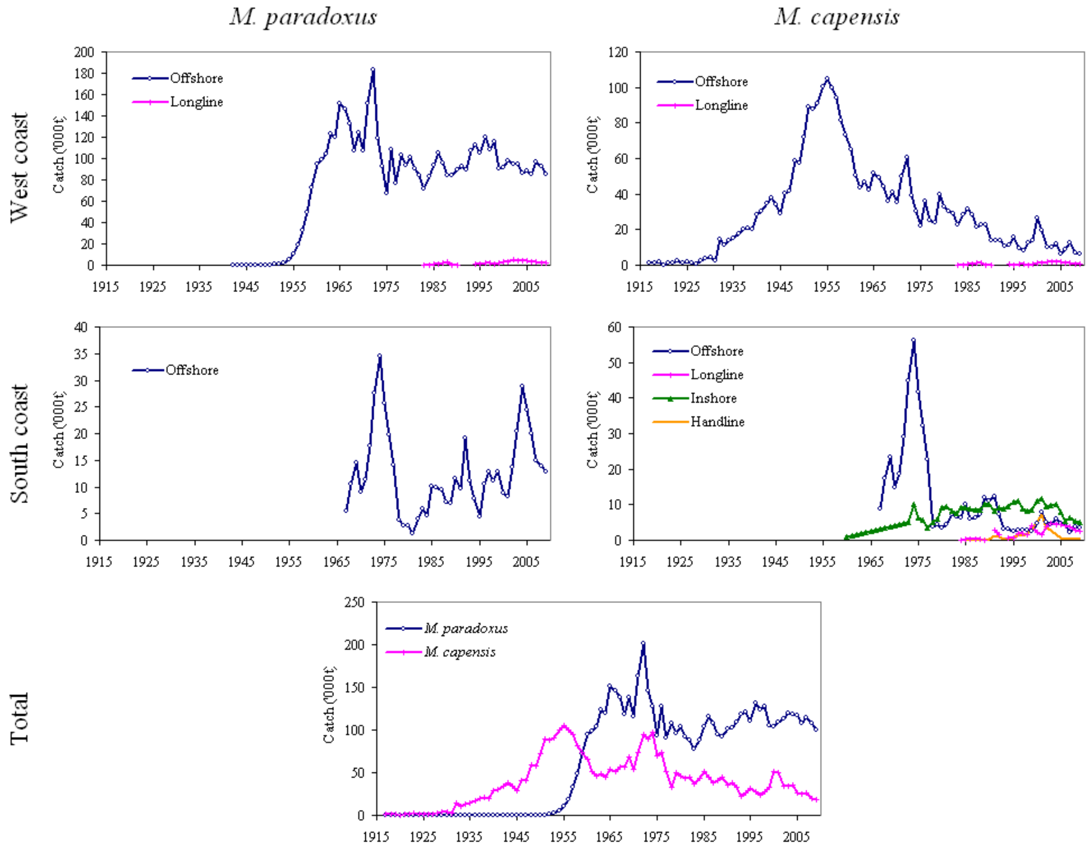


Figure App.8.I.1: Annual catches, see text for details, assuming 1958 as the centre year of the shift from a primarily *M. capensis* to a primarily *M. paradoxus* offshore trawl catch.

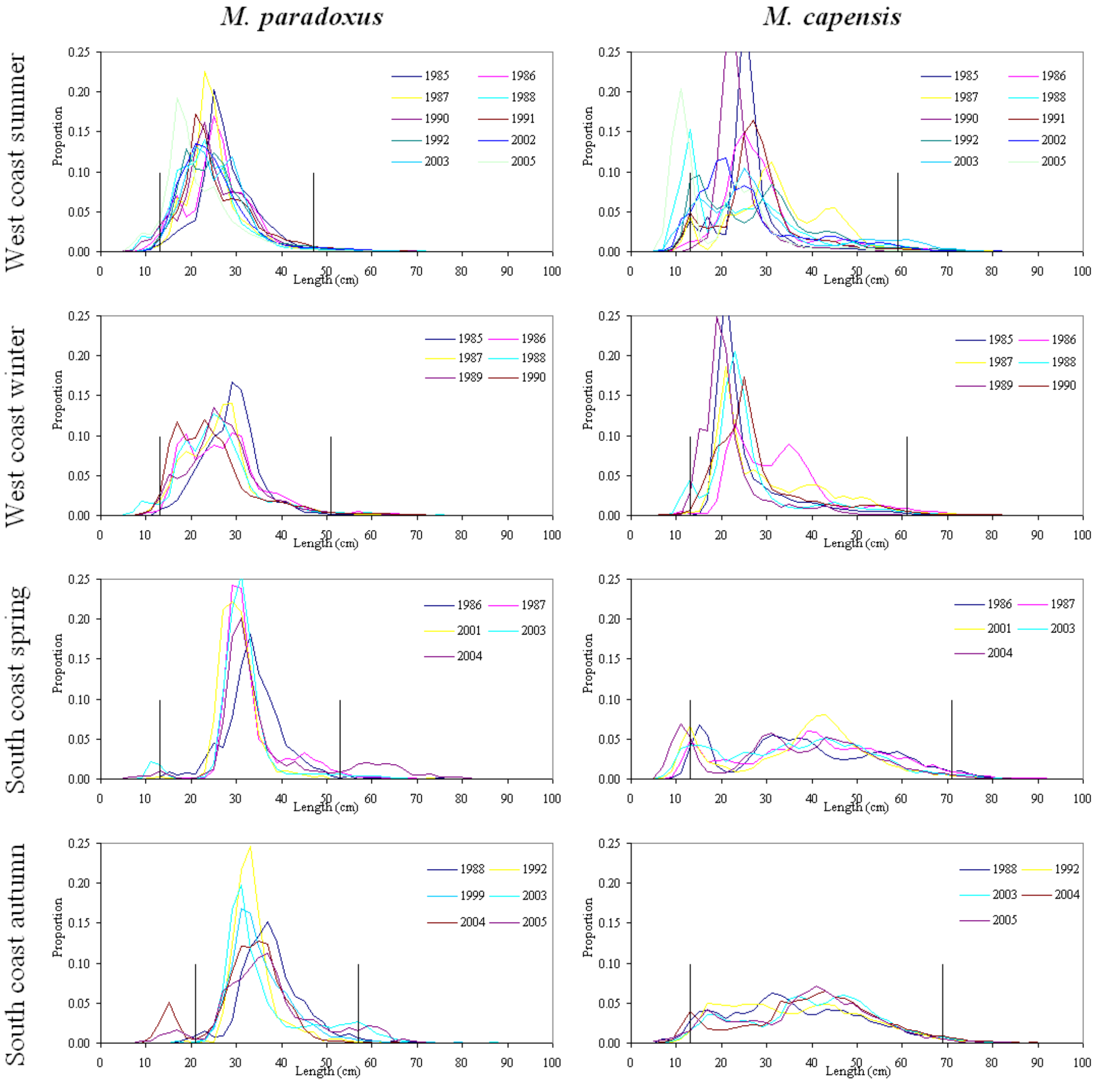


Figure App.8.I.2: Sex-aggregated survey catch-at-length information. The vertical bars show the minus and plus groups used.

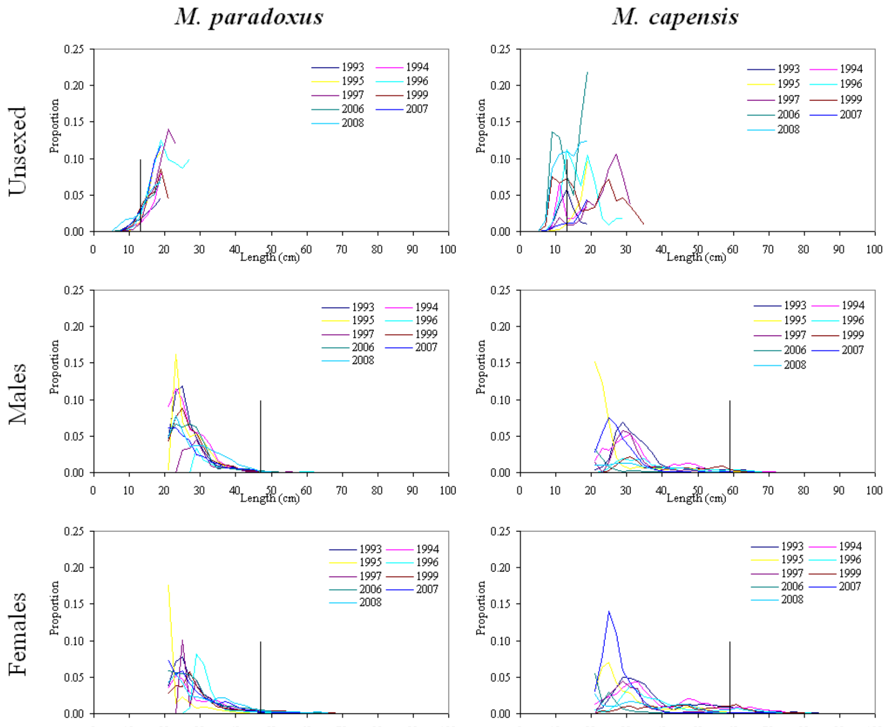


Fig App.8.I.3a: West coast summer gender-disaggregated survey catch-at-length information. The vertical bars show the minus and plus groups used.

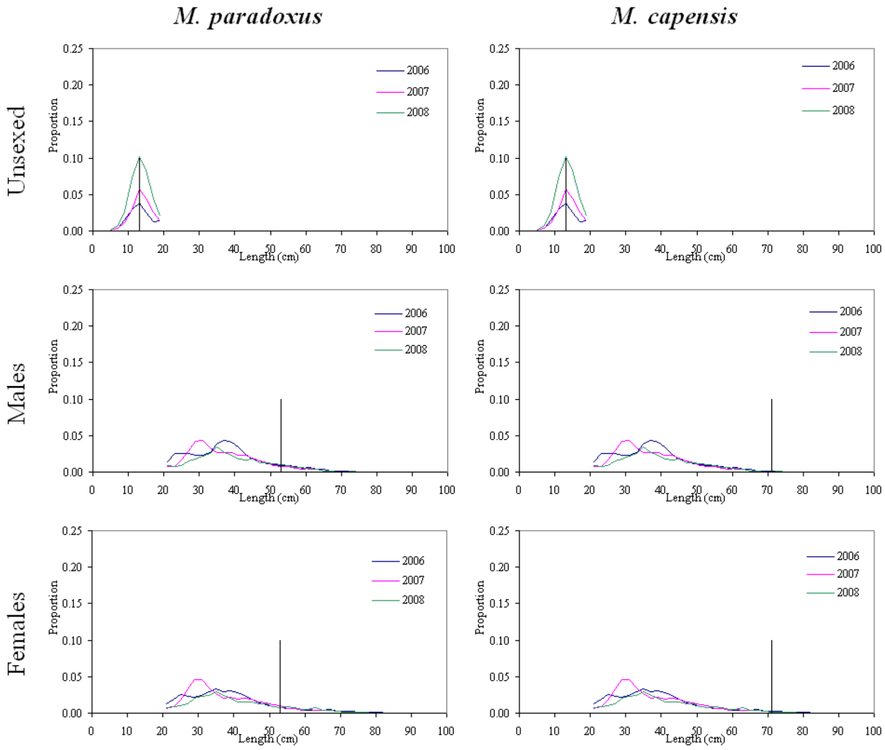


Fig App.8.I.3b: South coast spring gender-disaggregated survey catch-at-length information. The vertical bars show the minus and plus groups used.

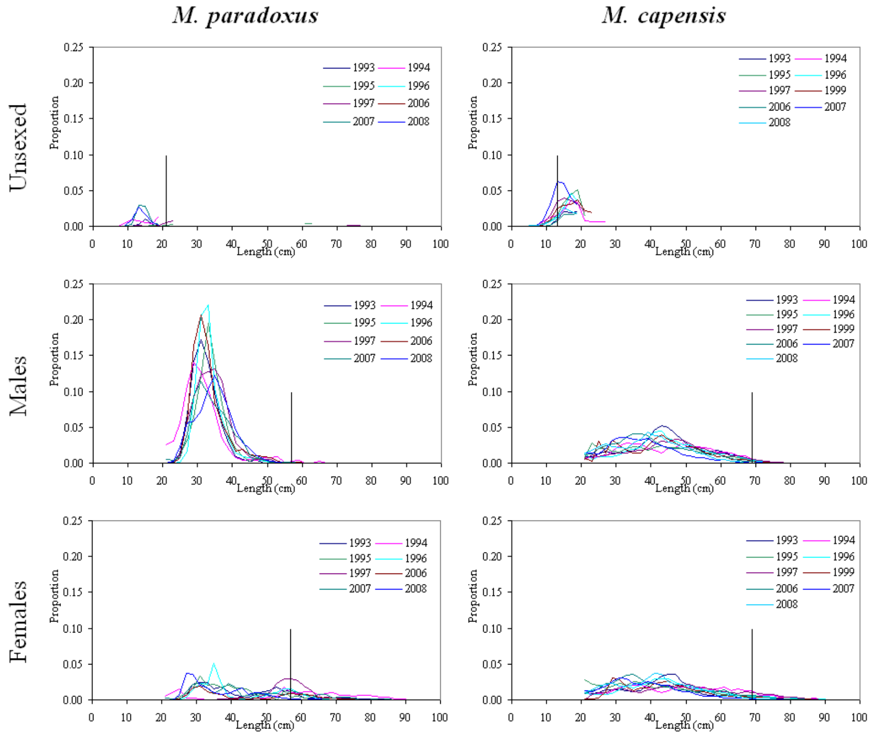


Fig App.8.I.3c: South coast autumn gender-disaggregated survey catch-at-length information. The vertical bars show the minus and plus groups used.

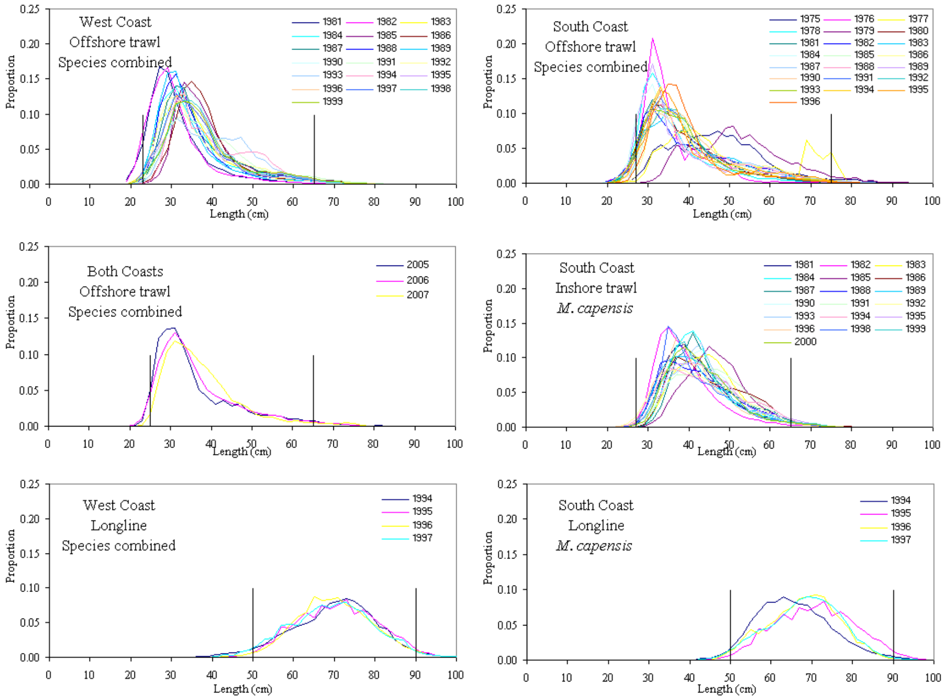
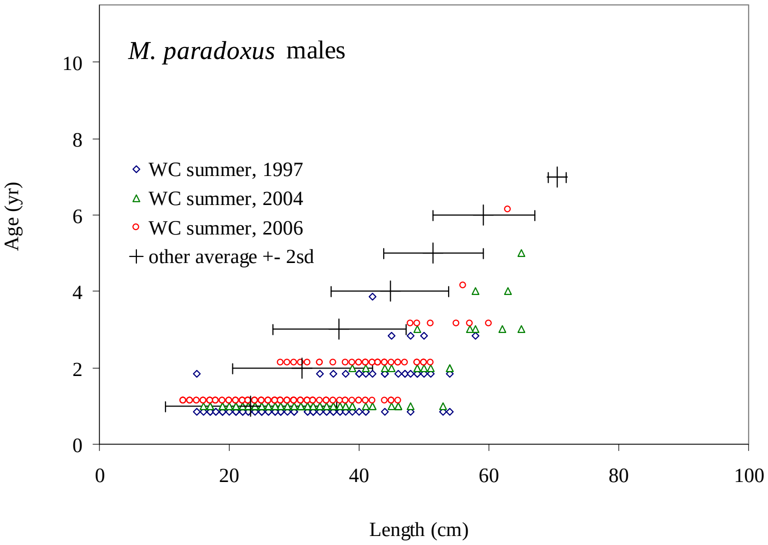


Fig App.8.I.4: Commercial catch-at-length information. The vertical bars show the minus and plus groups used.



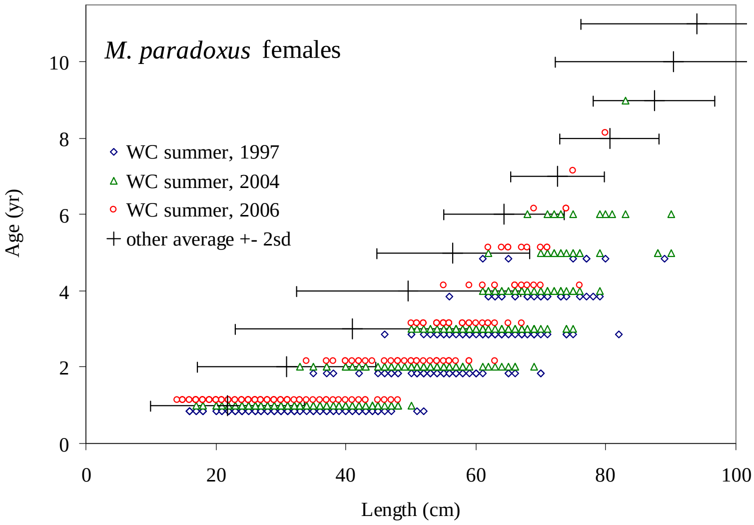


Figure App.8.I.5: Data points for each gender separately for the three *M. paradoxus* ALKs that have been omitted from the model fitting. The average of the other ALKs is shown with the error bars representing the ± 2 s.d. range.

APPENDIX 8.II

Gender-disaggregated, age-structured production model fitting to age-length keys

The model used is a gender-disaggregated Age-Structured Production Model (ASPM), which is fitted directly to age-length keys (ALKs) and length frequencies. The model also assesses the two species as two independent stocks and is fitted to species-disaggregated data as well as species-combined data. The general specifications and equations of the overall model are set out below, together with some key choices in the implementation of the methodology. Details of the contributions to the log-likelihood function from the different data considered are also given. Quasi-Newton minimisation is used to minimise the total negative log-likelihood function (implemented using AD Model Builder^{TM}, Otter Research, Ltd. (Fournier *et al*. 2011)).

8.II.1 Population Dynamics

8.II.1.1 Numbers-at-age

The resource dynamics of the two populations (*M. capensis* and *M. paradoxus*) of the South African hake are modelled by the following set of equations.

Note: for ease of reading, the ‘species’ subscript *s* has been omitted below where equations are identical for the two species.

$$N^g_{y+1,0} = R^g_{y+1} \qquad \text{(App.8.II.1)}$$

$$N^g_{y+1,a+1} = \left(N^g_{ya} e^{-M^g_a/2} - \sum_f C^g_{fya} \right) e^{-M^g_a/2} \qquad \text{for } 0 \le a \le m-2 \qquad \text{(App.8.II.2)}$$

$$\begin{aligned} N^g_{y+1,m} = {} & \left(N^g_{y,m-1} e^{-M^g_{m-1}/2} - \sum_f C^g_{f,y,m-1} \right) e^{-M^g_{m-1}/2} \\ & + \left(N^g_{ym} e^{-M^g_m/2} - \sum_f C^g_{fym} \right) e^{-M^g_m/2} \end{aligned} \qquad \text{(App.8.II.3)}$$

where

N^g_{ya} is the number of fish of gender *g* and age *a* at the start of year *y*[11];

R^g_y is the recruitment (number of 0-year-old fish) of fish of gender *g* at the start of year *y*;

m is the maximum age considered (taken to be a plus-group);

M^g_a denotes the natural mortality rate on fish of gender *g* and age *a*; and

C^g_{fya} is the number of hake of gender *g* and age *a* caught in year *y* by fleet *f*.

8.II.1.2 Recruitment

The number of recruits (i.e. new zero-year old fish) at the start of year *y* is assumed to be related to the corresponding female spawning stock size (i.e., the biomass of mature female fish). The underlying assumptions are that female spawning output can limit subsequent recruitment, but that there are always sufficient males to provide adequate fertilisation. The recruitment and corresponding female spawning stock size are related by means of the Beverton-Holt (Beverton and Holt 1957) or a modified (generalised) form of the Ricker stock-recruitment relationship. These forms are parameterized in terms of the "steepness" of the stock-recruitment relationship, h, the pre-exploitation equilibrium female spawning biomass, $K^{♀sp}$, and the pre-exploitation recruitment, R_0 and assuming a 50:50 sex-split at recruitment.

---

[11] In the interests of less cumbersome notation, subscripts have been separated by commas only when this is necessary for clarity.

$$R_y^g = \frac{4hR_0 B_y^{♀,sp}}{K^{♀,sp}\left(1-h\right)+\left(5h-1\right)B_y^{♀,sp}} e^{\left(\varsigma_y-\sigma_R^2/2\right)} \qquad \text{(App.8.II.4a)}$$

for the Beverton-Holt stock-recruitment relationship and

$$R_y^g = \alpha B_y^{♀,sp} \exp\left(-\beta\left(B_y^{♀,sp}\right)^\gamma\right) e^{\left(\varsigma_y-\sigma_R^2/2\right)} \qquad \text{(App.8.II.4b)}$$

with

$$\alpha = R_0 \exp\left(\beta\left(K^{♀,sp}\right)^\gamma\right) \qquad \text{and} \qquad \beta = \frac{\ln\left(5h\right)}{\left(K^{♀,sp}\right)^\gamma\left(1-5^{-\gamma}\right)}$$

for the modified Ricker relationship (for the true Ricker, $\gamma=1$) where

ς_y reflects fluctuation about the expected recruitment in year *y*;

σ_R is the standard deviation of the log-residuals, which is input ($\sigma_R = 0.45$ and is taken to decrease from this value to 0.1 over the last five years to statistically stabilise estimates of recent recruitment) .

$B_y^{♀sp}$ is the female spawning biomass at the start of year *y*, computed as:

$$B_y^{♀,sp} = \sum_{a=1}^{m} f_a^♀ w_a^♀ N_{ya}^♀ \qquad \text{(App.8.II.5)}$$

where

w_a^g is the begin-year mass of fish of gender *g* and age *a*;

f_a^g is the proportion of fish of gender *g* and age *a* that are mature (converted from maturity-at-length, see equation App.8.II.47); and

$$R_0 = K^{♀,sp} \Bigg/ \left[\sum_{a=1}^{m-1} f_a^♀ w_a^♀ e^{-\sum_{a'=0}^{a-1} M_{a'}^g} + f_m^♀ w_m^♀ \frac{e^{-\sum_{a'=0}^{m-1} M_{a'}^g}}{1-e^{-M_m^g}}\right] \qquad \text{(App.8.II.6)}$$

For the Beverton-Holt form, *h* is bounded above by 0.98 to preclude high recruitment at extremely low spawning biomass, whereas for the modified Ricker form, *h* is bounded above by 1.5 to preclude extreme compensatory behaviour.

8.II.1.3 Total catch and catches-at-age

The fleet-disaggregated catch by mass, in year *y* is given by:

$$C_{fy} = \sum_{g}\sum_{a=0}^{m} \tilde{w}^{g}_{fy,a+1/2}\, C^{g}_{fya} = \sum_{g}\sum_{a=0}^{m} \tilde{w}^{g}_{fy,a+1/2}\, N^{g}_{ya} e^{-M^{g}_{a}/2} F_{fy} S^{g}_{fya} \qquad \text{(App.8.II.7)}$$

where

C^{g}_{fya} is the catch-at-age, i.e. the number of fish of gender *g* and age *a*, caught in year *y* by fleet *f*;

F_{fy} is the fishing mortality of a fully selected age class, for fleet *f* in year *y* (independent of *g*) ;

$$S^{g}_{fya} = \sum_{l} S^{g}_{fyl} P^{g}_{a+1/2,l} \qquad \text{(App.8.II.8)}$$

S^{g}_{fya} is the commercial selectivity of gender *g* at age *a* for fleet *f* and year *y*;

S^{g}_{fyl} is the commercial selectivity of gender *g* at length *l* for year *y*, and fleet *f;*

$$\tilde{w}^{g}_{fy,a+1/2} = \sum_{l} S^{g}_{fyl} w^{g}_{l} P^{g}_{a+1/2,l} \Big/ \sum_{l} S^{g}_{fyl} P^{g}_{a+1/2,l} \qquad \text{(App.8.II.9)}$$

$\tilde{w}^{g}_{fy,a+1/2}$ is the selectivity-weighted mid-year weight-at-age *a* of gender *g* for fleet *f* and year *y*;

w^{g}_{l} is the weight of fish of gender *g* and length *l*;

$P^{g}_{a+1/2,l}$ is the mid-year proportion of fish of age *a* and gender *g* that fall in the length group *l* (i.e., $\sum_{l} P^{g}_{a+1/2,l} = 1$ for all ages *a*).

The matrix *P* is calculated under the assumption that length-at-age is log-normally distributed about a mean given by the von Bertalanffy equation, i.e.:

$$\ln l_a \sim N\left[\ln(l_\infty(1-e^{-\kappa(a-t_0)}))\,;\left(\frac{\theta_a}{l_\infty(1-e^{-\kappa(a-t_0)})}\right)^2\right] \qquad \text{(App.8.II.10)}$$

where θ_a is the standard deviation of length-at-age *a*, which is estimated directly in the model fitting for age 0, and for ages 1 and above a linear relationship applies:

$$\theta_a = \begin{cases} B_0 & \text{for } a = 0 \\ (\beta a + \alpha) & \text{for } 1 \le a \le m \end{cases}$$

with species and gender-specific B_0, α and β estimated in the model fitting procedure. A penalty is added so that θ_a is increasing with age, i.e. β>0.

8.II.1.4 Exploitable and survey biomasses

The model estimate of the mid-year exploitable ("available") component of biomass for each species and fleet is calculated by converting the numbers-at-age into mid-year mass-at-age and applying natural and fishing mortality for half the year:

$$B^{ex}_{fy} = \sum_g \sum_{a=0}^{m} \tilde{w}^g_{fy,a+1/2} S^g_{fya} N^g_{ya} e^{-M^g_a/2}\left(1-\sum_f S^g_{fya}F_{fy}\Big/2\right) \qquad \text{(App.8.II.11)}$$

The model estimate of the survey biomass at the start of the year (summer) is given by:

$$B^{surv}_y = \sum_g \sum_{a=0}^{m_s} \tilde{w}^{g,sum}_a S^{g,sum}_a N^g_{ya} \qquad \text{(App. 8.II.12)}$$

and in mid-year (winter):

$$B^{surv}_y = \sum_g \sum_{a=0}^{m} \tilde{w}^{g,win}_{a+1/2} S^{g,win}_a N^g_{ya} e^{-M^g_a/2}\left(1-\sum_f S^g_{fya}F_{fy}\Big/2\right) \qquad \text{(App. 8.II.13)}$$

where

$S_a^{g,sum/win}$ is the survey selectivity of gender *g* for age *a,* converted from survey selectivity-at-length in the same manner as for the commercial selectivity (eqn App.II.8);

$\tilde{w}_a^{g,i}$ is the survey selectivity-weighted weight-at-age *a* of gender *g* for survey *i*, computed in the same manner as for the commercial selectivity-weight-at-age (equation App.II.9) and taking account of the begin-year ($\tilde{w}_{y,a}^{g,sum}$ from $P_{a,l}^g$) or mid-year ($\tilde{w}_{y,a+1/2}^{g,win}$ from $P_{a+1/2,l}^g$) nature of the surveys.

Note that both the spring and autumn surveys are taken to correspond to winter (mid-year).

It is assumed that the resource is at the deterministic equilibrium that corresponds to an absence of harvesting at the start of the initial year considered, i.e., $B_1^{g,sp} = K^{g,sp}$, and the year *y*=1 corresponds to 1917 when catches commence.

8.II.2 MSY and related quantities

The equilibrium catch for a fully selected fishing proportion *F** is calculated as:

$$C(F^*) = \sum_g \sum_a \tilde{w}_{a+1/2}^g S_a^g F^* N_a^g (F^*) e^{-((M_a^g + S_a^g F^*)/2)} \qquad \text{(App.8.II.14)}$$

where

S_a^g is the average selectivity across all fleets, for the most recent five years;

$$S_a^g = \frac{\sum_{y=2005}^{2009} \sum_f S_{fya}^g F_{fy}}{\max\left(\sum_{y=2005}^{2009} \sum_f S_{fya}^g F_{fy} \right)} \qquad \text{(App.8.II.15)}$$

where the maximum is taken over genders and ages; and with

$$N_a^g\left(F^*\right)=\begin{cases} R_1\left(F^*\right) & \text{for } a=1 \\ N_{a-1}^g\left(F^*\right)e^{-M_{a-1}^g}\left(1-S_{a-1}^g F^*\right) & \text{for } 1<a<m \\ \dfrac{N_{m-1}^g\left(F^*\right)e^{-M_{m-1}^g}\left(1-S_{m-1}^g F^*\right)}{\left(1-e^{-M_m^g}\left(1-S_m^g F^*\right)\right)} & \text{for } a=m \end{cases} \qquad \text{(App.8.II.16)}$$

where

$$R_1\left(F^*\right)=\frac{\alpha B^{♀,sp}\left(F^*\right)}{\beta+B^{♀,sp}\left(F^*\right)} \qquad \text{(App.8.II.17)}$$

for a Beverton-Holt stock–recruitment relationship.

The maximum of $C\left(F^*\right)$ is then found by searching over F^* to give F^*_{MSY}, with the associated female spawning biomass given by:

$$B_{MSY}^{♀,sp}=\sum_a f_a^{♀} w_a^{♀} N_a^{♀}\left(F^*_{\mathrm{MSY}}\right)$$

8.II.3 The likelihood function

The model is fit to CPUE and survey abundance indices, commercial and survey length frequencies, survey age-length keys, as well as to the stock-recruitment curve to estimate model parameters. Contributions by each of these to the negative of the log-likelihood ($-\ell\mathrm{n}L$) are as follows[12].

8.II.3.1 CPUE relative abundance data

The likelihood is calculated by assuming that the observed abundance index (here CPUE) is log-normally distributed about its expected value:

$$I_y^i=\hat{I}_y^i e^{\varepsilon_y^i} \quad \text{or} \quad \varepsilon_y^i=\ell\mathrm{n}\left(I_y^i\right)-\ell\mathrm{n}\left(\hat{I}_y^i\right) \qquad \text{(App.8.II.18)}$$

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[12] Strictly it is a penalised log-likelihood which is maximised in the fitting process, as some contributions that would correspond to priors in a Bayesian estimation process are added.

where

I_y^i is the abundance index for year *y* and series *i* (which corresponds to a specified species and fleet);

$\hat{I}_y^i = \hat{q}^i \hat{B}_{fy}^{ex}$ is the corresponding model estimate, where $\hat{B}_{fy}^{ex}$ is the model estimate of exploitable resource biomass, given by equation App.8.II.11;

$\hat{q}^i$ is the constant of proportionality for abundance series *I*; and

ε_y^i from $N\left(0, \left(\sigma_y^i\right)^2\right)$.

In cases where the CPUE series are based upon species-aggregated catches (as available pre-1978), the corresponding model estimate is derived by assuming two types of fishing zones: z1) an "*M. capensis* only zone", corresponding to shallow-water and z2) a "mixed zone" (Figure App.8.II.1).

The total catch of hake of both species (*BS*) by fleet *f* in year *y* ($C_{BS,fy}$) can be written as:

$$C_{BS,fy} = C_{C,fy}^{z1} + C_{C,fy}^{z2} + C_{P,fy} \qquad \text{(App.8.II.19)}$$

where

$C_{C,fy}^{z1}$ is the *M. capensis* catch by fleet *f* in year *y* in the *M. capensis* only zone (z1);

$C_{C,fy}^{z2}$ is the *M. capensis* catch by fleet *f* in year *y* in the mixed zone (z2); and

$C_{P,fy}$ is the *M. paradoxus* catch by fleet *f* in year *y* in the mixed zone.

Catch rate is assumed to be proportional to exploitable biomass. Furthermore, let γ be the proportion of the *M. capensis* exploitable biomass in the mixed zone ($\gamma = B_{C,fy}^{ex,z2} / B_{C,fy}^{ex}$) (assumed to be constant throughout the period for simplicity) and ψ_{fy} be the proportion of the effort of fleet *f* in the mixed zone in year *y* ($\psi_{fy} = E_{fy}^{z2} / E_{fy}$), so that:

$$C_{C,fy}^{z1} = q_C^{i,z1} B_{Cfy}^{ex,z1} E_{fy}^{z1} = q_C^{i,z1}(1-\gamma) B_{C,fy}^{ex}(1-\psi_{fy}) E_{fy} \qquad \text{(App.8.II.20)}$$

$$C_{C,fy}^{z2} = q_C^{i,z2} B_{C,fy}^{ex,z2} E_{fy}^{z2} = q_C^{i,z2} \gamma B_{C,fy}^{ex} \psi_{fy} E_{fy} \text{ and} \qquad \text{(App.8.II.21)}$$

$$C_{P,fy} = q_P^i B_{P,fy}^{ex} E_{fy}^{z2} = q_P^i B_{P,fy}^{ex} \psi_{fy} E_{fy} \qquad \text{(App.8.II.22)}$$

where

$E_{fy} = E_{fy}^{z1} + E_{fy}^{z2}$ is the total effort of fleet *f*, corresponding to combined-species CPUE series *i* which consists of the effort in the *M. capensis* only zone (E_{fy}^{z1}) and the effort in the mixed zone (E_{fy}^{z2});

$q_C^{i,zj}$ is the catchability for *M. capensis* (*C*) for abundance series *i*, and zone *zj*; and

q_P^i is the catchability for *M. paradoxus* (*P*) for abundance series *i*.

It follows that:

$$C_{C,fy} = B_{C,fy}^{ex} E_{fy} \left[q_C^{i,z1}(1-\gamma)(1-\psi_{fy}) + q_C^{i,z2} \gamma \psi_{fy} \right] \qquad \text{(App.8.II.23)}$$

$$C_{P,fy} = B_{P,fy}^{ex} E_{fy} q_P^i \psi_{fy} \qquad \text{(App.8.II.24)}$$

From solving equations App.8.II.23 and App.8.II.24:

$$s_{fy} = \frac{q_C^{i,z1}(1-\gamma)}{\left\{ \frac{C_{C,fy} B_{P,fy}^{ex} q_P^i}{B_{C,fy}^{ex} C_{P,fy}} - q_C^{i,z2}\gamma + q_C^{i,z1}(1-\gamma) \right\}} \qquad \text{(App.8.II.25)}$$

and:

$$\hat{I}_y^i = \frac{C_{fy}}{E_{fy}} = \frac{C_{fy} B_{P,fy}^{ex} q_P^i \psi_{fy}}{C_{P,fy}} \qquad \text{(App.8.II.26)}$$

Zone 1 (z1): *M. capensis* only	Zone 2 (z2): Mixed zone
M. capensis: biomass (B_C^{z1}), catch(C_C^{z1})	*M. capensis*: biomass (B_C^{z2}), catch(C_C^{z2}) *M. paradoxus*: biomass (B_P), catch(C_P)
Effort in zone 1 (E^{z1})	Effort in zone 2 (E^{z2})

Figure App.8.II.1: Diagrammatic representation of the two conceptual fishing zones.

Two species-aggregated CPUE indices are available: the ICSEAF West Coast and the ICSEAF South Coast series. For consistency, *q*'s for each species (and zone) are forced to be in the same proportion:

$$q_s^{SC} = rq_s^{WC} \qquad \text{(App.8.II.27)}$$

To correct for possible negative bias in estimates of variance $\left(\sigma_y^i\right)$ and to avoid according unrealistically high precision (and so giving inappropriately high weight) to the CPUE data, lower bounds on the standard deviations of the residuals for the logarithm of the CPUE series have been enforced: for the historic ICSEAF CPUE series (separate West Coast and South Coast series) the lower bound is set to 0.25, and to 0.15 for the recent GLM-standardised CPUE series, i.e.: $\sigma^{ICSEAF} \geq 0.25$ and $\sigma^{GLM} \geq 0.15$.

The contribution of the CPUE data to the negative of the log-likelihood function (after removal of constants) is then given by:

$$-\ell n\, L^{CPUE} = \sum_i \sum_y \left[\ell n\left(\sigma_y^i\right) + \left(\varepsilon_y^i\right)^2 / 2\left(\sigma_y^i\right)^2\right] \qquad \text{(App.8.II.28)}$$

where

σ_y^i is the standard deviation of the residuals for the logarithms of index *i* in year *y*.

Homoscedasticity of residuals for CPUE series is customarily assumed[13], so that $\sigma_y^i = \sigma^i$ is estimated in the fitting procedure by its maximum likelihood value:

$$\hat{\sigma}^i = \sqrt{1/n_i \sum_y \left(\ell n(I_y^i) - \ell n(\hat{I}_y^i)\right)^2} \qquad \text{(App.8.II.29)}$$

where n_i is the number of data points for abundance index *i*.

In the case of the species-disaggregated CPUE series, the catchability coefficient q^i for abundance index *i* is estimated by its maximum likelihood value, which in the more general case of heteroscedastic residuals is given by:

$$\ln \hat{q}^i = \frac{\sum_y \left(\ln I_y^i - \ln \hat{B}_{fy}^{ex}\right) \Big/ \left(\sigma_y^i\right)^2}{\sum_y 1 \Big/ \left(\sigma_y^i\right)^2} \qquad \text{(App.8.II.30)}$$

In the case of the species-combined CPUE, $q_C^{WC,z1}$, $q_C^{WC,z2}$, q_P^{WC}, *r* and γ are estimated directly in the fitting procedure.

8.II.3.2 Survey abundance data

Data from the research surveys are treated as relative abundance indices in a similar manner to the species-disaggregated CPUE series above, with survey selectivity function $S_a^{g,sum/win}$ replacing the commercial selectivity S_{fya}^g (see equations App.8.II.12 and App.8.II.13 above, which also take account of the begin- or mid-year nature of the survey).

An estimate of sampling variance is available for most surveys and the associated σ_y^i is generally taken to be given by the corresponding survey CV. However, these estimates likely fail to include all sources of variability, and unrealistically high precision (low variance and hence high weight) could hence be accorded to these indices. The contribution of the survey data to the negative log-likelihood is of the same form as that of the CPUE abundance data (see equation App.8.II.28). The procedure adopted takes into

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[13] There are insufficient data in any series to enable this to be tested with meaningful power.

account an additional variance $(\sigma_A)^2$ which is treated as another estimable parameter in the minimisation process. This procedure is carried out enforcing the constraint that $(\sigma_A)^2$ >0, i.e. the overall variance cannot be less than its externally input component.

In June 2003, the trawl gear on the *Africana* was changed and a different value for the multiplicative bias factor *q* is taken to apply to the surveys conducted with the new gear. Calibration experiments have been conducted between the *Africana* with the old gear (hereafter referred to as the "old *Africana*") and the *Nansen*, and between the *Africana* with the new gear ("new *Africana*") and the *Nansen*, in order to provide a basis to relate the multiplicative biases of the *Africana* with the two types of gear (q_{old} and q_{new}). A GLM analysis assuming negative binomial distributions for the catches made (Brandão *et al.*, 2004) provided the following estimates:

$\Delta\ell nq^{capensis} = -0.494$ with $\sigma_{\Delta\ell nq^{capensis}} = 0.141$ i.e. $\left(q^{new}/q^{old}\right)^{capensis} = 0.610$ and

$\Delta\ell nq^{paradoxus} = -0.053$ with $\sigma_{\Delta\ell nq^{paradoxus}} = 0.117$ i.e. $\left(q^{new}/q^{old}\right)^{paradoxus} = 0.948$

where

$\ell nq^{s}_{new} = \ell nq^{s}_{old} + \Delta\ell nq^{s}$ with *s* = *capensis* or *paradoxus* (App.8.II.31)

No plausible explanation has yet been found for the particularly large extent to which catch efficiency for *M. capensis* is estimated to have decreased for the new research survey trawl net. It was therefore recommended (BENEFIT 2004) that the ratio of the catchability of the new to the previous *Africana* net be below 1, but not as low as the ratio estimated from the calibration experiments. $\Delta\ell nq^{capensis}$ is therefore taken as -0.223, i.e. $\left(q^{new}/q^{old}\right)^{capensis} = 0.8$.

The following contribution is therefore added as a penalty (or a log prior in a Bayesian context) to the negative log-likelihood in the assessment:

$$-\ell nL^{q-ch} = \left(\ell nq_{new} - \ell nq_{old} - \Delta\ell nq\right)^2 / 2\sigma^2_{\Delta\ell nq} \qquad \text{(App.8.II.32)}$$

A different length-specific selectivity is estimated for the "old *Africana*" and the "new *Africana*".

The survey's coefficients of catchability *q* (for the survey with the old *Africana* gear) are constrained to values below 1 (i.e. it is assumed that the nets do not herd the hake):

$$pen^q = \sum_i \left(q^i_{old} - 1\right)^2 \Big/ 0.02^2 \quad \text{if} \qquad q^i_{old} > 1 \tag{App.8.II.33}$$

8.II.3.3 Commercial proportions at length

Commercial proportions at length cannot be disaggregated by species and gender. The model is therefore fit to the proportions at length as determined for both species and gender combined.

The catches at length are computed as:

$$C_{fyl} = \sum_s \sum_g \sum_{a=0}^{m} N^g_{sya} F_{sfy} S^g_{sfyl} P^g_{s,a+1/2,l} e^{-M^g_{sa}/2} \left(1 - \sum_f S^g_{sfya} F_{fy} \Big/ 2\right) \tag{App.8.II.34}$$

with the predicted proportions at length:

$$\widehat{p}^i_{yl} = C_{fyl} \Big/ \sum_{l'} C_{fyl'} \tag{App.8.II.35}$$

The contribution of the proportion at length data to the negative of the log-likelihood function when assuming an "adjusted" lognormal error distribution is given by:

$$-\ell\mathrm{n}\, L^{\mathrm{length}} = 0.1 \sum_y \sum_l \left[\ell n \left(\sigma^i_{len} / \sqrt{p^i_{yl}}\right) + p^i_{yl} \left(\ell n p^i_{yl} - \ell n\, \hat{p}^i_{yl}\right)^2 / 2\left(\sigma^i_{len}\right)^2\right] \tag{App.8.II.36}$$

where

the superscript '*i*' refers to a particular series of proportions at length data which reflect a specified fleet, and species (or combination thereof); and

σ^i_{len} is the standard deviation associated with the proportion at length data, which is estimated in the fitting procedure by:

$$\hat{\sigma}^i_{len} = \sqrt{\sum_y \sum_l p^i_{yl} \left(\ln p^i_{yl} - \ln \hat{p}^i_{yl} \right)^2 / \sum_y \sum_l 1} \qquad \text{(App.8.II.37)}$$

The initial 0.1 multiplicative factor is a somewhat arbitrary downweighting to allow for correlation between proportions in adjacent length groups. The coarse basis for this adjustment is the ratio of effective number of age-classes present to the number of length groups in the minimisation, under the argument that independence in variability is likely to be more closely related to the former.

Commercial proportions at length are incorporated in the likelihood function using equation App.8.II.36, for which the summation over length *l* is taken from length l_{minus} (considered as a minus group) to l_{plus} (a plus group). The length for the minus- and plus-groups are fleet specific and are chosen so that typically a few percent, but no more, of the fish sampled fall into these two groups.

8.II.3.4 Survey proportions at length

The survey proportions at length are incorporated into the negative of the log-likelihood in an analogous manner to the commercial catches-at-age, assuming an adjusted log-normal error distribution (equation App.8.II.36). In this case however, data are disaggregated by species, and for some surveys further disaggregated by gender:

$p^{g,surv}_{syl} = \dfrac{C^{g,surv}_{syl}}{\sum_{l'} C^{g,surv}_{syl'}}$ is the observed proportion of fish of species *s*, gender *g* and length *l* from survey *surv* in year *y*; and

$\hat{p}^{g,surv}_{syl}$ is the expected proportion of fish of species *s*, gender *g* and length *l* in year *y* in the survey *surv*, given by:

$$\hat{p}^{g,surv}_{syl} = \frac{\sum_a S^{g,sum}_{sl} P^g_{sal} N^g_{sya}}{\sum_{l'} \sum_a S^{g,sum}_{sl'} P^g_{sal'} N^g_{sya}} \qquad \text{(App.8.II.38)}$$

for begin-year (summer) surveys, or

$$\hat{p}^{g,surv}_{syl} = \frac{\sum_{a} S^{g,win}_{sl} P^{g}_{s,a+1/2,l} N^{g}_{sya} e^{-M^{g}_{sa}/2}\left(1-\sum_{f} S^{g}_{sfya} F_{sfy} \Big/ 2\right)}{\sum_{l'}\sum_{a} S^{g,win}_{sl'} P^{g}_{s,a+1/2,l'} N^{g}_{sya} e^{-M^{g}_{sa}/2}\left(1-\sum_{f} S^{g}_{sfya} F_{sfy} \Big/ 2\right)} \qquad \text{(App.8.II.39)}$$

for mid-year (autumn, winter or spring) surveys.

8.II.3.5 Age-length keys

Under the assumption that fish are sampled randomly with respect to age within each length-class, the contribution to the negative log-likelihood for the ALK data (ignoring constants) is:

$$-\ln L^{ALK} = -w\sum_{i}\sum_{l}\sum_{a}\left[A^{obs}_{i,l,a}\ln\left(\hat{A}_{i,l,a}\right) - A^{obs}_{i,l,a}\ln\left(A^{obs}_{i,l,a}\right)\right] \qquad \text{(App.8.II.40)}$$

where

w is a downweighting factor to allow for overdispersion in these data compared to the expectation for a multinomial distribution with independent data; this weight factor is set to 0.01;

$A^{obs}_{i,a,l}$ is the observed number of fish of age *a* that fall in the length class *l*, for ALK *i* (a specific combination of survey, year, species and gender);

$\hat{A}_{i,a,l}$ is the model estimate of $A^{obs}_{i,a,l}$, computed as:

$$\hat{A}_{i,a,l} = W_{i,l}\frac{C_{i,l}A_{a,l}}{\sum_{a'} C_{i,l}A_{a',l}} \qquad \text{(App.8.II.41)}$$

where

$W_{i,l}$ is the number of fish in length class *l* that were aged for ALK *i*,

$A_{a',l} = \sum_{a} P(a'|a)A_{a,l}$ is the ALK for age *a* and length *l* after accounting for age-reading error, with $P(a'|a)$, the age-reading error matrix, representing the probability of an animal of true age *a* being aged to be that age or some other age *a*'.

Age-reading error matrices have been computed for each reader and for each species as reported in Appendix 8.III.

When multiple readers age the same fish, these data are considered to be independent information in the model fitting.

8.II.3.6 Stock-recruitment function residuals

The stock-recruitment residuals are assumed to be log-normally distributed. Thus, the contribution of the recruitment residuals to the negative of the log-likelihood function is given by:

$$-\ell nL^{SR} = \sum_{s}\left[\sum_{y=y1}^{y2} {\varsigma_{sy}}^{2} \Big/ 2\sigma_R^2 + \left(\sum_{y=y1}^{y2} \varsigma_{sy}\right)^2 \Big/ 0.01^2\right] \qquad \text{(App.8.II.42)}$$

where

ς_{sy} is the recruitment residual for species *s*, and year *y*, which is assumed to be log-normally distributed with standard deviation σ_R and which is estimated for year *y1* to *y2* (see equation App.8.II.4) (estimating the stock-recruitment residuals is made possible by the availability of catch-at-age data, which give some indication of the age-structure of the population); and

σ_R is the standard deviation of the log-residuals, which is input.

The stock-recruitment residuals are estimated for years 1985 to 2006, with recruitment for other years being set deterministically (i.e. exactly as given by the estimated stock-recruitment curve) as there is insufficient catch-at-age information to allow reliable residual estimation for earlier years. A limit on the recent recruitment fluctuations is set by having the σ_R (which measures the extent of variability in recruitment – see equation – App.II.42) decreasing linearly from 0.45 in 2004 to 0.1 in 2009, effectively forcing recruitment over the last years to lie closer to the stock-recruitment relationship curve.

The second term on the right hand side is introduced to force the average of the residuals estimated over the period from *y1* to *y2* to be close to zero, for reasons elaborated in the main text.

8.II.4 Model parameters

8.II.4.1 Estimable parameters

The primary parameters estimated are the species-specific female virgin spawning biomass $\left(K_s^{\female sp}\right)$ and "steepness" of the stock-recruitment relationship (h_s). The standard deviations σ^i for the CPUE series residuals (the species-combined as well as the GLM-standardised series) as well as the additional variance $\left(\sigma_A^i\right)^2$ for each survey abundance series are treated as estimable parameters in the minimisation process. Similarly, in the case of the species-combined CPUE, $q_C^{WC,z1}$, $q_C^{WC,z2}$, q_P^{WC}, r and γ are directly estimated in the fitting procedure.

The species- and gender-specific von Bertalanffy growth curve parameters (l_∞, κ and t_0) are estimated directly in the model fitting process, as well as B_0 , α and β, values used to compute the standard deviation of the length-at-age a.

The following parameters are also estimated in the model fits undertaken (if not specifically indicated as fixed):

8.II.4.1.1 Natural mortality:

Natural mortality (M_{sa}^g) is assumed to be age-specific and is calculated using the following functional form (the selection of the specific form here is based on convenience and is somewhat arbitrary):

$$M_{sa}^{♀} = \begin{cases} M_{s2}^{♀} & \text{for} \quad a \le 1 \\ \alpha_s^M + \dfrac{\beta_s^M}{a+1} & \text{for} \quad 2 \le a \le 5 \\ M_{s5}^{♀} & \text{for} \quad a > 5 \end{cases} \qquad \text{(App.8.II.43)}$$

and

$$M_{sa}^{males} = \upsilon^s M_{sa}^{females} \qquad \text{(App.8.II.44)}$$

M_{s0} and M_{s1} are set equal to M_{s2} $(=\alpha_s^M + \beta_s^M/3)$ as there are no data (hake of ages younger than 2 are rare in catch and survey data) which would allow independent estimation of M_{s0} and M_{s1}.

When *M* values are estimated in the fit, a penalty is added to the total –lnL so that $M_{s2} \ge M_{s5}$:

$$pen^M = \sum_s \left(M_{s5} - M_{s2}\right)^2 / 0.01^2 \qquad \text{if } M_{s2} < M_{s5} \qquad \text{(App.8.II.45)}$$

8.II.4.1.2 Stock-recruitment residuals:

Stock-recruitment residuals ς_{sy} are estimable parameters in the model fitting process. They are estimated separately for each species from 1985 to the present, and set to zero pre-1985 because there are no catch-at-length data for that period to provide the information necessary to inform estimation.

Table App.8.II.1 summarises the estimable parameters, excluding the selectivity parameters.

8.II.4.1.3 Survey fishing selectivity-at-length:

The survey selectivities are estimated directly for seven pre-determined lengths for *M. paradoxus* and *M. capensis*. When the model was fitted to proportion-at-age rather than proportion-at-length, survey selectivities were estimated directly for each age (i.e. seven age classes). The lengths at which selectivity is estimated directly are survey specific (at constant intervals between the minus and plus groups) and are given in Table App.8.II.2. Between these lengths, selectivity is assumed to change linearly. The slope from lengths l_{minus} to l_{minus}+1 is assumed to continue exponentially to lower lengths down to length *1*, and similarly the slope from lengths l_{plus}-1 to l_{plus} for *M. paradoxus* and *M. capensis* to continue for greater lengths.

For the South Coast spring and autumn surveys, gender-specific selectivities are estimated for *M. paradoxus*. Furthermore, the female selectivities are scaled down by a parameter estimated for each of these two surveys to allow for the male predominance in the survey catch.

A penalty is added to the total –lnL to smooth the selectivities:

$$pen^{survS} = \sum_{i} \sum_{L=L_1+1}^{L_7-1} 3\left(S_{L-1}^{i} - 2S_{L}^{i} + S_{L+1}^{i}\right)^2 \qquad \text{(App.8.II.46)}$$

where *i* is a combination of survey, species and gender.

8.II.4.1.4 Commercial fishing selectivity-at-length:

The fishing selectivity-at-length (gender independent) for each species and fleet, S_{sfl}, is estimated in terms of a logistic curve given by:

$$S_{sfl} = \left[1 + \exp\left(-\left(l - l_{sf}^{c}\right)/\,\delta_{sf}^{c}\right)\right]^{-1} \qquad \text{(App.8.II.47)}$$

where

l_{sf}^{c} cm is the length-at-50% selectivity,

δ_{sf}^{c} cm^{-1} defines the steepness of the ascending limb of the selectivity curve.

The selectivity is sometimes modified to include a decrease in selectivity at larger lengths, as follows:

$$S_{sfl} = S_{s,f,l-1}e^{-s_{sfl}} \qquad \text{for } l > l_{slope}, \qquad \text{(App.8.II.48)}$$

where

s_{sfl} measures the rate of decrease in selectivity with length for fish longer than l_{slope} for the fleet concerned, and is referred to as the "selectivity slope"; and

l_{slope} is fixed externally from the model, values for each fleet and species are given in Table App.8.II.2.

Periods of fixed and changing selectivity have been assumed for the offshore trawl fleet to take account of the change in the selectivity at low ages over time in the commercial catches, likely due to the phasing out of the (illegal) use of net liners to enhance catch rates.

On the South Coast, for *M. paradoxus*, the female offshore trawl selectivity (only the trawl fleet is assumed to catch *M. paradoxus* on the South Coast) is scaled down by a factor taken as the average of those estimated for the South Coast spring and autumn surveys. Although there is no gender information for the commercial catches, the South Coast spring and autumn surveys catch a much higher proportion of male *M. paradoxus* than female (ratios of about 7:1 and 3.5:1 for spring and autumn respectively). This is assumed to reflect a difference in distribution of the two genders which would therefore affect the commercial fleet similarly.

Details of the fishing selectivities (including the number of parameters estimated) that are used in the assessment are shown in Table App.8.II.4.

8.II.4.2 Input parameters and other choice for application to hake

8.II.4.2.1 Age-at-maturity:

The proportion of fish of species *s*, gender *g* and length *l* that are mature is assumed to follow a logistic curve with the parameter values given below (from Fairweather and Leslie 2008, "stage 2, >40cm" for females and Fairweather, pers. commn for males):

	l_{50} (cm)	N
M. paradoxus:		
Males	28.63	5.07
Females	42.24	4.46
M. capensis:		
Males	34.35	7.38
Females	40.80	7.51

Maturity-at-length is then converted to maturity-at-age as follows:

$$f_{sa}^{g} = \sum_{l} f_{sl}^{g} P_{a,l}^{g} \qquad \text{(App.8.II.49)}$$

8.II.4.2.2 Weight-at-length:

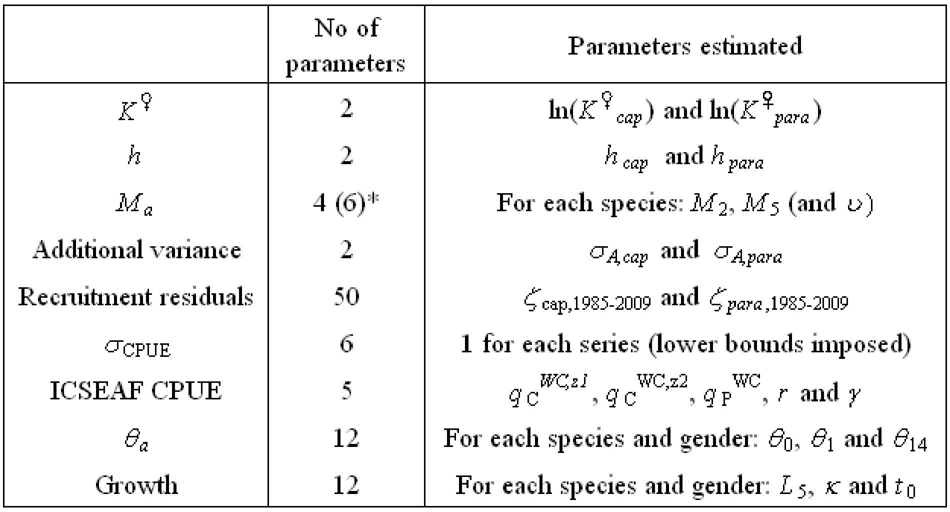
The weight-at-length for each species and gender is calculated from the mass-at-length function, with values of the parameters for this function listed below (from Fairweather 2008, taking the average of the West and South coasts):

	⊥ (gm/cm$^{⊥}$)	⊥
M. paradoxus:		
Males	0.007541	2.988
Females	0.005836	3.065
M. capensis:		
Males	0.006307	3.061
Females	0.005786	3.085

8.II.4.2.3 Minus- and plus-groups

Because of a combination of gear selectivity and mortality, a relatively small number of fish in the smallest and largest length classes are caught. In consequence, there can be relatively larger errors (in terms of variance) associated with these data. To reduce this effect, the assessment is conducted with minus- and plus-groups obtained by summing the data over the lengths below and above l_{minus} and l_{plus} respectively. The minus- and plus-group used are given in Table App.8.II.5 (and plotted in Figures.8.I.2 and 3). Furthermore, the proportions at length data (both commercial and survey) are summed into 2cm length classes for the model fitting.

Table App.8.II.1: Parameters estimated in the model fitting procedure, excluding selectivity parameters.



	No of parameters	Parameters estimated
$K^{♀}$	2	$\ln(K^{♀}_{cap})$ and $\ln(K^{♀}_{para})$
h	2	h_{cap} and h_{para}
M_a	4 (6)*	For each species: M_2, M_5 (and υ)
Additional variance	2	$\sigma_{A,cap}$ and $\sigma_{A,para}$
Recruitment residuals	50	$\zeta_{\mathrm{cap},1985\text{-}2009}$ and $\zeta_{para,1985\text{-}2009}$
σ_{CPUE}	6	1 for each series (lower bounds imposed)
ICSEAF CPUE	5	$q_{\mathrm{C}}^{WC,z1}$, $q_{\mathrm{C}}^{\mathrm{WC,z2}}$, $q_{\mathrm{P}}^{\mathrm{WC}}$, r and γ
θ_a	12	For each species and gender: θ_0, θ_1 and θ_{14}
Growth	12	For each species and gender: L_5, κ and t_0

* if not fixed on input

Table App.8.II.2: Lengths (in cm) at which survey selectivity is estimated directly.

M. paradoxus	West coast summer	13	18	23	28	32	37	42	47
	West coast winter	13	18	24	29	35	40	46	51
	South coast spring	21	26	30	35	39	44	48	53
	South coast autumn	21	26	31	36	42	47	52	65
M. capensis	West coast summer	13	20	26	33	39	46	52	59
	West coast winter	13	17	21	30	40	47	54	61
	South coast spring	13	19	28	38	46	54	63	71
	South coast autumn	13	19	28	36	44	52	61	69

Table App.8.II.3: Length (cm) at which selectivity starts to decrease (l_{slope}) for each species and fleet.

	M. paradoxus	*M. capensis*
WC offshore trawl	40	70
SC offshore trawl	70	70
SC inshore trawl	-	55
WC longline	85	85
SC longline	-	85
SC handline	-	70

Table App.8.II.4: Details for the commercial selectivity-at-length for each fleet and species combination, as well as indications of what data are available.

	M. paradoxus		*M. capensis*		data available
	No of est. parameters	Comments	No of est. parameters	Comments	
1. West coast offshore					
1917-1976	0	set equal to 1989	0	set equal to 1989	
1977-1984	3	two logistic parameters estimated (same slope as 1993+)	0	differential shift compared to 1993+ as for paradoxus, slope 1/3 of inshore	species combined
1985-1992	0	linear change between 1984 and 1993 selectivity	0	linear change between 1984 and 1993 selectivity	species combined
1993-2009	2	two logistic + slope parameters estimated	0	same as SC inshore but shifted to the right by 5 cm, slope 1/3 of inshore	species combined
2. South coast offshore					
1917-1976	0	set equal to 1989	0	set equal to 1989	
1977-1984	3	differential shift compared to 1993+ as for WC (same slope as 1993+)	0	differential shift compared to 1993+ as for paradoxus, slope 1/3 of inshore	species combined
1985-1992	0	linear change between 1984 and 1993 selectivity	0	linear change between 1984 and 1993 selectivity	species combined
1993-2009	3	two logistic + slope parameters estimated	0	same as SC inshore but shifted to the right by 10 cm, slope 1/3 of inshore	species combined
	0	female downscaling factor (av. of SC spring and autumn surveys's factors)			
3. South coast inshore	-	-	3	two logistic + slope parameters estimated	*M. capensis*
4. West coast longline	3	two logistic + slope parameters estimated	0	same as South Coast longline	species combined
5. South coast longline	-	-	3	two logistic + slope parameters estimated	*M. capensis*
6. South coast handline	-	-	0	average of South Coast longline and inshore	
West coast summer survey					
Africana old	7	estimated for 7 specified lengths	7	estimated for 7 specified lengths	species disaggregated
Africana new	5	same slope as old	5	same slope as old	species disaggregated
West coast winter survey					
Africana old	7	estimated for 7 specified lengths	7	estimated for 7 specified lengths	species disaggregated
South coast spring survey					
Africana old	7	estimated for 7 specified lengths	7	estimated for 7 specified lengths	species disaggregated
Africana new	5	same slope as old	5	same slope as old	species disaggregated
	1	female downscaling factor			
South coast autumn survey					
Africana old	7	estimated for 7 specified lengths	7	estimated for 7 specified lengths	species disaggregated
Africana new	5	same slope as old	5	same slope as old	species disaggregated
	1	female downscaling factor			
Total	59		49		

Table App.8.II.5: Minus- and plus-groups taken for the surveys and commercial proportion at length data.

SURVEY DATA

	M. paradoxus		*M. capensis*	
	Minus	Plus	Minus	Plus
West coast summer	13	47	13	59
West coast winter	13	51	13	61
South coast spring	21	53	13	71
South coast autumn	21	65	13	69

COMMERCIAL DATA

	Minus	Plus
West coast offshore, species combined	23	65
South coast offshore, species combined	27	75
South coast inshore, *M. capensis*	27	65
West coast longline, species combined	51	91
South coast longline, *M. capensis*	51	91
Both coasts offshore, species combined	25	65

APPENDIX 8.III

Age-reading error matrices for *Merluccius paradoxus and M. capensis*

8.III.1 Introduction

The current stock assessment models used for the South African *M. paradoxus* and *M. capensis* resources are age structured models, making use of ageing data, either in the form of catch-at-age data or more recently directly as age-length keys. Until this assessment the assumption had been made that age classes are determined without error, when in fact some level of misclassification is often to be expected. Age-reading error occurs when estimates of age based on reading hard structures such as otoliths differ from the true age of the animal concerned. There are two sources of uncertainty in the relationship between the ages obtained from reading otoliths and the true age of the animal: bias and imprecision. Ageing bias occurs when there is a systematic difference between the true age of an animal and the age assigned to it, whereas ageing imprecision occurs when age-reading errors occur at random (Punt *et al*. 2008).

Errors in ageing can be taken into account by supplying an ageing-error matrix (Fournier and Archibald 1982; Richards *et al*. 1992; Punt *et al*. 2008), which defines the probability of assigning a particular age to a fish with a given true age. The method described in Punt *et al*. (2008) is used here to construct such matrices for the two hake species for use in these assessments.

8.III.2 Data and Method

Punt *et al*. (2008) model the probability of reader *i* (of *I* readers) assigning an animal of true age *a* an age of a', $P^i(a'|a)$, by assuming that both the ageing bias and the age-reading error standard deviation depend on the reader and the true age of the animal, and that age-reading error is normally distributed about the expected age (i.e., the expected age given any bias in age reading):

$$P^i\left(a'|a,\varphi\right) \propto \exp\left[\frac{-\left(a'-b_a^i(\varphi)\right)^2}{2\left(\sigma_a^i(\varphi)\right)^2}\right] \qquad \text{(App.8.III.1)}$$

where

b_a^i is the expected age when reader *i* determines the age of an animal of true age *a*;

σ_a^i is the standard deviation for reader *i* of the age-reading error for animals of true age *a*; and

φ is the vector of parameters that determines the age-reading error matrix.

The ageing bias is modelled by:

$$b_a = \begin{cases} b_L + \left(b_H - b_L\right)\dfrac{1-e^{-\lambda(a-L)}}{1-e^{-\lambda(H-L)}} & \text{if } \lambda \neq 0 \\ b_L + \left(b_H - b_L\right)\dfrac{a-L}{H-L} & \text{if } \lambda = 0 \end{cases} \qquad \text{(App.8.III.2)}$$

where

b_L is the expected age of animal of pre-specified minimum age *L*;

b_H is the expected age of animal of pre-specified maximum age *H*; and

λ determines the extent of nonlinearity between the true age and the expected age (note that λ =0 reflects the special case of linear dependence).

The age-reading error standard deviation is modelled by:

$$\sigma_a = \begin{cases} \sigma_L + \left(\sigma_H - \sigma_L\right)\dfrac{1-e^{-\alpha(a-L)}}{1-e^{-\alpha(H-L)}} & \text{if } \alpha \neq 0 \\ \sigma_L + \left(\sigma_H - \sigma_L\right)\dfrac{a-L}{H-L} & \text{if } \alpha = 0 \end{cases} \qquad \text{(App.8.III.3)}$$

where

σ_L is the age-reading error standard deviation for a pre-specified minimum age *L*;

σ_H is the age-reading error standard deviation for a pre-specified maximum age *H*; and

α determines the extent of nonlinearity between age and the age-reading error standard deviation (note that $\alpha = 0$ reflects the special case of linear dependence).

The values for the parameters that determine the age-reading error matrix for each reader are estimated by maximizing the following likelihood function:

$$L(A|\beta,\varphi) = \prod_{j=1}^{J} \sum_{a=L}^{H} \beta_a \prod_{i=1}^{I} P^i\left(a_{i,j}|a,\varphi\right) \qquad \text{(App.8.III.4)}$$

where

$a_{i,j}$ is the age assigned by reader *i* to the *j*th otolith;

A is the entire data set of otolith readings; and

β_a are nuisance parameters that can be interpreted as the relative frequency of animals of (true) age *a* in the sample (rather than in the population from which the sample was taken).

In general, not all otoliths are read by all readers. Therefore, the likelihood function is more generally the product of eqn (App.8.III.4) over sets of otoliths that were all read by the same group of readers, and a separate set of β's is estimated for each such set of otoliths.

For this hake case the ageing error matrices were computed for each species separately. The data were aggregated over sex and over all sources of data (survey, commercial offshore and commercial longline). For each species, the data were divided into three groups of three readers:

a) Alexia Daniels (AD), Luke Bester (LB) and 'Unknown Reader' (UR);

b) Kevin Gradie (KG), John Prinsloo (JP) and Andy Payne/Dave Japp (AP/DJ) (these two readers have been aggregated as they read otoliths only when KG and JP did not agree, so that relatively very few data are involved); and

c) Phoeby Mullins (PM), Teressa Akkers (TA) and Kashif Booley (KB).

Table App.8.III.1 give details on the data available for each group.

8.III.3 Results and Discussion

In each group of three readers, one reader at least was assumed to be unbiased, as the age-reading errors would be confounded otherwise (Punt *et al.*, 2008). For each group of three readers, Akaike's information criterion (AIC) was used to select among alternative models (including which reader should be assumed to be unbiased).

The final models for age-reading error are summarised in Table App.8.III.2, while Figures App.8.III.1 and App.8.III.2 show plots of the age-reading error matrices for each reader and species. Figure App.8.III.3 plots the estimated ageing bias for each reader within each set of three readers. The fact that in some instances there is a bias for the true age zero is related to the use of a minus group.

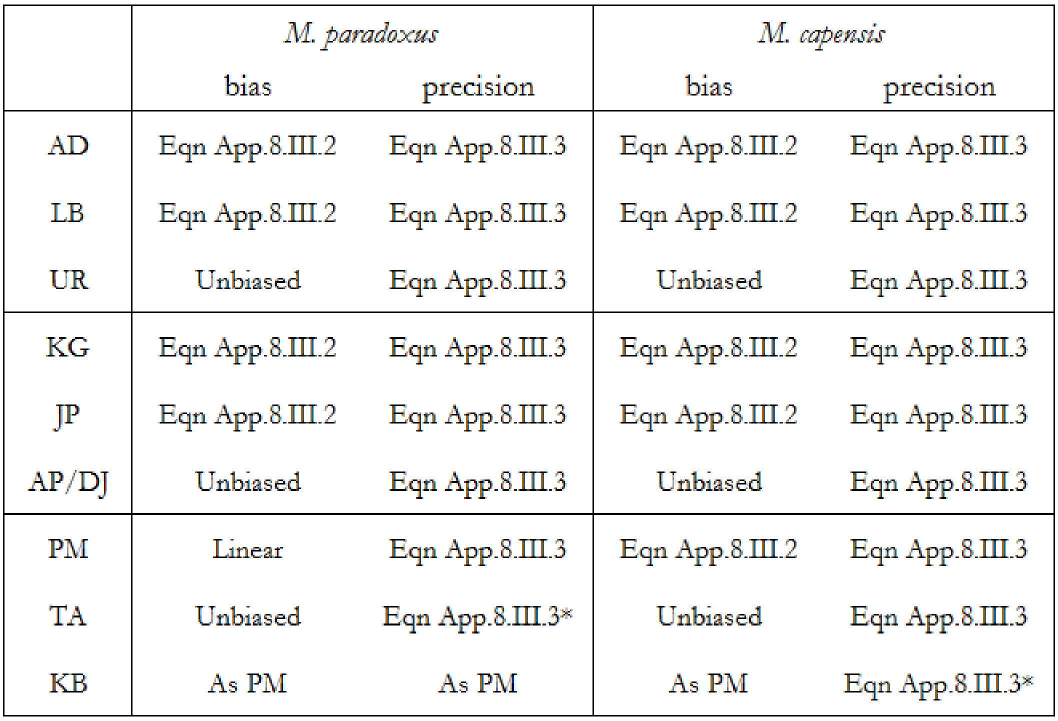
Table App.8.III.1: Number of aged hake by species for each reader.

		M. capensis			*M. paradoxus*		
Source	Year	UR	AD	LB	UR	AD	LB
					324		324
WC summer	1999	314	351	358	263	299	299
WC summer	2006					465	465
WC summer	2007		369	369		554	554
WC summer	2008		451	451		409	409
WC winter	2004		808	808			
SC spring	2006					243	243
SC autumn	1999		265	264		139	139
SC autumn	2005					192	192
SC autumn	2007		626	626		358	358
SC autumn	2008		638	638		214	214

		M. capensis			*M. paradoxus*		
Source	Year	KG	JP	AP/DJ	KG	JP	AP/DJ
WC summer	1992	389	389	33	310	310	44
WC summer	1993	351	351	62	311	311	49
WC summer	1994	282	282	6	290	290	4
WC summer	1995	0	368		0	303	0
SC autumn	1992	329	329	91	40	40	5
SC autumn	1993	407	407	40	95	95	23
SC autumn	1994	390	391	83	72	69	27
Comm Offshore	1992	260	260	28	521	521	46
Comm Offshore	1993	115	115	17	645	645	75
Comm Offshore	1994	126	126	5	330	330	38
Comm Longline	1994				314	314	9

		M. capensis			*M. paradoxus*		
Source	Year	PM	TA	KB	PM	TA	KB
WC autumn	1999	408	406	400	140	140	140

Table App.8.III.2: Selected model for age-reading error for each reader and species.



	M. paradoxus		*M. capensis*	
	bias	precision	bias	precision
AD	Eqn App.8.III.2	Eqn App.8.III.3	Eqn App.8.III.2	Eqn App.8.III.3
LB	Eqn App.8.III.2	Eqn App.8.III.3	Eqn App.8.III.2	Eqn App.8.III.3
UR	Unbiased	Eqn App.8.III.3	Unbiased	Eqn App.8.III.3
KG	Eqn App.8.III.2	Eqn App.8.III.3	Eqn App.8.III.2	Eqn App.8.III.3
JP	Eqn App.8.III.2	Eqn App.8.III.3	Eqn App.8.III.2	Eqn App.8.III.3
AP/DJ	Unbiased	Eqn App.8.III.3	Unbiased	Eqn App.8.III.3
PM	Linear	Eqn App.8.III.3	Eqn App.8.III.2	Eqn App.8.III.3
TA	Unbiased	Eqn App.8.III.3*	Unbiased	Eqn App.8.III.3
KB	As PM	As PM	As PM	Eqn App.8.III.3*

* Eqn App.8.III.3 pertains to the coefficient of variation rather than the standard deviation.

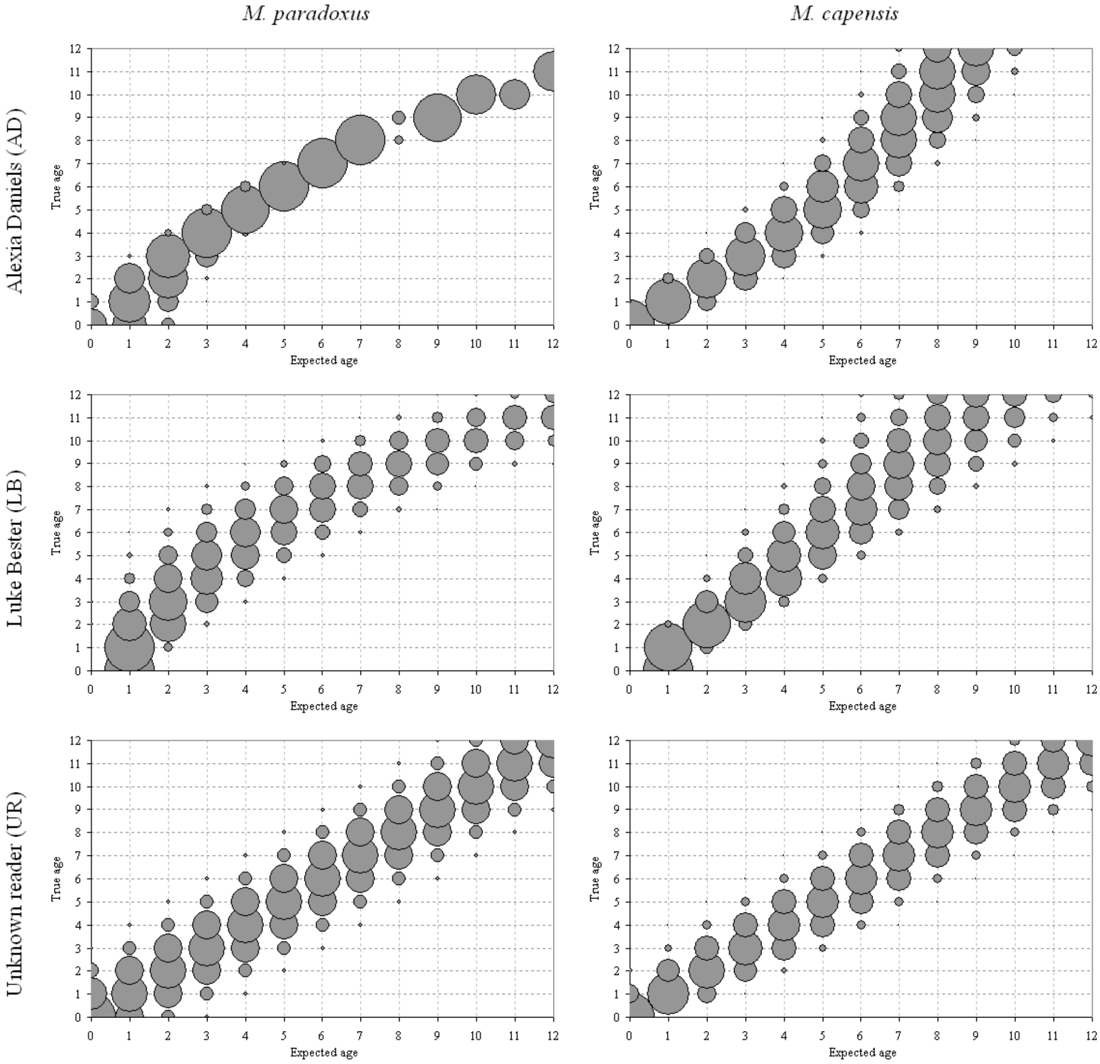


Figure App.8.III.1: Plots of the ageing-error matrices (‘true’ vs. expected age – the area of the bubble represents the proportion expected at each age) for *M. paradoxus* and *M. capensis*, for the two current readers (AD and LB) and the ‘unknown reader’.

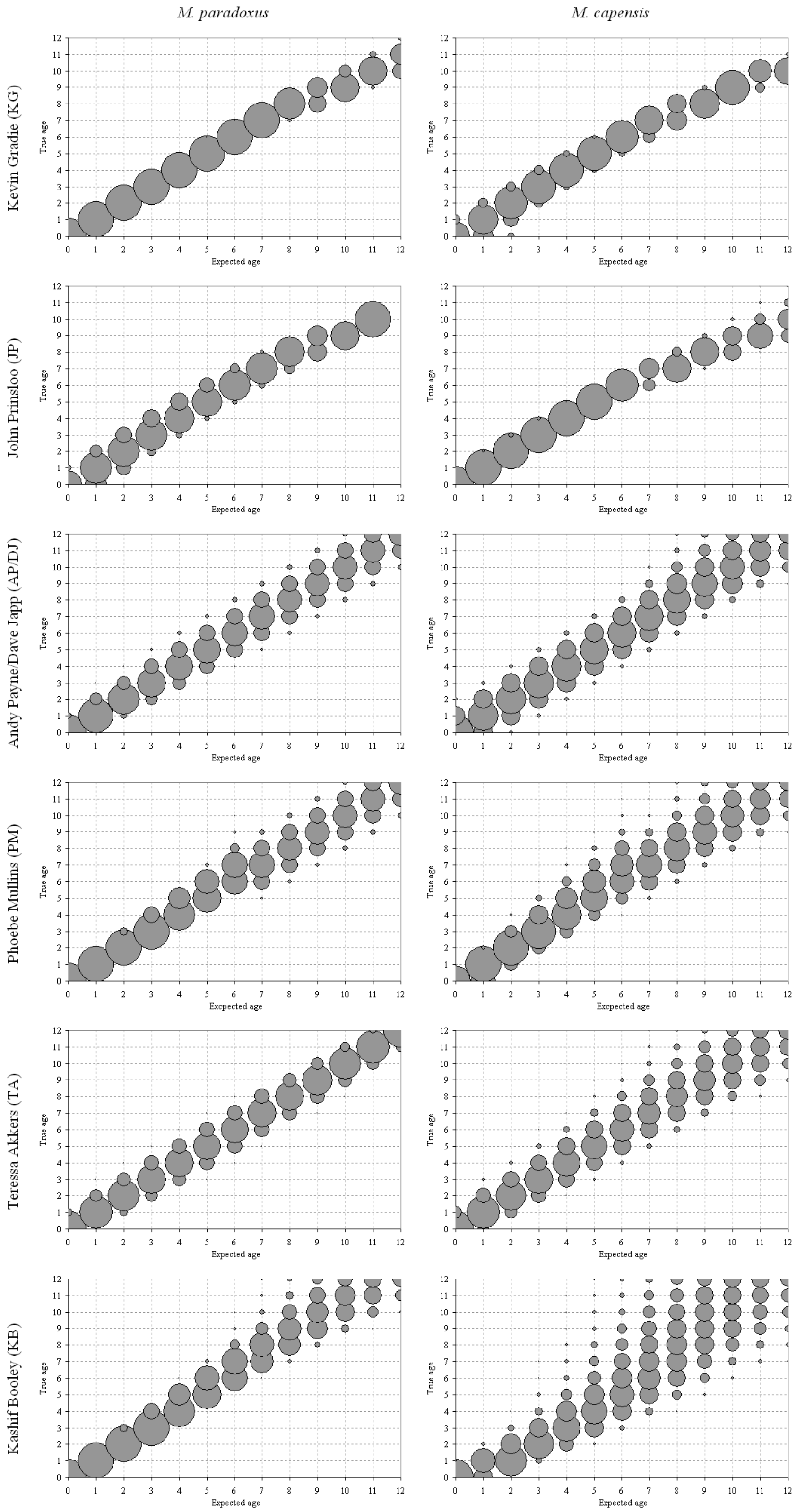


Figure App.8.III.2: Plots of the ageing-error matrices (‘true’ vs. expected age – the area of the bubble represents the proportion expected at each age) for *M. paradoxus* and *M. capensis* for past readers (KG, JP, AP/DJ, PM and KB).

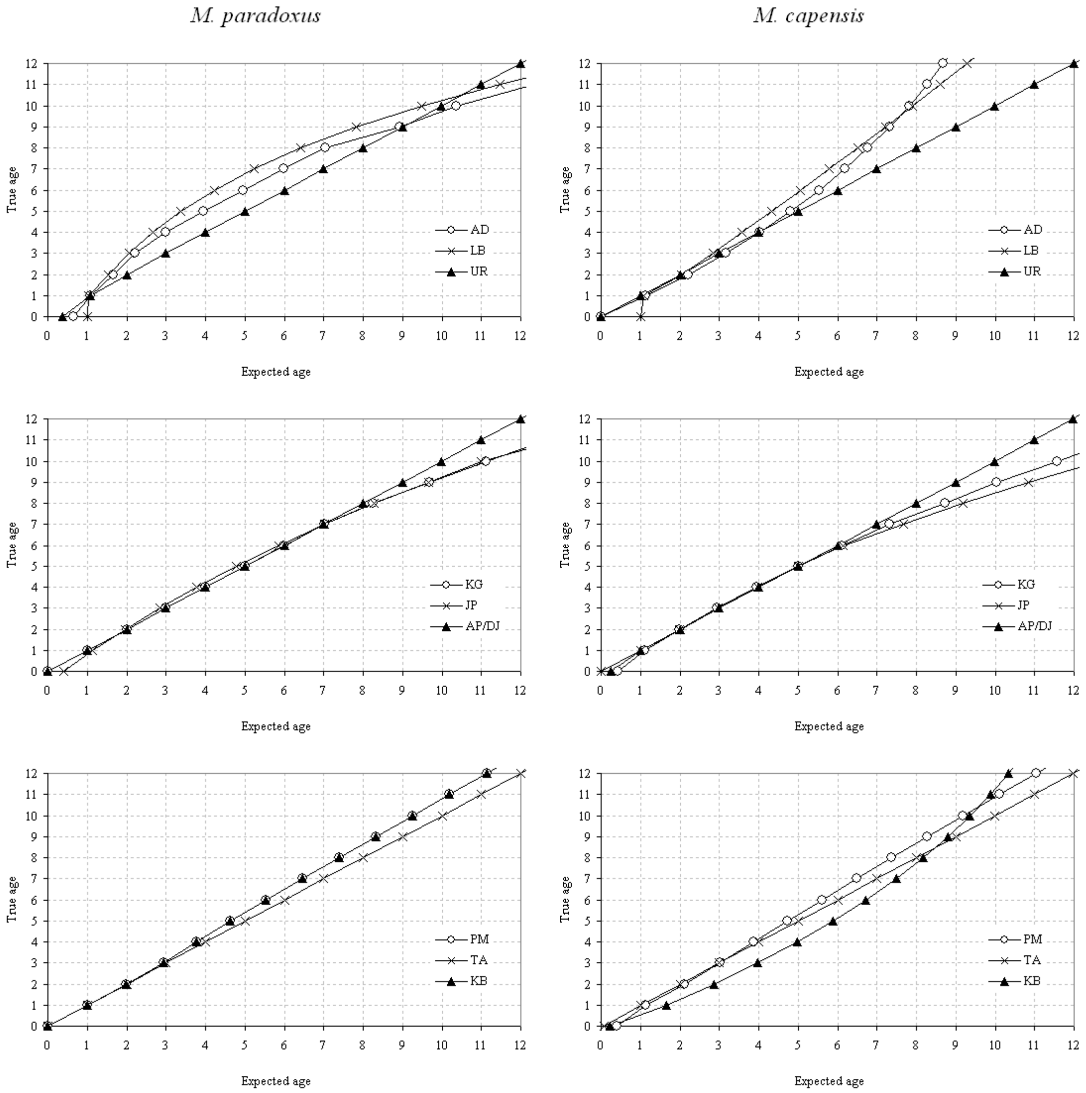


Figure App.8.III.3: Plots of the true vs. mean expected age across readers for *M. paradoxus* and *M. capensis*.

Chapter 9

The development of a Reference Set and robustness tests for OMP-2011 testing

Summary

A Reference Set (RS) of 12 scenarios is selected as the primary basis to be used to simulation test candidates for the revised OMP for hake, OMP-2011. The principal uncertainty axes spanned by this RS are the central year for the switch from a primarily *M. capensis* to a primarily *M. paradoxus* fishery, values for natural mortality at age, and the form of the stock-recruitment relationship. The various data sets are generally reasonably fitted by these models, with the recent GLM-standardised CPUE series having the greatest influence. Results for conditioning of the full set of robustness/sensitivity tests are also given. Projections are carried out under a constant catch strategy to select a core set of robustness tests to run in the CMP selection process.

9.1 Introduction

The first aim of this Chapter is to describe the primary uncertainties of the New Reference Case and present the set of Operating Models (OMs) to form a Reference Set (RS) to be used for testing a revised OMP for the hake resource (OMP-2011). Three factors contribute to most of the variability in the assessment results:

a) pre-1978 species split of the offshore trawl catches
b) natural mortality at age specifications; and
c) the stock-recruitment relationship.

9.2 Uncertainty in past catches

Commercial catches are not disaggregated by species and hence the species split of the catches that are needed for an assessment capable of distinguishing the two species, is carried out external to the model. From 1978 onwards, the catches made by the offshore trawl fleet are split by species by applying survey-based species proportion-by-depth relationships. Prior to 1978, there is no depth information recorded for the landings and the catch data for the period 1917–1977 are split by assuming that the proportion of *M. capensis* caught follows a logistic function over this period. The RS of OMs used for the testing of OMP-2007 (Chapter 4) included three choices for the central shift year from a primarily *M. capensis* to a primarily *M. paradoxus* fishery: 1940, 1950 and 1957. The reasons later years were excluded is that they led to poorer fits to the data, and also to what was considered to be an unrealistically high ratio of the then current biomass of *M. capensis* to *M. paradoxus*.

Runs were carried out based on the new RC for the central year ranging from 1940 to 1972. Figure 9.1 shows time trends of the proportion of *M. capensis* in the catch for these alternatives. These results were repeated for three different choices for the natural mortality vector assumed. All runs show results for a modified Ricker choice for the stock-recruitment relationship, as for the new RC. Results are shown in Tables 9.1 and 9.2 which respectively list estimates and differences in –lnL from that for the best fitting of all these models. Results are shown for more choices for the central year for the intermediate natural mortality vector case than for the high and low options.

It is evident from the results in Table 9.1 that the two reasons for favouring earlier years for the control shift year in the previous RS (better likelihoods and plausible ratio of the current biomass of *M. capensis* to *M. paradoxus*) are no longer as strong. Amongst the scenarios shown, only for the 1972 choice does the likelihood deteriorate sufficiently to argue strongly against plausibility (except for the higher natural mortality option, but for that there are other questionable features such as the very low B_{MSY}^{sp}/K^{sp} estimate and the highish current *M. capensis* to *M. paradoxus* biomass ratio). This latter concern does however now seem to come into play only for choices for the central year of 1970 and sometimes 1965.

An interesting feature of the results for *M. paradoxus* is that except at the extremes of the range for choice of the central year, the current spawning biomass B^{sp}_{2009}, expressed either in absolute terms or as a proportion of B^{sp}_{MSY}, does not change greatly as the choice for the central year is modified (though it does depend on the natural mortality vector chosen). This is an important result, as a key condition for the revised OMP, as set out in the MSC re-certification report for the hake trawl fishery (MSC 2010c), is consideration of limit reference points, and the defaults for these are typically $0.5B^{sp}_{MSY}$ (more discussion in Chapter 10). The assessments generally put *M. paradoxus* somewhat above or at least close to this default.

This in turn suggests that debate on the most appropriate choices for the central year in the RS scenarios may not be that crucial in terms of the performance which the new OMP needs to demonstrate.

In terms of likelihoods, there is little to choose amongst the various scenarios in Table 9.1, except that the choice of 1972 can likely be excluded. But this then means that the data are not able to reliably distinguish choices between 1940 and 1970. It is important to check whether other information might allow some discrimination within this range as the OMP needs to demonstrate robust performance across the chosen range.

9.2.1 Implications of the depths of trawling operations

Leslie and Glazer (2010) present information on the (recent) *M. capensis* : *M. paradoxus* species ratio in catches by depth range (their tables 1 (for offshore commercial catches) and 2 (for surveys) (reproduced here as Tables 9.3 and 9.4 respectively)). Assuming that the species ratio by depth range in the 1940s was similar to that estimated in recent years, they then infer the possible species composition of the hake catch in the late 1940s from the average fishing depths reported by Scott (1949): an average fishing depth of about 250-300m on the West coast in 1948 would suggest a *M. paradoxus* proportion of 63-89% in the hake catches at that time and with an average fishing depth of less than 180m on the Southeast coast, hake catches probably consisted of close to 100% *M. capensis*. With about 80% of the total hake catch taken from West coast grounds, 50-71% of the hake catch in 1948 may have been *M. paradoxus*.

Tables 9.3 and 9.4 are further contrasted with Table 9.5, which reports the species ratio for the cumulative catch to 1977 (after which data-based estimation replaces assumption) for alternative choices for the central shift year. If from Table 9.5 one notes, for example, that a central shift year choice of 1970 corresponds to a *M. capensis* overall proportion of 0.81, and contrasts this to the commercial catch information in Table 9.3, the coarse inference is that West Coast catches would have had to be restricted to less than some 200m depth until 1977 if the choice of a central shift year of 1970 (with a current *M. paradoxus* spawning biomass depletion of 0.37) is to be considered plausible.

The above is not an “exact” result, however, because although the dependence of estimates of current species depletion on the choice of the central shift year are primarily influenced by the species ratio for this cumulative catch, there is also some subsidiary dependence on how this ratio changes over time.

To investigate this further, guided by Leslie and Glazer (2010) who report that depths of fishing in 1949 already indicate a substantial proportion of *M. paradoxus* in the West Coast catch, results are given in Table 9.6 for the current spawning biomass depletions that follow for the new Reference Case for modifications of the ogive-based approach for splitting the catches by species from 1917 to 1977. Instead of setting the *M. capensis* ratio at the commencement of the fishery to 100% as in the new Reference Case, these modifications rather set these initial values lower as indicated in that Table. This is done for three central shift year choices.

Since there was relatively little hake catch made prior to 1949, results in Leslie and Glazer (2010) for the *M. capensis* proportion of the hake catch in that year provide some guidance as to the relative plausibility of the various depletion estimates in Table 9.6. In particular Leslie and Glazer (2010) infer a West Coast *M. capensis* proportion in 1949 of between 11 and 37%. This suggests that only the scenarios considered in the two rightmost columns of Table 9.6 are realistic, which in turn implies that the current spawning biomass depletion for *M. paradoxus* is no more than 16%.

In terms then of a selection for the Reference Set, these results suggest that the higher values of the central shift year are less plausible.

Another study conducted by SADSTIA and OLRAC (2010) about the depth distribution of hake trawling in the mid 20th century is however sharply at variance with the information in Scott (1949) and the consequent inferences drawn about the species split at that time by Leslie and Glazer (2010). SADSTIA and OLRAC (2010) grouped the South African trawling fleet into classes of vessel for a series of years over the period 1950-1975. Each class of vessel was then assumed to fish at depth which are beta-distributed on the interval [0, D_C] where D_C is the limiting depth for class C, with a beta parameter of 2 (see Figure 9.2, reproduced from SADSTIA and OLRAC (2010)). The effort for each vessel was calculated and the overall distributions of effort over depth for each year on each coast was computed (see Figure 9.3. reproduced from SADSTIA and OLRAC (2010)). Applying the species proportion by depth relationship developed by Gaylard and Bergh (2004), they conclude that the *M. capensis* proportion of the catch in the early 1950s would have been around 75%, whereas Leslie and Glazer (2010) places it between 29 and 50%.

The results however may be highly dependent on the assumption of a beta distribution with (in particular) a lower bound of 0 and a beta parameter of 2 to model the distribution of fishing by depth for different vessel classes. The alpha parameters of these functions are conditioned on the modal depth assigned for each class. This leads to distributions with a large proportion of the fishing at depths well below the modal depth (see Figure 9.2). These distributions could just as reasonably by modeled by truncated normals whose modes are set to the modal depth assigned for each class and standard deviations set by truncating such that the 95%-ile falls at the maximum depth for the class. This would make a major change to Figure 9.2 and consequently the key results in Figure 9.3, possibly rendering those compatible with the information provided in the paper by Scott (1949).

9.2.2 Freeing 1978 conditions - linked to pre-1978 split of the catch debate.

The new Reference Case starts in 1917 assuming pre-exploitation equilibrium at carrying capacity. An assessment was run with a more recent start year, 1978, assuming that the stock is at a fraction (θ) of its pre-exploitation biomass in 1978 and that an average fishing proportion (ζ) applies to the years immediately preceding 1978 (with θ and ζ estimated in the model fitting procedure). Although important information is then ignored (the decline in the historical CPUE series over the period 1954-1977), this method allows one to be free of any assumption regarding the pre-1978 species-split of the catches. Furthermore, assuming pre-exploitation equilibrium in 1917 as in the new RC might be constraining the fit to the recent catch-at-length and catch-rate data. This assessment is included in the list of robustness test (Rob17, see Section 9.4 below on robustness tests). Spawning biomass trajectories relative to pre-exploitation biomass for both species for this robustness test are very similar to those estimated in the new RC (Figure 9.6), with current depletions estimated at 16% for *M. paradoxus* and 50% for *M. capensis* (compared to 15% and 54% respectively for the new RC). Results in absolute terms differ however, and the current *M. capensis* : *M. paradoxus* spawning biomass ratio is estimated at about 58% for Rob17, compared to 121% for the new RC. Comparing the current depletion estimated for *M. paradoxus* in Rob17 with the depletions in Table 9.1 for a series of choices for the central year of the *M. capensis* to *M. paradoxus* shift would suggest again that central year should be pre-1965.

In light of these studies, it was agreed that the RS should be robust to any choice of the central year between 1950 and 1965.

9.3 The Reference Set

Two further aspects were found to account for most of the uncertainty regarding the key considerations of resource status and productivity: the natural mortality of each species and the stock-recruitment functions. Attempts to fit natural mortality at age vectors freely led to widely varying results from scenario to scenario, so it was considered best to fix two vectors which arguably span the plausible range: a high M scenario of M_2=0.9, M_5=0.5. and a low M scenario of M_2=0.6, M_5=0.25. For the stock-recruitment relationship, three options were put forward: a Beverton-Holt with the steepness parameter h estimated or fixed, and a modified Ricker with γ estimated (see equations App.8.II.4a,b).

The RS consists of 12 cases, detailed in Table 9.7. These 12 cases vary their choices of factors along the three axes that contribute most variability to assessment results. The primary design intended a full cross of 2 centre-years x 2 natural mortality vectors x 3 stock recruitment relationships, but subject to the constraint that a fit with a –lnL difference of more than about 15 from that for the best of the fits would be excluded on the basis of poor compatibility with the data. (Of course, in strict likelihood terms such a large difference implies enormously different relative likelihoods across these scenarios, but that would be over-interpreting the likelihood function used here which has not attempted to take full account of non-independence amongst the data fitted.)

With the Beverton-Holt fits indicating estimates of steepness *h* at its upper bound of 0.98, it was considered important to include scenarios with lower values of *h* in the RS to admit greater possibilities of recruitment overfishing taking place, but the –lnL difference constraint excluded three of the associated four scenarios, leaving only RS10 amongst the RS.

The primary RS runs combined either both high *Ms* or both low *M*s for the two species, *M. paradoxus* and *M. capensis*. Scenarios which crossed high and low *M* values across the two species were also investigated, but mainly found to fail to meet the –lnL difference criterion. However, one exception to this was a scenario (RS11) with both a good fit to the data and a qualitatively different trajectory for *M. capensis* (reflecting a rather more heavily depleted *M. capensis* resource than do the other scenarios). It is considered important to retain this in the RS, together with a variant with slightly different specifications of natural mortality at age for *M. capensis* (RS12) which also showed this different trajectory behaviour for *M. capensis*. In subsequent presentation of candidate OMP results, the RS is be split into two: RSa (RS1 to RS10) and RSb (RS11 to RS12), so as not to mix results across qualitatively different *M. capensis* trajectories.

The RS is completed by the “central” Reference Case scenario, corresponding to a mid-year choice for the shift from a primarily *M. capensis* to *M. paradoxus* fishery, and an average of the two *M* vectors for natural mortality at age. The modified Ricker was preferred to the Beverton-Holt stock recruitment relationship for this scenario because it tends to yield slightly better fits to the data. Most robustness tests are single factor variants of this RC.

Table 9.8 summarises the key management quantity estimates across the RS, while Table 9.9 compares the different contributions to the total negative log-likelihood.

Figure 9.4 plots the estimated spawning biomass trajectories for the RS. Figure 9.5 shows their fits to the CPUE series. Only the CPUE series fits have been shown here, because as is evident from Table 9.9 it is fits to the CPUE, and particularly the more recent GLM-CPUE series, that are the main determinants of the overall likelihood of the scenario.

Scenarios with the lower value of 0.25 for M_{5+} often lead to arguably unrealistically high pristine spawning biomass values. These can however be reduced, with little impact on other important management-related variables, by postulating an increase in natural mortality at higher ages (see Rob16 results).

Fits of the assessment model to the data are generally reasonable. From Tables 9.9 and 9.12 it is evident that fits to the CPUE data and to the commercial catches-at-length are the primary determinants of the overall likelihood. The more recent GLM-standardised CPUE plays the greatest role, particularly for *M. paradoxus* where many of the model variants have some difficulty in matching the earliest and the very recent values.

The primary consideration in proposing a RS is that its component OMs should span most of the range of plausible possibilities for the underlying dynamics. Table 9.8 suggests that this criterion is reasonably satisfied for *M. paradoxus* depletion and productivity (reflected by MSY). There is lesser variability amongst the RSa depletion estimates for *M. capensis*, but the scenarios in RSb would seem adequate to cover the possibility that the RSa depletion estimates for *M. capensis* might be misleading.

9.4 Robustness tests

9.4.1 Tests related to *M. paradoxus*

Table 9.10 summarises the full set of robustness/sensitivity tests considered. Some of these tests should be considered as “sensitivities” rather than formal robustness tests to provide OMs for candidate OMP testing, because they are included more to indicate impacts of specification variation on results than as arguably alternative plausible representations of reality. While Rob1 to Rob29 involve different assumptions about the resource dynamics or past data, it is only in their projections that Rob30 to Rob38 change from the Reference Case (RS1).

Table 9.11 summarises the key management quantities for Rob1 to Rob29, while Table 9.12 compares their different contributions to the total negative log-likelihood. Figure 9.6 plots the estimated spawning biomass trajectories for these tests.

9.4.2 Tests related to *M. capensis*

The robustness tests described in Table 9.5 are based mostly on RS1, i.e. they are representative of RSa, for which *M. capensis* is currently well above MSYL. Robustness tests are also needed in the case when the extent of *M. capensis* depletion is estimated to be relatively high (RSb) and six robustness tests have been selected to be run on RS11 (one of the RSb OMs). For changes in the past, three of the four robustness tests selected for *M. paradoxus* robustness testing (see below) have been chosen (Rob5, Rob13 and Rob25, but not Rob17 which is of a different nature and does not show *M. capensis* to be heavily depleted) and for changes in the future, Rob37 (decrease in *K*) has been selected.

Table 9.8 summarises the key management quantities for the four tests based on RS11, while Table 9.9 compares their different contributions to the total negative log-likelihood. Figure 9.7 plots the estimated spawning biomass trajectories for these tests.

9.5 Constant catch projections

Projections have been carried out under a constant catch strategy of 150 000t. Although the final one or two CMPs are checked on the complete suite of robustness tests, only a selected subset of robustness tests are used to test the CMPs routinely. The intention here is therefore to reduce the number of robustness tests that are run routinely on the CMPs by selecting the ones which appear under constant catch projections to present the greatest challenges from a resource conservation perspective. (Naturally constant catch projections do not provide discrimination amongst tests that involve changes to default assumptions for aspects of future data such as changes in precision, so that such tests remain retained in this selected set.) A projected constant catch of 150 000t was been chosen as this will be more informative (in terms of the poor resource conservation performers) than a constant catch set at the current TAC.

Three performance statistics ($B^{sp}_{2027}\big/B^{sp}_{MSY}$, $B^{sp}_{2030}\big/K^{sp}$ and $B^{sp}_{2030}\big/B^{sp}_{2010}$ for the female component of the population) are plotted in Figure 9.8 and 9.9 for the full set of RS and robustness tests under a constant catch of 150 000t.

On this basis the following robustness tests related to *M. paradoxus* were retained in the selected set:

Changes in the past: robustness tests Rob5 (true Ricker), Rob13 (decrease in *K*), Rob17 (start in 1978) and Rob25 (lower steepness *h*).

Changes in the future: robustness tests 31f (case of no surveys and an undetected catchability trend for CPUE), Rob35 (undetected catchability trend for CPUE) and Rob37 (decrease in *K*).

With the exception of tests Rob31 and Rob35 for which constant catch trials do not provide a test of the issue involved, the reason for these selections is inadequate increase of spawning biomass towards its MSY level.

The four robustness tests related to *M. capensis* were retained in the selected set.

9.6 Summary of key changes and their implications

The key changes, and their implications, in the new RS compared to that of 2006 (Chapter 4) on which the previous OMP was based, are summarised below.

9.6.1 Important methodological changes

a) The assessment is now gender-disaggregated as well as species-disaggregated.

b) In earlier assessments the fitting was to catch- and survey-proportion-at-age estimates where these were available and to length distribution data where these age data were not (and this led to some inconsistencies in results), with selectivity taken to be age-specific. Now a consistent (by construction) approach is used throughout of fitting to the length distribution data for all years plus the age length keys where available, with selectivity taken more realistically to be length-specific.

c) In the OMP-2007 RS, age-at-maturity was taken to be knife-edge at 4. Now recent fecundity-at-length information is input directly in ogive form; though the mean age at maturity is not too different, this does mean that some hake are mature at age 3, for example.

d) A generalised Ricker stock-recruitment curve is preferred to the Beverton-Holt, not only because it more readily allows the possibility of recruitment overfishing, but also particularly because it leads to better fits to the data. The effect of this tends to be to reduce the estimated K but not the estimated B_{current} (in terms of spawning biomass).

e) Data for four more years are now available, with data trends over that period indicating an improved *M. paradoxus* status.

9.6.2 Important changes to assessment results

a) Previously the B_{current}/K for *M. paradoxus* spawning biomass for 2006 (median over RS of OMs) was about 8%. For the updated RS it is about 16%.

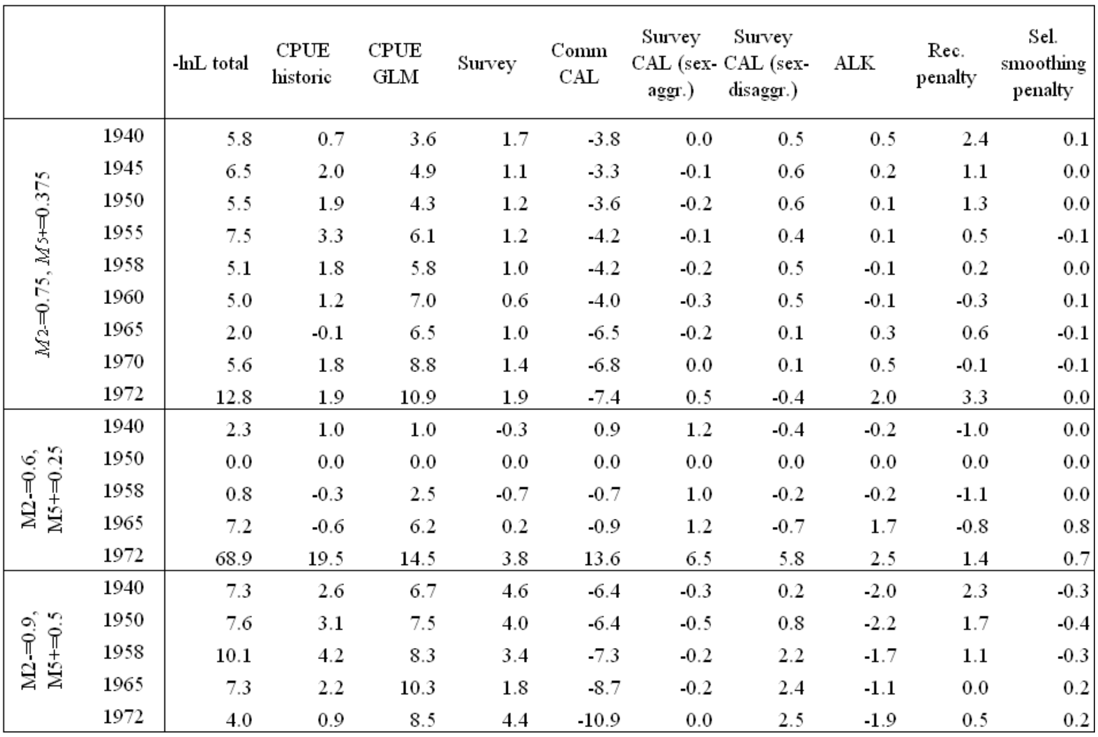
b) The *M. paradoxus* depletion is very sensitive to assumptions about the pre-1977 split of the catch between *M. capensis* and *M. paradoxus*. The previous assessment favoured (in likelihood terms) lower values in the range from 1940 to 1970 for the mid-year of the central year of the shift from a primarily *M. capensis* to a primarily *M. paradoxus* fishery, and this led to lower values for B_{current}/K for *M. paradoxus*. However, the likelihoods for the current assessment no longer favour any choice of shift year within this 1940-1970 period. Historic information has been examined to throw light on this shift year, but different approaches yielded differing inferences. The *M. paradoxus* B_{current}/K (in terms of spawning biomass) ranges from about 10% to a little over 30% across this range of values for the central shift year.

c) Importantly however, though K estimates for *M. paradoxus* vary depending on the choice for this central shift year for the species dominating the catch, estimates of B_{current} and B_{MSY} are broadly stable across the range considered, with $B_{\text{current}}/B_{MSY}$ quite consistently in the range of higher 50%s to lower 60%s. Thus the statistic $B_{\text{current}}/B_{MSY}$ appears the more robustly estimated, which suggests using this as the primary measure on which to base reporting of current status and selection of recovery targets for *M. paradoxus* instead of B_{current}/K.

Table 9.1: Estimates of management quantities for runs for a set of choices for the central year of the *M. capensis* to *M. paradoxus* shift, and for *M* values. Values in bold have been fixed. B^{sp}_{2009}/K^{sp} is for both genders combined, while B^{sp}_{MSY}/K^{sp} and $B^{sp}_{2009}/B^{sp}_{MSY}$ are in terms of the female only spawning biomass. A * on a value for steepness (*h*) indicates a constraint boundary; the species ratio values given relate to *M. capensis* relative to *M. paradoxus*.

		M. paradoxus									*M. capensis*									2009 species ratio B^{sp}
	-lnL	K^{sp}	h	B^{sp}_{2009}	B^{sp}_{2009}/K^{sp}	B^{sp}_{MSY}/K^{sp}	$B^{sp}_{2009}/B^{sp}_{MSY}$	MSY	M_{2-}	M_{5+}	K^{sp}	h	B^{sp}_{2009}	B^{sp}_{2009}/K^{sp}	B^{sp}_{MSY}/K^{sp}	$B^{sp}_{2009}/B^{sp}_{MSY}$	MSY	M_{2-}	M_{5+}	
1940	-93.9	2148	0.93	205	0.10	0.15	0.61	110	**0.75**	**0.38**	490	0.85	271	0.55	0.54	1.00	68	**0.75**	**0.38**	1.32
1945	-93.1	1610	0.92	200	0.12	0.22	0.54	112	**0.75**	**0.38**	500	0.90	274	0.55	0.51	1.03	67	**0.75**	**0.38**	1.37
1950	-94.1	1585	0.94	201	0.13	0.22	0.55	112	**0.75**	**0.38**	442	0.92	239	0.54	0.53	0.99	64	**0.75**	**0.38**	1.19
1955	-92.1	1428	1.02	203	0.14	0.23	0.57	112	**0.75**	**0.38**	544	0.89	301	0.55	0.50	1.07	69	**0.75**	**0.38**	1.48
1958	-94.5	1363	1.08	208	0.15	0.24	0.59	113	**0.75**	**0.38**	516	1.01	279	0.54	0.47	1.12	69	**0.75**	**0.38**	1.34
1960	-94.6	1306	1.13	214	0.16	0.25	0.60	114	**0.75**	**0.38**	582	1.50*	315	0.54	0.34	1.56	83	**0.75**	**0.38**	1.47
1965	-97.7	1018	1.36	242	0.24	0.34	0.66	117	**0.75**	**0.38**	666	1.50*	408	0.61	0.43	1.39	118	**0.75**	**0.38**	1.69
1970	-94.0	644	1.38	240	0.37	0.50	0.69	120	**0.75**	**0.38**	1322	0.63	832	0.63	0.54	1.15	123	**0.75**	**0.38**	3.47
1972	-86.9	543	1.20	230	0.42	0.58	0.71	113	**0.75**	**0.38**	1318	0.79	828	0.63	0.48	1.28	135	**0.75**	**0.38**	3.60
1940	-97.3	2777	1.09	294	0.11	0.27	0.43	123	**0.60**	**0.25**	801	1.50*	400	0.50	0.37	1.34	68	**0.60**	**0.25**	1.36
1950	-99.6	2842	1.05	286	0.10	0.26	0.42	121	**0.60**	**0.25**	735	1.18	379	0.52	0.48	1.08	65	**0.60**	**0.25**	1.33
1958	-98.9	2436	1.22	288	0.12	0.27	0.47	121	**0.60**	**0.25**	792	1.50*	404	0.51	0.39	1.31	70	**0.60**	**0.25**	1.40
1965	-92.4	1683	1.50*	354	0.21	0.34	0.64	121	**0.60**	**0.25**	1793	1.50*	1156	0.65	0.42	1.52	166	**0.60**	**0.25**	3.27
1972	-30.7	1747	0.50	792	0.45	0.77	0.63	122	**0.60**	**0.25**	3113	0.45	2052	0.66	0.62	1.06	128	**0.60**	**0.25**	2.59
1940	-92.3	1435	0.87	165	0.12	0.11	0.80	110	**0.90**	**0.50**	354	0.64	206	0.58	0.60	0.91	63	**0.90**	**0.50**	1.25
1950	-92.0	967	0.86	156	0.16	0.19	0.65	110	**0.90**	**0.50**	367	0.62	214	0.58	0.61	0.91	63	**0.90**	**0.50**	1.37
1958	-89.5	869	0.97	177	0.20	0.25	0.65	111	**0.90**	**0.50**	417	0.63	247	0.59	0.59	0.96	69	**0.90**	**0.50**	1.40
1965	-92.3	662	1.14	199	0.30	0.37	0.68	111	**0.90**	**0.50**	442	1.50*	279	0.63	0.41	1.44	110	**0.90**	**0.50**	1.40
1972	-95.6	820	1.50*	219	0.27	0.06	3.83	181	**0.90**	**0.50**	998	0.66	640	0.64	0.51	1.21	135	**0.90**	**0.50**	2.92

Table 9.2: For each contribution to the total negative log-likelihood (-lnL), differences in –lnL compared to the case with the lowest –lnL.



		-lnL total	CPUE historic	CPUE GLM	Survey	Comm CAL	Survey CAL (sex-aggr.)	Survey CAL (sex-disaggr.)	ALK	Rec. penalty	Sel. smoothing penalty
M_2=0.75, M_{5+}=0.375	1940	5.8	0.7	3.6	1.7	-3.8	0.0	0.5	0.5	2.4	0.1
	1945	6.5	2.0	4.9	1.1	-3.3	-0.1	0.6	0.2	1.1	0.0
	1950	5.5	1.9	4.3	1.2	-3.6	-0.2	0.6	0.1	1.3	0.0
	1955	7.5	3.3	6.1	1.2	-4.2	-0.1	0.4	0.1	0.5	-0.1
	1958	5.1	1.8	5.8	1.0	-4.2	-0.2	0.5	-0.1	0.2	0.0
	1960	5.0	1.2	7.0	0.6	-4.0	-0.3	0.5	-0.1	-0.3	0.1
	1965	2.0	-0.1	6.5	1.0	-6.5	-0.2	0.1	0.3	0.6	-0.1
	1970	5.6	1.8	8.8	1.4	-6.8	0.0	0.1	0.5	-0.1	-0.1
	1972	12.8	1.9	10.9	1.9	-7.4	0.5	-0.4	2.0	3.3	0.0
M2-=0.6, M5+=0.25	1940	2.3	1.0	1.0	-0.3	0.9	1.2	-0.4	-0.2	-1.0	0.0
	1950	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	1958	0.8	-0.3	2.5	-0.7	-0.7	1.0	-0.2	-0.2	-1.1	0.0
	1965	7.2	-0.6	6.2	0.2	-0.9	1.2	-0.7	1.7	-0.8	0.8
	1972	68.9	19.5	14.5	3.8	13.6	6.5	5.8	2.5	1.4	0.7
M2-=0.9, M5+=0.5	1940	7.3	2.6	6.7	4.6	-6.4	-0.3	0.2	-2.0	2.3	-0.3
	1950	7.6	3.1	7.5	4.0	-6.4	-0.5	0.8	-2.2	1.7	-0.4
	1958	10.1	4.2	8.3	3.4	-7.3	-0.2	2.2	-1.7	1.1	-0.3
	1965	7.3	2.2	10.3	1.8	-8.7	-0.2	2.4	-1.1	0.0	0.2
	1972	4.0	0.9	8.5	4.4	-10.9	0.0	2.5	-1.9	0.5	0.2

Table 9.3: Average proportions of *M. capensis* and *M. paradoxus* per depth range for the West and South Coasts, estimated by applying the species splitting algorithm to the offshore commercial catch data included in the GLM over the period 2004-2008. (from Leslie and Glazer 2010, with permission).

Depth	West Coast		South Coast	
	M. capensis	*M. paradoxus*	*M. capensis*	*M. paradoxus*
101-200m	0.81	0.19	0.84	0.16
201-250m	0.59	0.41	0.47	0.53
251-300m	0.37	0.63	0.34	0.66
301-400m	0.09	0.91	0.11	0.89
401-500m	0.01	0.99	0.01	0.99
>500m	0.00	1.00	0.00	1.00

Table 9.4: Average proportions of *M. capensis* and *M. paradoxus* observed per depth range for the West and South Coasts observed during all research surveys by *FRS Africana* over the period 2001 to 2009. (from Leslie and Glazer 2010, with permission).

Depth (m)	West Coast		South Coast	
	M. capensis	*M. paradoxus*	*M. capensis*	*M. paradoxus*
000-050	1.00	0.00	1.00	0.00
051-100	1.00	0.00	1.00	0.00
101-150	0.86	0.14	1.00	0.00
151-200	0.54	0.46	0.79	0.21
201-250	0.17	0.83	0.32	0.68
251-300	0.11	0.89	0.16	0.84
301-350	0.08	0.92	0.11	0.89
351-400	0.04	0.96	0.07	0.93
401-450	0.01	0.99	0.02	0.98
451-500	0.00	1.00	0.01	0.99
501-600	0.00	1.00		

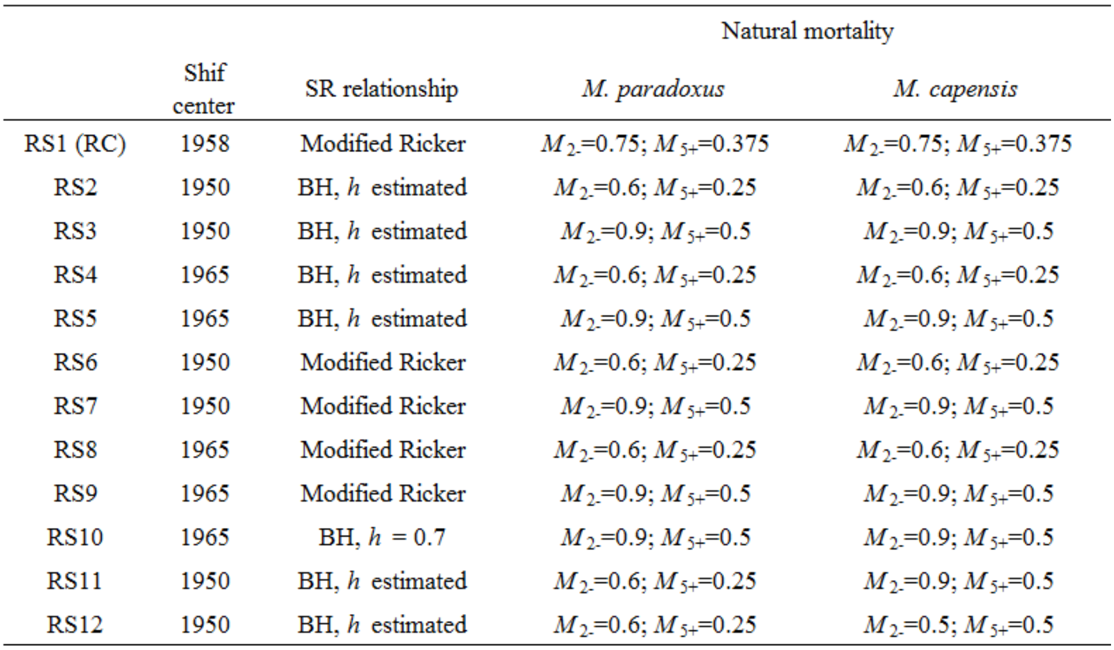
Table 9.5: West and South coasts cumulative (1917-1977) *M. capensis* proportion in the offshore trawl catches for a series of choices for the central year of the *M. capensis* to *M. paradoxus* shift.

	West Coast	South Coast
1940	0.28	0.62
1945	0.31	0.62
1950	0.35	0.62
1955	0.43	0.62
1958	0.49	0.62
1960	0.54	0.62
1965	0.67	0.63
1970	0.81	0.70
1972	0.87	0.76

Table 9.6: Estimated *M. paradoxus* and *M. capensis* current spawning biomass depletions for a series of initial (1917) *M. capensis* proportions in the offshore trawl catches for different central shift years.

Central shift year		Initial *M. capensis* proportion WC: 100% SC: 100%	WC: 80% SC: 100%	WC: 60% SC: 100%	WC: 40% SC: 100%	WC: 40% SC: 80%
1958	B^{sp}_{2009}/K^{sp}: *M. paradoxus*	0.15	0.16	0.16	0.14	0.14
	B^{sp}_{2009}/K^{sp}: *M. capensis*	0.54	0.54	0.56	0.57	0.57
1965	B^{sp}_{2009}/K^{sp}: *M. paradoxus*	0.24	0.24	0.25	0.16	0.15
	B^{sp}_{2009}/K^{sp}: *M. capensis*	0.61	0.59	0.51	0.55	0.55
1970	B^{sp}_{2009}/K^{sp}: *M. paradoxus*	0.37		0.34	0.10	0.10
	B^{sp}_{2009}/K^{sp}: *M. capensis*	0.63		0.58	0.56	0.55

Table 9.7: Description of the 12 cases forming the RS.



	Shif center	SR relationship	Natural mortality *M. paradoxus*	*M. capensis*
RS1 (RC)	1958	Modified Ricker	M_{2-}=0.75; M_{5+}=0.375	M_{2-}=0.75; M_{5+}=0.375
RS2	1950	BH, h estimated	M_{2-}=0.6; M_{5+}=0.25	M_{2-}=0.6; M_{5+}=0.25
RS3	1950	BH, h estimated	M_{2-}=0.9; M_{5+}=0.5	M_{2-}=0.9; M_{5+}=0.5
RS4	1965	BH, h estimated	M_{2-}=0.6; M_{5+}=0.25	M_{2-}=0.6; M_{5+}=0.25
RS5	1965	BH, h estimated	M_{2-}=0.9; M_{5+}=0.5	M_{2-}=0.9; M_{5+}=0.5
RS6	1950	Modified Ricker	M_{2-}=0.6; M_{5+}=0.25	M_{2-}=0.6; M_{5+}=0.25
RS7	1950	Modified Ricker	M_{2-}=0.9; M_{5+}=0.5	M_{2-}=0.9; M_{5+}=0.5
RS8	1965	Modified Ricker	M_{2-}=0.6; M_{5+}=0.25	M_{2-}=0.6; M_{5+}=0.25
RS9	1965	Modified Ricker	M_{2-}=0.9; M_{5+}=0.5	M_{2-}=0.9; M_{5+}=0.5
RS10	1965	BH, h = 0.7	M_{2-}=0.9; M_{5+}=0.5	M_{2-}=0.9; M_{5+}=0.5
RS11	1950	BH, h estimated	M_{2-}=0.6; M_{5+}=0.25	M_{2-}=0.9; M_{5+}=0.5
RS12	1950	BH, h estimated	M_{2-}=0.6; M_{5+}=0.25	M_{2-}=0.5; M_{5+}=0.5

Table 9.8: Estimates of management quantities for the RS. Values in bold have been fixed. B^{sp}_{2009}/K^{sp} is for both genders combined, while B^{sp}_{MSY}/K^{sp} and $B^{sp}_{2009}/B^{sp}_{MSY}$ are in terms of the female only spawning biomass.

		M. paradoxus								*M. capensis*								
	-lnL	K^{sp}	h	B^{sp}_{2009}/K^{sp}	B^{sp}_{MSY}/K^{sp}	$B^{sp}_{2009}/B^{sp}_{MSY}$	MSY	M_2	M_{5+}	K^{sp}	h	B^{sp}_{2009}/K^{sp}	B^{sp}_{MSY}/K^{sp}	$B^{sp}_{2009}/B^{sp}_{MSY}$	MSY	M_2	M_{5+}	2009 species ratio B^{sp}
RS1	-94.5	1363	1.08	0.15	0.24	0.59	113	**0.75**	**0.38**	516	1.01	0.54	0.47	1.12	69	**0.75**	**0.38**	1.34
RS2	-86.6	3009	0.98*	0.10	0.24	0.45	119	**0.60**	**0.25**	1990	0.98*	0.57	0.20	2.88	89	**0.60**	**0.25**	3.80
RS3	-87.6	906	0.91	0.17	0.20	0.63	110	**0.90**	**0.50**	941	0.98*	0.59	0.17	3.41	119	**0.90**	**0.50**	3.65
RS4	-76.0	3474	0.98*	0.19	0.20	1.09	118	**0.60**	**0.25**	2853	0.98*	0.64	0.20	3.24	128	**0.60**	**0.25**	2.78
RS5	-85.3	962	0.98*	0.27	0.11	2.19	124	**0.90**	**0.50**	1061	0.98*	0.61	0.17	3.54	134	**0.90**	**0.50**	2.46
RS6	-99.6	2842	1.05	0.10	0.26	0.42	121	**0.60**	**0.25**	735	1.18	0.52	0.48	1.08	65	**0.60**	**0.25**	1.33
RS7	-92.0	967	0.86	0.16	0.19	0.65	110	**0.90**	**0.50**	367	0.62	0.58	0.61	0.91	63	**0.90**	**0.50**	1.37
RS8	-92.4	1683	1.50*	0.21	0.34	0.64	121	**0.60**	**0.25**	1793	1.50*	0.65	0.42	1.52	166	**0.60**	**0.25**	3.27
RS9	-92.3	662	1.14	0.30	0.37	0.68	111	**0.90**	**0.50**	442	1.50*	0.63	0.41	1.44	110	**0.90**	**0.50**	1.40
RS10	-82.8	1412	**0.70**	0.33	0.28	1.12	123	**0.90**	**0.50**	1861	**0.70**	0.65	0.30	2.10	170	**0.90**	**0.50**	2.57
RS11	-93.4	3024	0.98*	0.10	0.24	0.44	118	**0.60**	**0.25**	788	0.39	0.18	0.41	0.42	40	**0.90**	**0.50**	0.49
RS12	-96.0	3022	0.98*	0.10	0.24	0.45	118	**0.60**	**0.25**	804	0.39	0.17	0.41	0.39	40	**0.50**	**0.50**	0.45

* Constraint boundary

Table 9.9: For each contribution to the total negative log-likelihood (-lnL), differences in –lnL compared to the case with the lowest total –lnL (RS6) across the RS.

	-lnL total	CPUE historic	CPUE GLM	Survey	Comm CAL	Survey CAL (sex-aggr.)	Survey CAL (sex-disaggr.)	ALK	Rec. penalty	Sel. smoothing penalty
RS1	5.1	1.8	5.8	1.0	-4.2	-0.2	0.5	-0.1	0.2	0.0
RS2	13.1	-0.4	10.6	-1.1	1.8	0.5	0.7	0.5	-0.1	0.5
RS3	12.0	3.2	15.1	3.1	-8.4	0.2	1.2	-2.0	-0.1	-0.2
RS4	23.7	0.6	20.8	2.7	-3.5	-0.4	-0.2	0.9	0.9	1.6
RS5	14.4	2.1	15.1	3.8	-8.1	-0.8	2.2	-1.1	0.5	0.2
RS6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
RS7	7.6	3.1	7.5	4.0	-6.4	-0.5	0.8	-2.2	1.7	-0.4
RS8	7.2	-0.6	6.2	0.2	-0.9	1.2	-0.7	1.7	-0.8	0.8
RS9	7.3	2.2	10.3	1.8	-8.7	-0.2	2.4	-1.1	0.0	0.2
RS10	16.8	4.9	17.2	5.1	-10.6	-0.7	0.1	-0.5	0.2	0.9
RS11	6.2	-0.5	7.2	-1.3	1.4	-0.3	2.1	-0.8	-0.5	-1.1
RS12	3.6	-0.4	7.3	-1.7	0.0	0.4	0.0	0.5	-0.6	-1.9

Table 9.10: Description of the robustness/sensitivity tests.

	Shift center	SR relationship	Natural mortality		Other
			M. paradoxus	*M. capensis*	
Changes in the past					
Rob1	1965	BH, *h* estimated	M_{2-}=0.6; M_{5+}=0.25	M_{2-}=0.9; M_{5+}=0.5	
Rob2	1950	BH, *h* estimated	M_{2-}=0.9; M_{5+}=0.5	M_{2-}=0.6; M_{5+}=0.25	
Rob3	1965	BH, *h* estimated	M_{2-}=0.9; M_{5+}=0.5	M_{2-}=0.6; M_{5+}=0.25	
Rob4	1950	True Ricker	M_{2-}=0.6; M_{5+}=0.25	M_{2-}=0.6; M_{5+}=0.25	
Rob5	1950	True Ricker	M_{2-}=0.9; M_{5+}=0.5	M_{2-}=0.9; M_{5+}=0.5	
Rob6			as RC		σ_R = 0.25
Rob7			as RC		W_{ALK} = 0.001
Rob8			as RC		W_{ALK} = 0.1
Rob9			as RC		W_{CAL} = 0.01
Rob10			as RC		W_{CAL} = 1.0
Rob11			as RC		*M* gender dependent (+0.05 for males, -0.05 for females)
Rob12			as RC		All commercial and survey selectivity slopes (in cm^{-1}): a)+0.04, b) +0.02, c) -0.04 and d) -0.02
Rob13			as RC		Decrease in *K* (30% linear decrease between 1980 and 2000 for both spp)
Rob14			as RC		Added weighting (5x) to last 5 year's CPUE and survey data to fit recent abundance indices more closely
Rob15			as RC		No shrinkage of recent recruitments towards the stock-recruitment relationship prediction
Rob 16			as RS2		Increasing *M* at large ages (linear from 0.25 at age 8 to 1 at age 15)
Rob17			as RC		Start in 1978, estimating θ and ζ
Rob 18			as RC		Change in efficiency in the offshore trawl fleet 1994/1995
Rob 19			as RC		Different CPUE series: a. all offshore vessels incl.; b. alt. depth stratifications; c. omit days with nominal CPUE=0; (d. updated after database check)
Rob 20			as RC		Survey calibration factor: a. incr. cap. factor to 0.9; b. decr. cap. factor to 0.6; c. both cap. and para. factors estimated
Rob 21			as RC		Ageing of both species out by one year
Rob 22			as RC		Ageing of both species to be halved
Rob 23			as RC		Alternative assumption for the cap. offshore selectivity
Rob 24			as RC		Alternative assumption re SC female paradoxus selectivity scaling factor: a. as lower; b. as higher
Rob 25			as RC		Alternative maturity-at-length with fixed lower *h* values
Rob 26			as RC		Include discards in the past
Rob 27			as RC		40/60 male/female ratio at birth instead of 50/50
Rob 28			as RC		Alternative species split algorithm (post-1978 catches and CPUE series)
Rob 29			as RC		From 1997 to 2002 q for CPUE dropped by 20% as a result of shorter tows
Changes in the future					
Rob 30			as RC		Maximum proportion of cohort catchable in one year decrease from 90% to 70%
Rob 31			as RC		Missing/reduced surveys in the future: a. no surveys; b. only WC surveys; c. only SC surveys; d. both surveys missing every 3 years; e. increase all future surveys CVs by multiplicative factor of sqrt(2); f. no surveys plus undetected increase catchability related to CPUE
Rob 32			as RC		Decrease all future survey CVs by a multiplicative factor of 1/sqrt(2)
Rob 33			as RC		MPA possible effects on future CPUE: a. no CPUE; b. new CPUE series with prior on *q*; c. new CPUE series with lower *q*; d. new CPUE series with higher *q*; and e. new CPUE series with no prior on *q*
Rob 34			as RC		Trend in F_{ratio} over time in the future: a) 2% p.a. and b) -2% p.a., for 10 years then constant
Rob 35			as RC		Undectected 2% p.a. increase in catchability related to CPUE in the future
Rob 36			as Rob26		Change in discard pattern in the future: a) past, but no future discards; b) past and future discards; c) past discards are halved in the future.
Rob 37			as RC		Decrease in *K* in the future (30% linear decrease between 2011 and 2016 for both spp)
Rob 38			as RC		Allow for serial correlation in recruitment residuals (estimate from RC fit)

Table 9.11: Estimates of management quantities for RS1 and Rob1 to Rob29. K^{sp} and B^{sp}_{2009}/K^{sp} are for both genders combined, while B^{sp}_{MSY}/K^{sp} and $B^{sp}_{2009}/B^{sp}_{MSY}$ are in terms of the female only spawning biomass.

		M. paradoxus								*M. capensis*								2009
	-lnL total	K^{sp}	h	$\frac{B^{sp}_{2009}}{K^{sp}}$	$\frac{B^{sp}_{MSY}}{K^{sp}}$	$\frac{B^{sp}_{2009}}{B^{sp}_{MSY}}$	*MSY*	M_{2-}	M_{5+}	K^{sp}	h	$\frac{B^{sp}_{2009}}{K^{sp}}$	$\frac{B^{sp}_{MSY}}{K^{sp}}$	$\frac{B^{sp}_{2009}}{B^{sp}_{MSY}}$	*MSY*	M_{2-}	M_{5+}	spp ratio B^{sp}
RS1	-94.5	1395	1.06	0.15	0.24	0.59	113	0.75	0.38	499	1.41	0.52	0.36	1.39	70	0.75	0.38	1.21
Rob1	-81.0	3511	0.98*	0.19	0.20	1.09	119	0.60	0.25	1030	0.98*	0.60	0.16	3.59	131	0.90	0.50	0.94
Rob2	-82.0	911	0.90	0.17	0.20	0.62	109	0.90	0.50	2083	0.98*	0.58	0.20	2.95	94	0.60	0.25	7.85
Rob3	-79.8	1049	0.92	0.28	0.17	1.47	122	0.90	0.50	3002	0.98*	0.64	0.20	3.28	134	0.60	0.25	6.52
Rob4	-82.3	2210	1.21	0.18	0.42	0.49	133	0.60	0.25	774	1.50*	0.50	0.38	1.30	68	0.60	0.25	0.95
Rob5	-81.0	717	1.01	0.28	0.39	0.58	120	0.90	0.50	413	1.02	0.56	0.40	1.30	68	0.90	0.50	1.14
Rob6	-85.5	1522	0.95	0.15	0.21	0.65	108	0.75	0.38	486	1.45	0.59	0.36	1.57	70	0.75	0.38	1.27
Rob7	-212.2	1567	1.02	0.15	0.24	0.61	117	0.75	0.38	423	1.32	0.54	0.35	1.42	71	0.75	0.38	0.97
Rob8	958.2	1662	0.95	0.07	0.21	0.21	119	0.75	0.38	487	1.50*	0.49	0.34	1.38	69	0.75	0.38	2.09
Rob9	-96.1	1816	0.97	0.08	0.20	0.24	133	0.75	0.38	608	1.15	0.56	0.43	1.27	77	0.75	0.38	2.49
Rob10	-678.5	941	1.19	0.30	0.30	0.88	113	0.75	0.38	609	0.41	0.67	0.83	0.77	69	0.75	0.38	1.44
Rob11	-92.1	1528	1.09	0.14	0.23	0.55	113	0.75	0.38	531	1.50*	0.51	0.33	1.43	70	0.75	0.38	1.24
Rob12a	-76.6	1748	0.96	0.19	0.29	0.68	122	0.75	0.38	620	0.78	0.56	0.52	1.06	69	0.75	0.38	1.03
Rob12b	-88.2	1594	1.01	0.17	0.26	0.67	118	0.75	0.38	562	0.91	0.55	0.48	1.10	68	0.75	0.38	1.12
Rob12c	-75.4	952	1.15	0.22	0.27	0.66	107	0.75	0.38	416	1.50*	0.55	0.40	1.32	70	0.75	0.38	1.10
Rob12d	-91.4	1219	1.12	0.17	0.26	0.58	110	0.75	0.38	458	1.50*	0.52	0.36	1.38	69	0.75	0.38	1.17
Rob13	-69.4	876	1.31	0.21	0.34	0.63	95	0.75	0.38	639	0.95	0.34	0.26	1.24	44	0.75	0.38	1.17
Rob14	-236.4	1208	1.23	0.19	0.24	0.72	114	0.75	0.38	484	1.16	0.49	0.45	1.05	70	0.75	0.38	1.05
Rob15	-96.5	1464	0.98	0.15	0.22	0.65	110	0.75	0.38	518	1.06	0.53	0.45	1.14	68	0.75	0.38	1.25
Rob16	-85.6	2302	0.93	0.11	0.27	0.41	123	0.60	0.25	1343	0.98*	0.52	0.22	2.38	88	0.60	0.25	2.80
Rob17	-73.3	2080	0.85	0.16	0.27	0.60	124	0.75	0.38	384	1.50*	0.50	0.41	1.19	63	0.75	0.38	0.58
Rob18	-119.7	1184	1.27	0.21	0.24	0.79	115	0.75	0.38	502	1.24	0.55	0.41	1.31	70	0.75	0.38	1.14
Rob19a	-124.3	1236	1.16	0.16	0.23	0.64	111	0.75	0.38	545	1.03	0.52	0.43	1.14	67	0.75	0.38	1.38
Rob19b	-105.0	1315	1.12	0.15	0.23	0.59	112	0.75	0.38	525	0.95	0.56	0.48	1.13	68	0.75	0.38	1.53
Rob19c	-98.6	1391	1.05	0.14	0.22	0.59	111	0.75	0.38	496	1.40	0.46	0.35	1.25	69	0.75	0.38	1.16
Rob20a	-94.6	1395	1.06	0.15	0.24	0.59	113	0.75	0.38	498	1.42	0.51	0.36	1.38	70	0.75	0.38	1.20
Rob20b	-92.4	1393	1.06	0.15	0.24	0.59	113	0.75	0.38	504	1.38	0.53	0.36	1.42	70	0.75	0.38	1.26
Rob20c	-95.6	1406	1.05	0.14	0.24	0.55	112	0.75	0.38	498	1.41	0.51	0.36	1.39	70	0.75	0.38	1.28
Rob21	-72.5	1229	1.00	0.16	0.22	0.67	116	0.75	0.38	470	0.85	0.57	0.52	1.05	69	0.75	0.38	1.34
Rob22	-83.3	995	1.16	0.13	0.25	0.47	114	0.75	0.38	404	0.51	0.60	0.75	0.78	74	0.75	0.38	1.92
Rob23	-84.4	1468	1.01	0.18	0.26	0.65	114	0.75	0.38	743	0.78	0.57	0.50	1.13	74	0.75	0.38	1.62
Rob24a	-94.6	1397	1.06	0.16	0.26	0.60	113	0.75	0.38	507	1.35	0.52	0.37	1.35	70	0.75	0.38	1.20
Rob24b	-94.1	1394	1.06	0.15	0.23	0.59	113	0.75	0.38	491	1.47	0.51	0.34	1.43	70	0.75	0.38	1.20
Rob25	-43.1	1575	0.70	0.12	0.29	0.46	102	0.75	0.38	762	0.70	0.50	0.40	1.25	65	0.75	0.38	2.01
Rob26	-97.4	1510	1.06	0.15	0.23	0.61	113	0.75	0.38	492	1.50*	0.47	0.31	1.45	86	0.75	0.38	1.02
Rob27	-91.2	1300	1.02	0.15	0.25	0.62	112	0.75	0.38	499	1.22	0.51	0.37	1.44	69	0.75	0.38	1.28
Rob28	-91.0	1106	1.24	0.17	0.23	0.66	107	0.75	0.38	532	1.02	0.52	0.46	1.09	70	0.75	0.38	1.49
Rob29	-95.6	1406	1.08	0.14	0.25	0.54	114	0.75	0.38	522	1.38	0.49	0.33	1.42	69	0.75	0.38	1.27

Table 9.12: For each contribution to the total negative log-likelihood (-lnL), differences in -lnL compared to the Reference Case (RS1).

	-lnL total	CPUE historic	CPUE GLM	Survey	Comm. CAL	Survey CAL (sex-aggr.)	Survey CAL (sex-disaggr.)	ALK	Recruitment penalty	Selectivity smoothing penalty
RS1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Rob1	13.4	-1.4	9.1	1.5	-0.3	0.2	1.4	-0.4	1.4	1.8
Rob2	12.5	1.7	14.1	3.0	-5.1	1.8	-1.9	-0.2	0.1	-0.7
Rob3	14.7	2.2	14.9	4.0	-6.4	0.7	-1.2	0.7	-0.1	0.1
Rob4	12.2	13.9	-3.5	-0.3	2.6	0.9	-1.6	0.8	-0.5	0.2
Rob5	13.4	14.1	4.1	2.0	-2.6	-0.6	-0.7	-1.8	-0.5	-0.2
Rob6	9.0	-1.8	4.0	0.2	1.1	-0.5	2.1	-1.0	5.1	-0.2
Rob7*	-117.7	-1.0	-1.5	-2.7	2.8	0.2	-7.3	-107.5	0.6	-1.4
Rob8*	1052.6	-2.9	7.3	11.5	13.6	6.1	14.8	1002.2	1.0	-1.0
Rob9*	-1.6	-2.3	-18.2	-12.3	57.7	31.6	40.4	-5.1	-2.0	-14.1
Rob10*	-584.1	3.2	20.9	3.6	-538.9	-9.8	-18.3	37.8	9.5	37.5
Rob11	2.4	-0.3	-0.7	-0.4	-0.4	-0.5	3.0	2.6	-0.1	-0.6
Rob12a	17.8	9.5	-3.5	0.5	10.6	-1.4	0.9	0.4	0.5	0.0
Rob12b	6.3	5.1	-3.4	0.4	3.7	-0.8	0.3	0.3	0.7	0.0
Rob12c	19.1	1.1	6.5	2.6	4.3	2.3	-1.1	3.2	0.2	0.0
Rob12d	3.1	0.0	3.6	0.9	-1.4	0.7	-0.6	0.0	0.0	0.0
Rob13	25.1	15.2	0.4	3.8	-2.2	0.4	-0.5	2.4	5.5	-0.1
Rob14*	-142.0	-0.5	-78.1	-64.6	-1.7	0.2	0.5	0.4	1.6	0.1
Rob15	-2.0	-0.9	-0.9	0.4	-0.8	-0.3	-0.7	0.2	0.9	-0.2
Rob16	8.8	-1.6	7.4	-1.7	2.6	2.4	0.0	1.0	-1.0	0.0
Rob17*	21.1	-	-4.8	-0.4	-7.4	-0.5	-1.7	0.2	-0.4	-0.7
Rob18	-25.3	-0.8	-18.3	-7.3	-1.6	-0.5	0.8	2.7	0.4	-0.8
Rob19a	-29.9	-0.9	-27.3	0.3	-1.3	-0.2	0.2	0.0	-0.4	-0.4
Rob19b	-10.6	-0.6	-10.7	1.6	-1.5	1.2	0.4	-0.4	-0.4	-0.3
Rob19c	-4.1	-0.5	-8.2	2.7	1.7	-0.3	0.0	-0.6	1.2	-0.1
Rob20a	-0.1	0.0	-0.2	0.0	0.1	0.0	0.0	0.0	0.1	-0.1
Rob20b	2.1	0.0	0.7	1.1	-0.1	0.0	0.1	0.0	-0.3	0.6
Rob20c	-1.2	-0.4	0.0	0.0	0.1	-0.2	-0.1	-0.2	0.1	-0.4
Rob21	21.9	0.2	1.2	-0.7	-4.6	-1.9	-0.1	25.3	3.3	-0.8
Rob22	11.2	-1.8	4.6	-1.8	-8.8	6.6	4.1	7.6	4.5	-4.1
Rob23	10.1	2.7	-2.1	0.3	5.4	0.1	1.0	1.0	0.6	0.9
Rob24a	-0.2	0.0	0.5	-0.1	-0.3	-0.1	-0.1	0.1	0.0	0.0
Rob24b	0.3	0.1	-0.3	0.1	0.3	0.1	0.1	0.0	0.0	0.0
Rob25	51.3	22.3	11.7	-0.2	-0.2	0.9	1.8	3.8	11.0	0.1
Rob26	-3.0	-0.4	-1.1	-0.3	0.7	-0.6	-0.6	0.2	-0.4	-0.3
Rob27	3.3	-0.6	-0.2	-0.6	-0.1	0.3	1.7	3.2	0.0	-0.4
Rob28	3.4	-0.9	9.9	-2.1	-2.9	0.0	0.6	0.7	-0.8	-1.2
Rob29	-1.2	-0.4	-1.1	-3.1	1.0	0.4	1.7	-0.2	0.4	0.1

* These likelihood contributions are not comparable to the others because of different weightings or data.

Table 9.13: Estimates of management quantities for RS11 and three robustness tests based on this OM. K^{sp} and B^{sp}_{2009}/K^{sp} are for both genders combined, while B^{sp}_{MSY}/K^{sp} and $B^{sp}_{2009}/B^{sp}_{MSY}$ are in terms of the female only spawning biomass.

		M. paradoxus								*M. capensis*								2009
	-lnL total	K^{sp}	h	$\frac{B^{sp}_{2009}}{K^{sp}}$	$\frac{B^{sp}_{MSY}}{K^{sp}}$	$\frac{B^{sp}_{2009}}{B^{sp}_{MSY}}$	MSY	M_{2-}	M_{5+}	K^{sp}	h	$\frac{B^{sp}_{2009}}{K^{sp}}$	$\frac{B^{sp}_{MSY}}{K^{sp}}$	$\frac{B^{sp}_{2009}}{B^{sp}_{MSY}}$	MSY	M_{2-}	M_{5+}	spp ratio B^{sp}
RS11	-93.4	3024	0.98*	0.10	0.24	0.44	118	0.60	0.25	788	0.39	0.18	0.41	0.42	40	0.90	0.50	0.49
Rob5(RS11)	-76.6	2041	1.32	0.17	0.41	0.45	134	0.60	0.25	717	0.39	0.20	0.47	0.41	42	0.90	0.50	0.42
Rob13(RS11)	-63.2	3328	0.97	0.09	0.17	0.65	86	0.60	0.25	524	0.88	0.31	0.17	1.74	42	0.90	0.50	0.51
Rob25(RS11)	-65.5	3233	0.70	0.15	0.33	0.57	111	0.60	0.25	627	0.39	0.15	0.40	0.36	37	0.90	0.50	0.19

Table 9.14: For each contribution to the total negative log-likelihood (-lnL), differences in -lnL compared to RS11.

	-lnL total	CPUE historic	CPUE GLM	Survey	Comm. CAL	Survey CAL (sex-aggr.)	Survey CAL (sex-disaggr.)	ALK	Recruitment penalty	Selectivity smoothing penalty
RS11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Rob5(RS11)	16.7	16.8	4.2	-0.6	-1.9	-0.6	0.0	0.0	-0.8	-0.3
Rob13(RS11)	30.1	1.7	-11.0	2.2	5.1	3.6	2.6	4.6	19.7	1.6
Rob25(RS11)	27.9	13.4	8.7	2.4	-5.1	-0.2	1.3	2.9	2.7	1.8

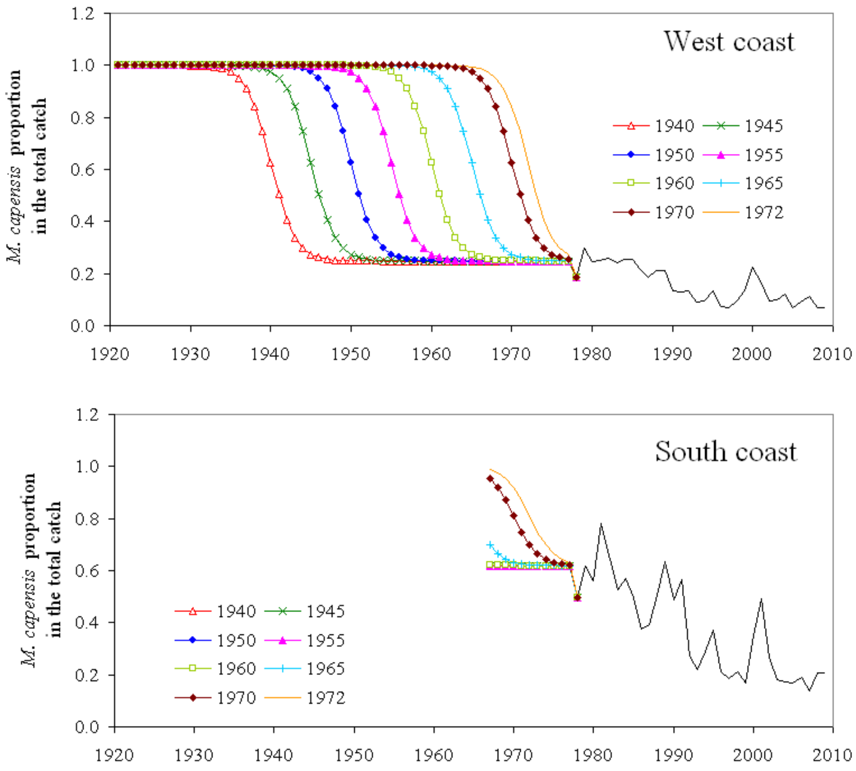


Figure 9.1: Assumed *M. capensis* proportion in the offshore trawl catches (West and South Coasts separately) for different choices for the central year for the switch from a primarily *M. capensis* to a primarily *M. paradoxus* deep-sea trawl fishery. From 1978 onwards, the survey species-proportion at depth relationship has been used to split the catches.

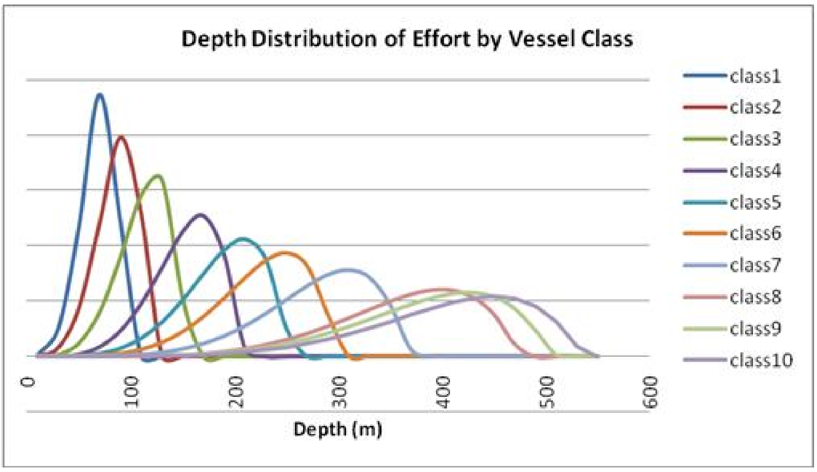


Figure 9.2: Beta distributions of effort over depth assumed for each of the 10 vessel classes (reproduced from SADSTIA and OLRAC (2010) with permission).

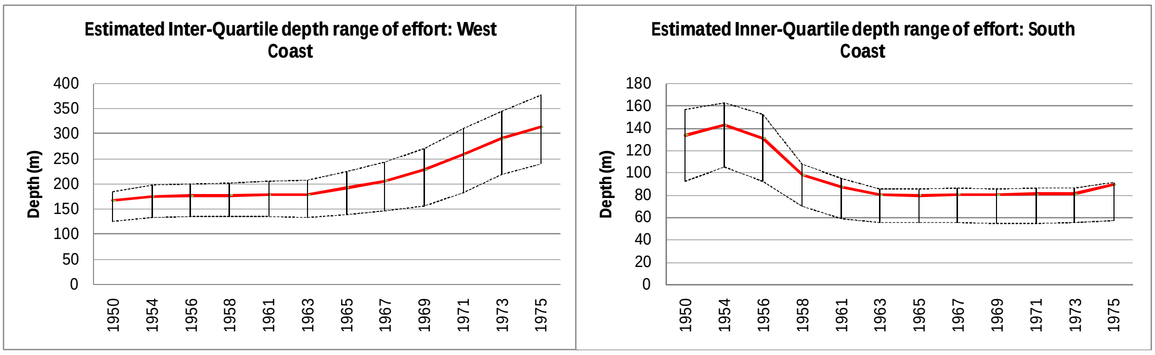


Figure 9.3: Estimated mean depth (solid red line) and the first and third quartiles (dashed lines) of the effort by depth distribution on the West and South coasts 1950 to 1975 (reproduced from SADSTIA and OLRAC (2010), with permission).

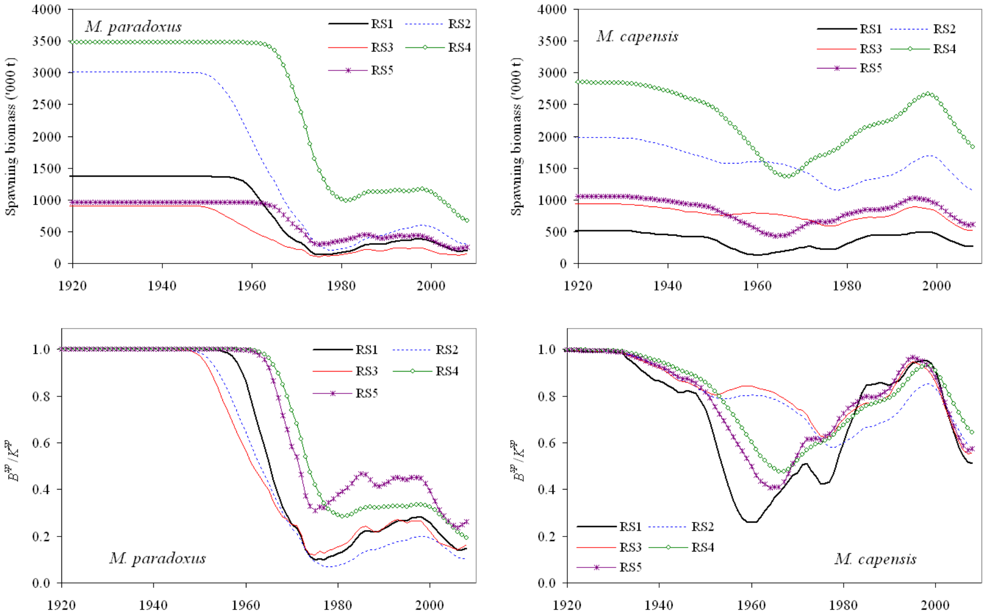


Figure 9.4a: Estimated spawning biomass trajectories for *M. paradoxus* and *M. capensis*, both in absolute terms and relative to the pre-exploitation level for RS1 to RS5.

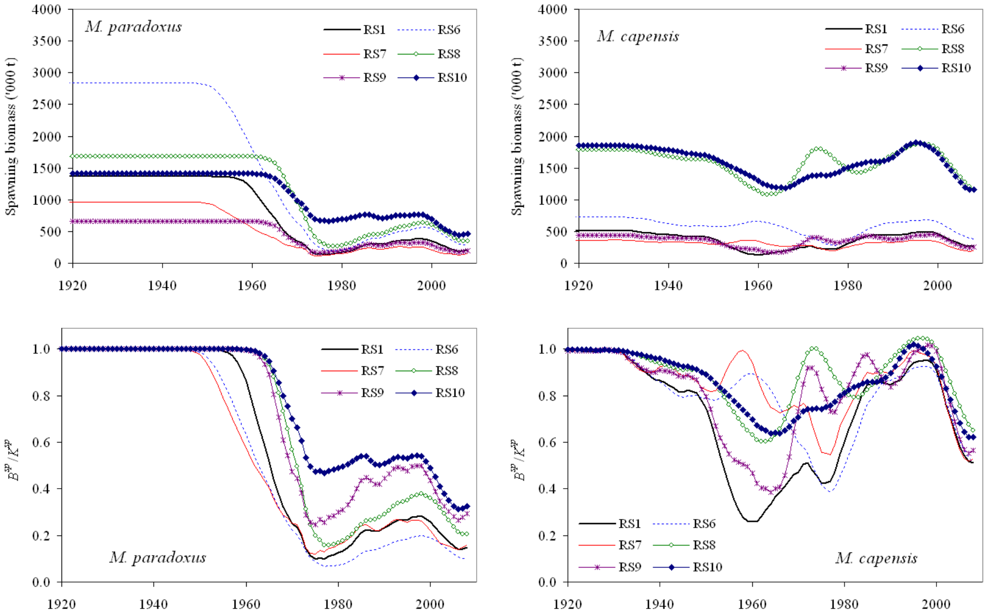


Figure 9.4b: Estimated spawning biomass trajectories for *M. paradoxus* and *M. capensis*, both in absolute terms and relative to the pre-exploitation level for RS1 and RS6 to RS10.

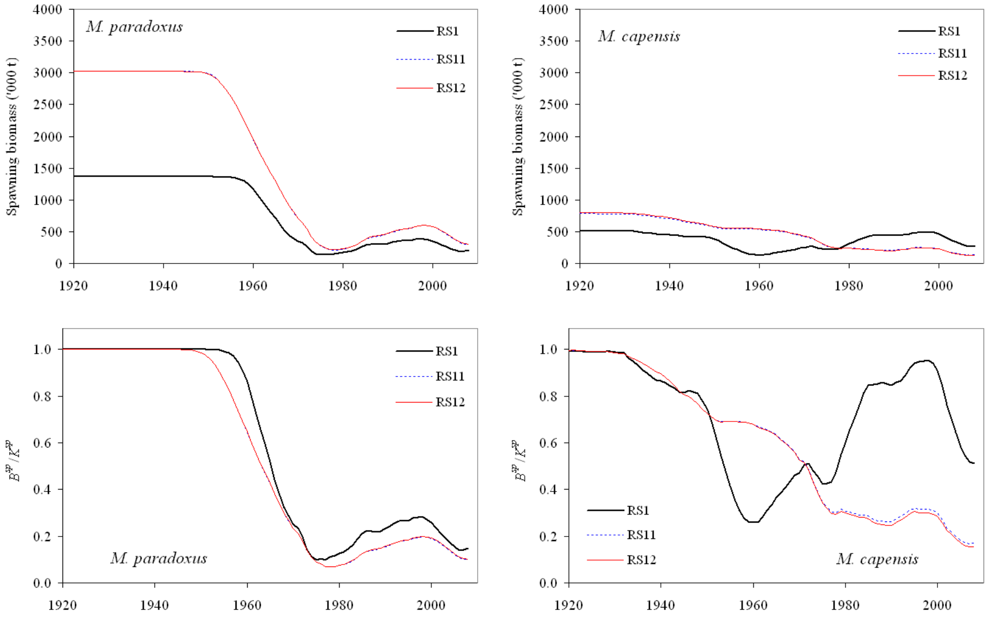


Figure 9.4c: Estimated spawning biomass trajectories for *M. paradoxus* and *M. capensis*, both in absolute terms and relative to the pre-exploitation level for RS1, RS11 and RS12. Note that the RS11 and RS12 trajectories are virtually on top of each other.

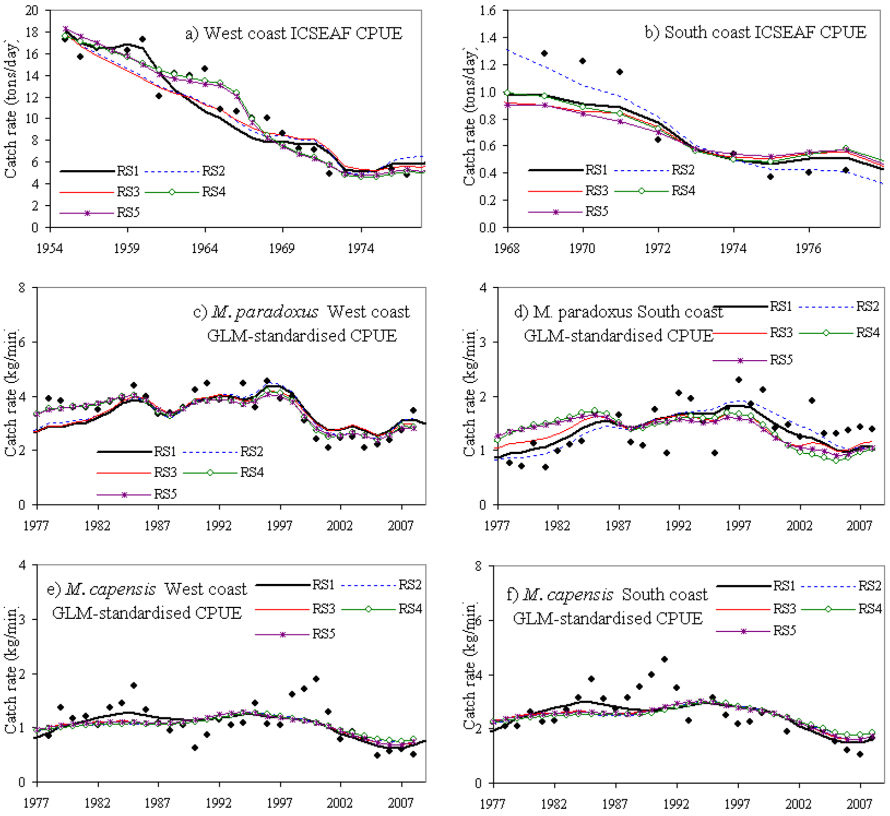


Figure 9.5a: Fit to the CPUE data for RS1 to RS5.

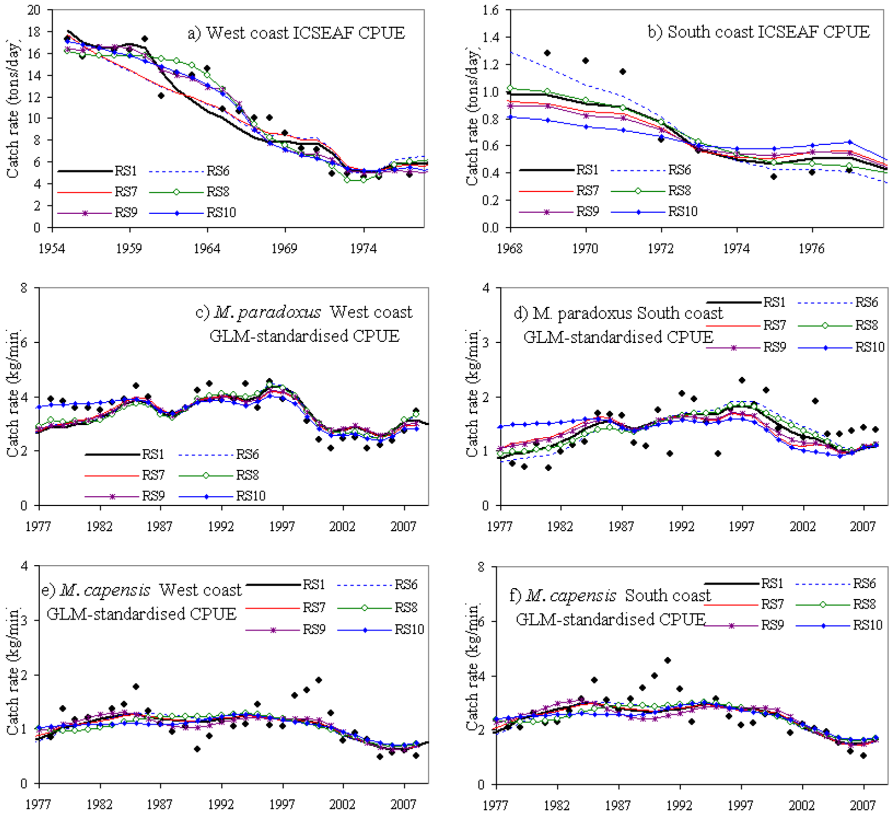


Figure 9.5b: Fit to the CPUE data for RS1 and RS6 to RS10.

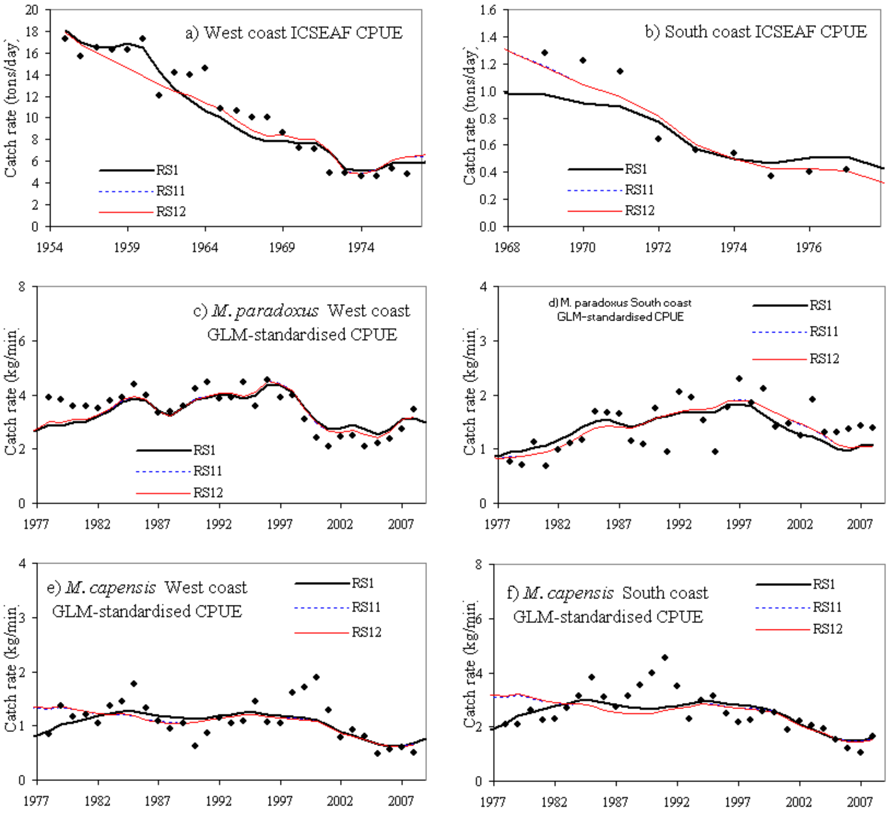


Figure 9.5c: Fit to the CPUE data for RS1, RS11 and RS12. Note that the RS11 and RS12 trajectories are virtually on top of each other.

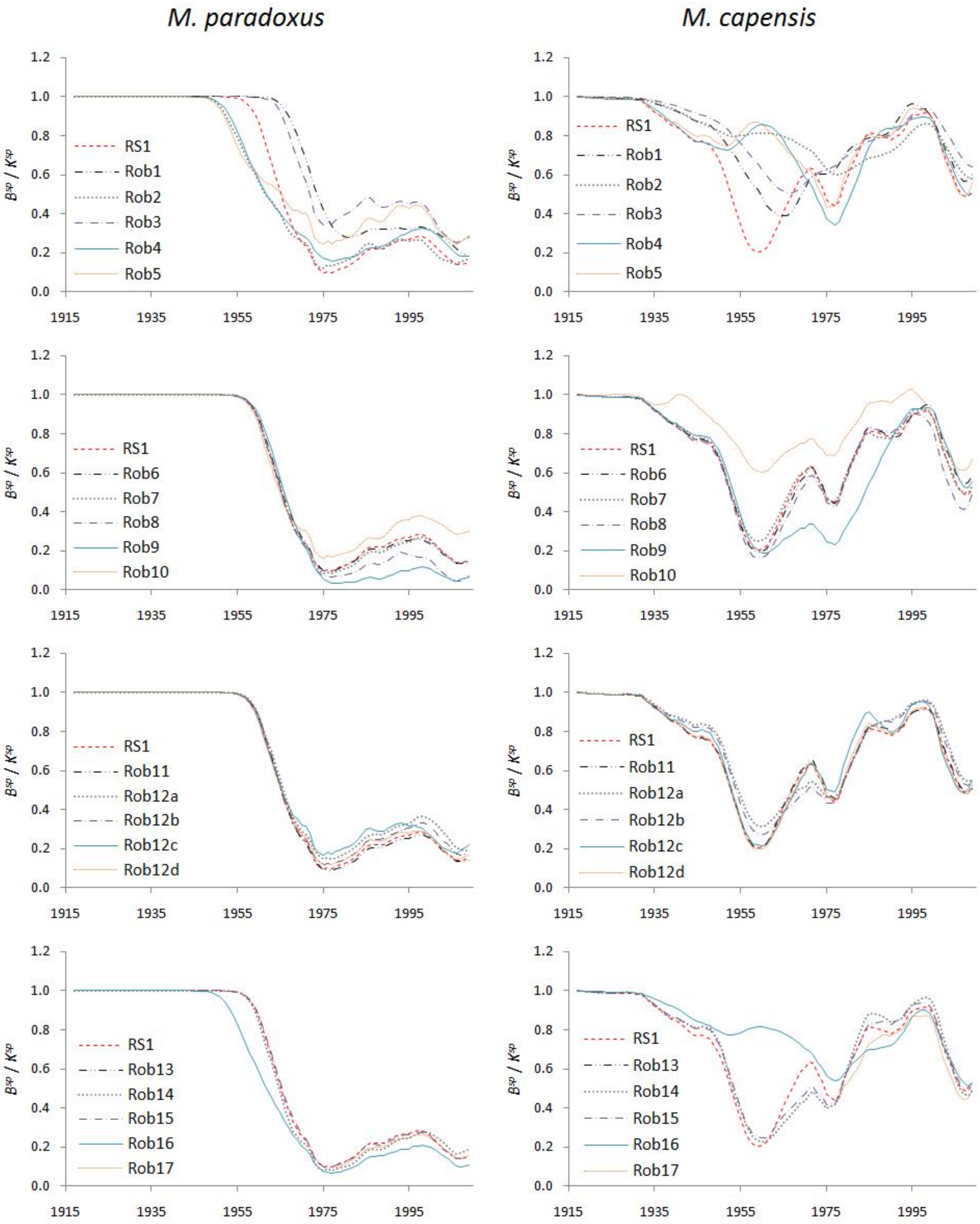


Figure 9.6: Estimated gender-aggregated spawning biomass trajectories for *M. paradoxus* and *M. capensis*, relative to pre-exploitation levels, for the RC (RS1) and robustness tests Rob1-Rob29.

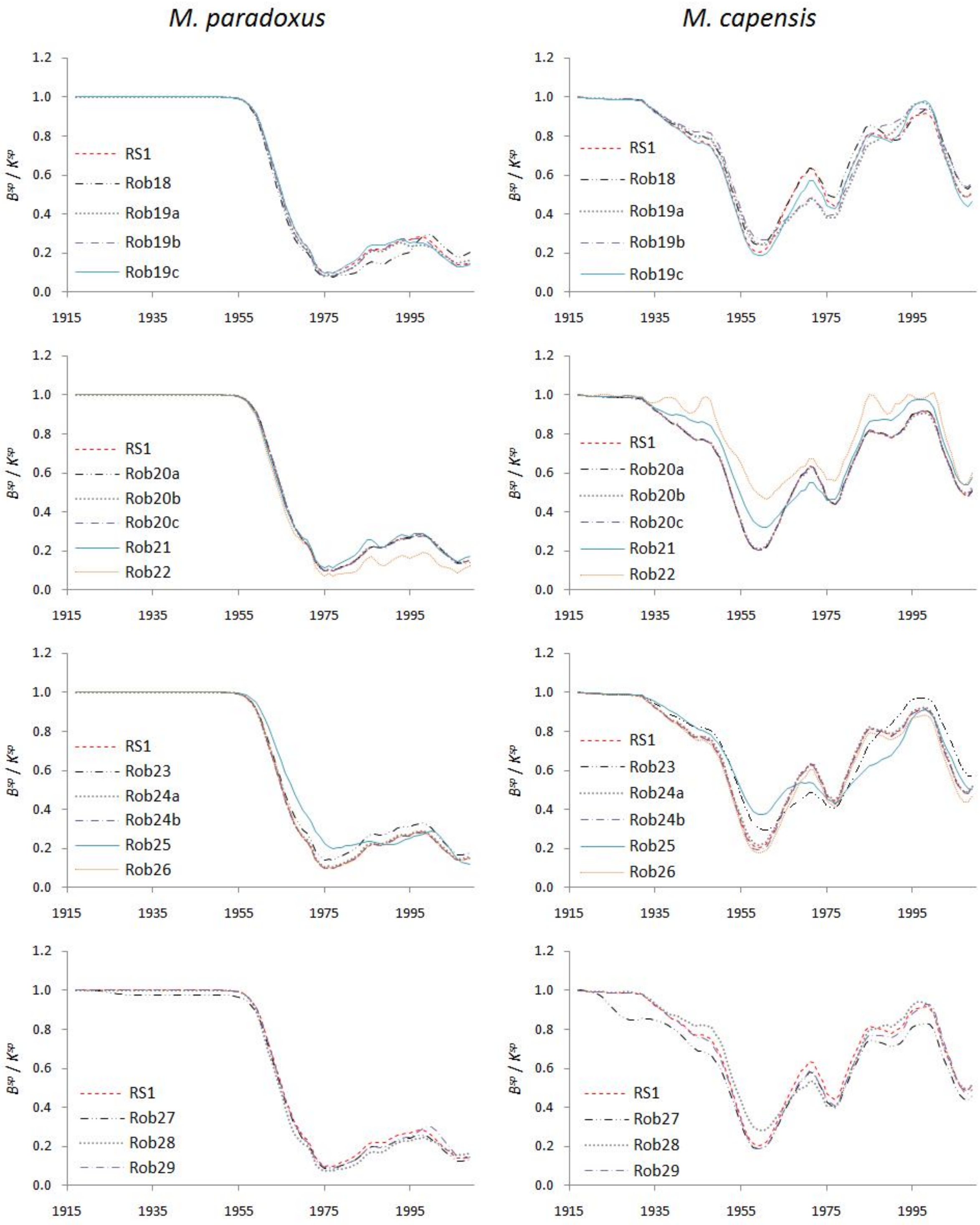


Figure 9.6: continued

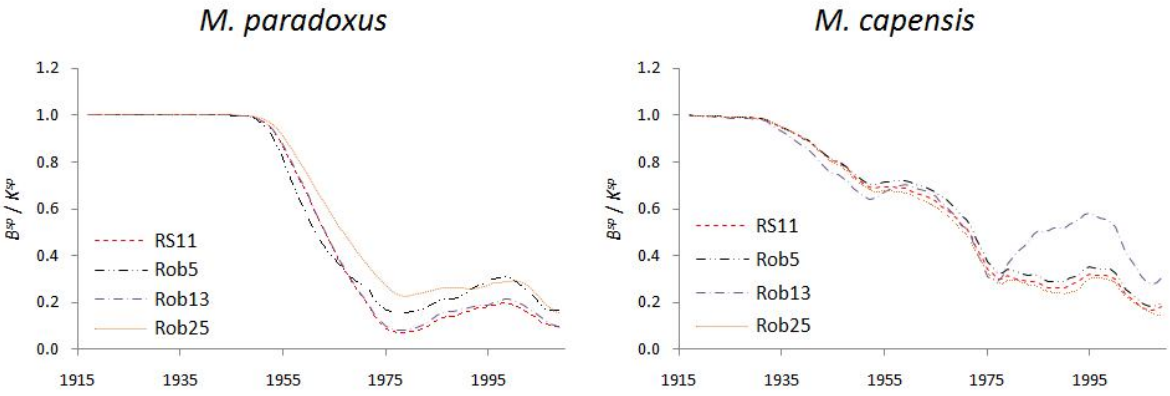


Figure 9.7: Estimated gender-aggregated spawning biomass trajectories for *M. paradoxus* and *M. capensis*, relative to pre-exploitation levels, for the RS11 and three robustness tests based on this OM.

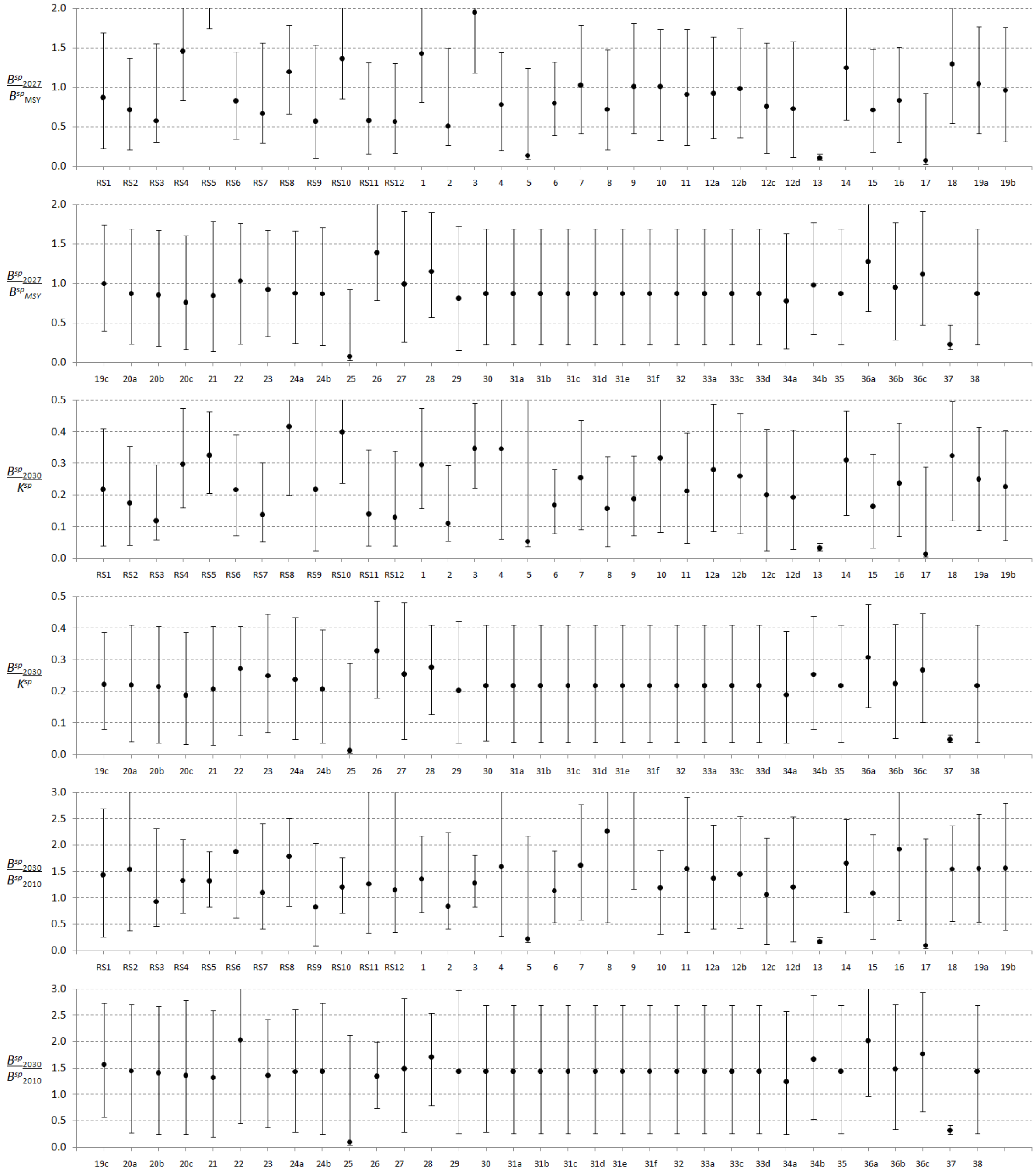


Figure 9.8a: Three performance statistics ($B^{sp}_{2027}/B^{sp}_{MSY}$, B^{sp}_{2030}/K^{sp} and $B^{sp}_{2030}/B^{sp}_{2010}$, in terms of female biomass only) for *M. paradoxus* for the full set of RS and robustness tests under a projected constant catch of 150 000t. In some instance, the statistics are outside the area covered by the plot.

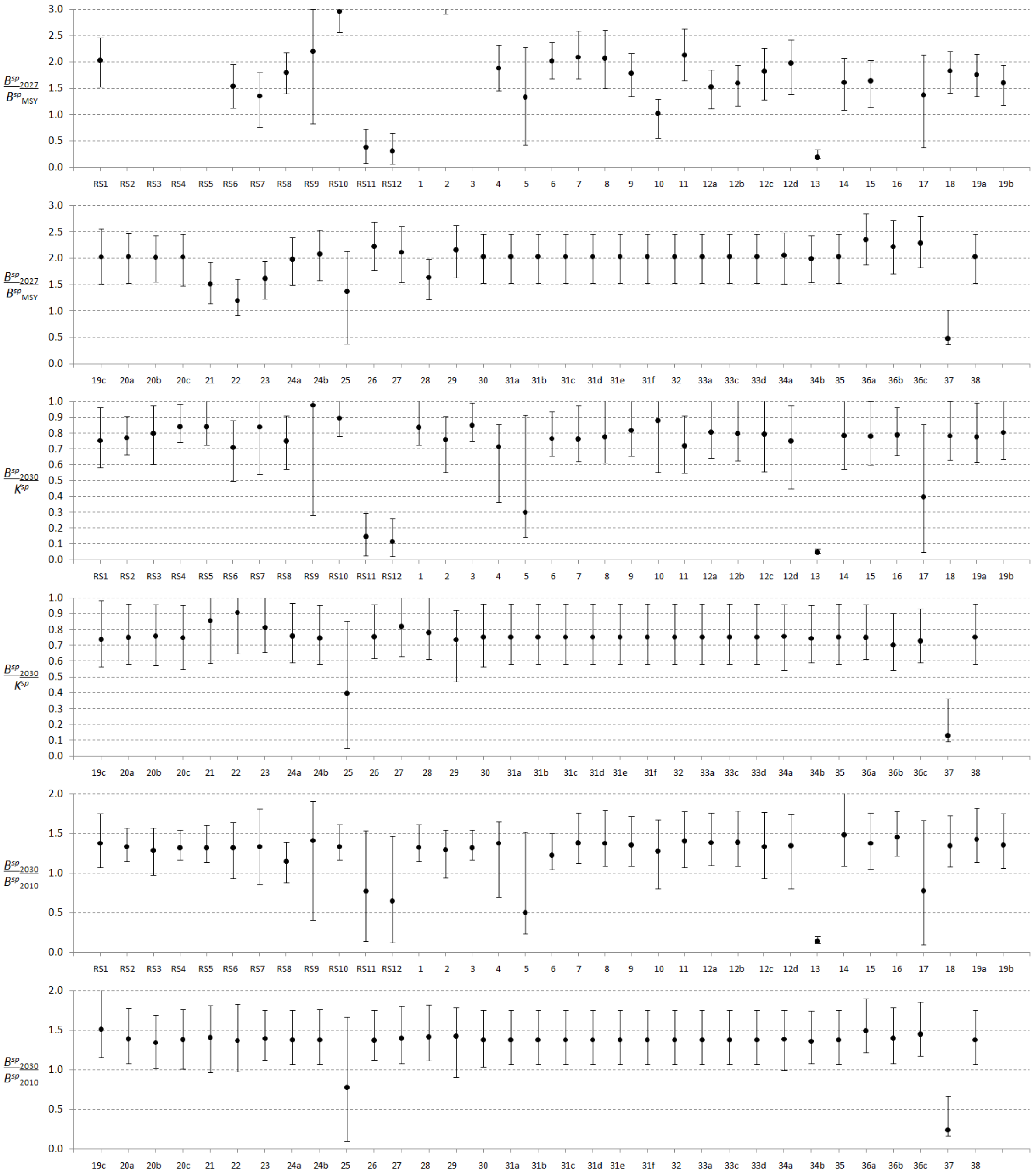


Figure 9.8b: Three performance statistics ($B^{sp}_{2027}/B^{sp}_{MSY}, B^{sp}_{2030}/K^{sp}$ and $B^{sp}_{2030}/B^{sp}_{2010}$, in terms of female biomass only) for *M. capensis* for the full set of RS and robustness tests under a projected constant catch of 150 000t. In some instance, the statistics are outside the area covered by the plot.

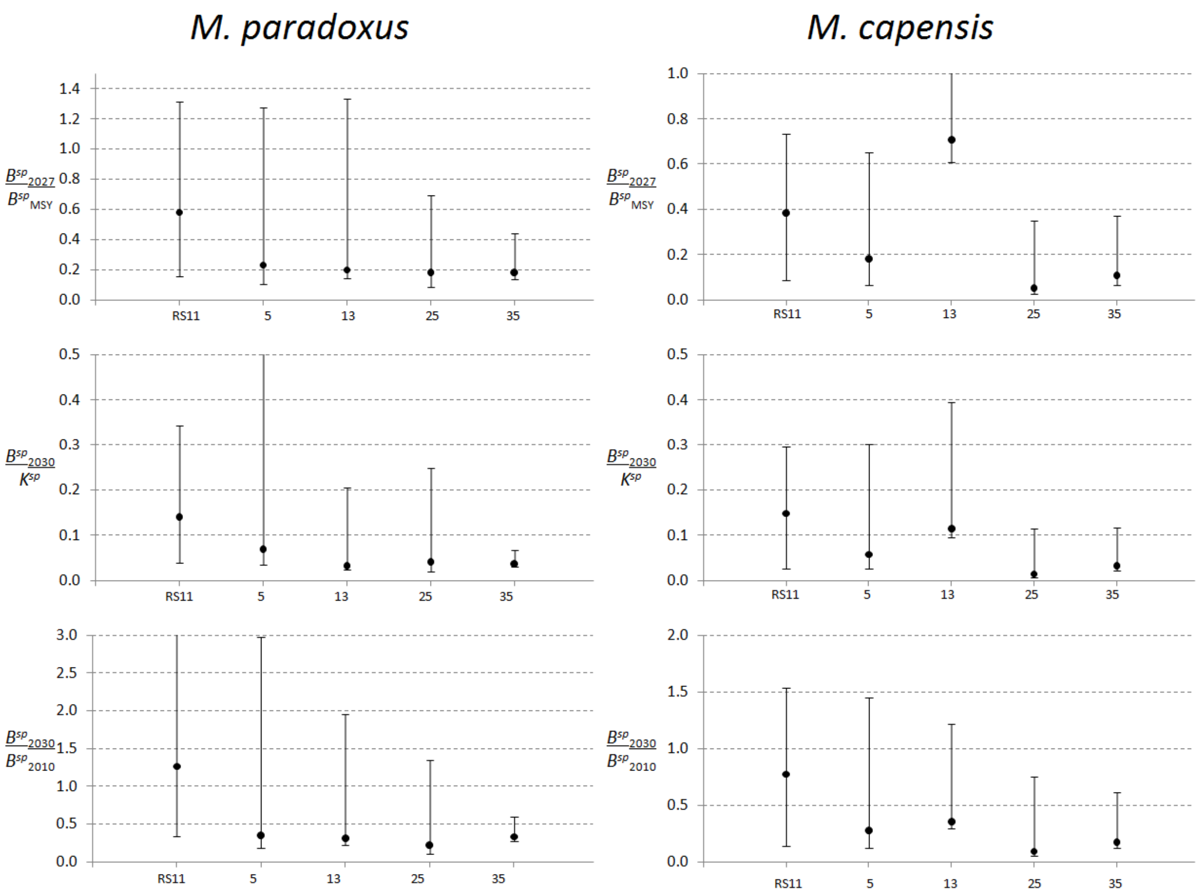


Figure 9.9 Three performance statistics ($B^{sp}_{2027}/B^{sp}_{MSY}$, B^{sp}_{2030}/K^{sp} and $B^{sp}_{2030}/B^{sp}_{2010}$, in terms of female biomass only) for *M. paradoxus* and *M. capensis* for RS11 and four robustness tests based on this OM under a projected constant catch of 150 000t.

Chapter 10

Selecting OMP-2011

Summary

This Chapter presents results for the anticipated performances of a series of illustrative Candidate Management Procedures (CMPs) for the South African hake resource for the Reference Set of trials. The final choice CMP (OMP-2011) to provide TAC recommendations for 2011 to 2014 is detailed, with associated results presented for the RS and a wide range of robustness tests. In making the final choice for OMP-2011 the Demersal Working Group focused on trade-offs related to i) future TACs compared to the risk of *M. paradoxus* depletion (together with subsequent recovery) for the Reference Set of trials and for the most difficult of the robustness tests (a decrease in carrying capacity *K* in the past), and also ii) the extent of inter-annual TAC variability.

10.1 Background

Performance statistics for a series of illustrative Candidate Management Procedures (CMPs) are evaluated for the updated Reference Set (RS) of Operating Models (OMs) as well as the associated robustness tests. The RS described in Chapter 9 consists of two parts: the primary RSa of ten OMs for which, even though there has been a decline over recent years, the current status of *M. capensis* remains above MSYL in nearly all cases and is not a concern, and RSb which comprises two OMs for which *M. capensis* is well below MSYL.

Any OMP revision exercise has to be closely linked to the objectives for the management of the resource. The objectives for the hake OMP adopted in 2006 were (see Chapter 5):

a) Improve catch rates in the short term, considered operationally as increasing the expected CPUE for the offshore trawlers by 50% over its average for the 2003-2005 period by 2016.

b) Limit inter-annual TAC variations, with an operational implementation that these not exceed 10% p.a.

c) Recover the *M. paradoxus* resource, taken operationally to mean to reach its MSYL (B^{sp}_{MSY}) by 2027.

d) Have a low probability of further decline in the *M. paradoxus* resource, taken operationally to mean that the lower 2.5%-ile of the *M. paradoxus* spawning biomass should be above the corresponding 2007 level in 2027.

These objectives were reviewed in discussions amongst stakeholders. The re-certification of the hake trawl fishery by the MSC was granted in March 2010 with a condition regarding certain aspects of the OMP revision process. In revising the objectives set for OMP-2007, some of the requirements for continued MSC certification had therefore to be taken into account.

a) In the re-certification exercise, the certification team emphasised the importance that recovery targets not be extended in time (MSC officials had also expressed concern about the length of the 20-year period set for the recovery of *M. paradoxus* to its MSYL in 2006).

b) A condition was attached to the re-certification (MSC 2010c):

> **Condition 7. Appropriate limit and target reference points for *M. paradoxus* based on stock biomass and/or fishing mortality**
>
> **Action required:** The limit reference point is the lower 95% confidence interval of the recovery trajectory in the 2006 OMP meaning the limit reference point is not a constant, but a level that will vary over time. At its lowest point, a *M. paradoxus* spawning biomass might not be low enough to trigger management override of the default OMP response, risking recruitment failure.
> SG 80 states: 'Limit and target/precautionary reference points should be justified based on stock biology (e.g. a stock-recruitment relationship) and measurable given data and assessment limitations. Reference points may be probability based'.
> It is anticipated that the OMP will undergo revision during 2010. This condition could be addressed within this planning process and thereby formally linked to the harvest control rules (OMP) that will be used to set TACs for the period of certification. The OMP revision process in 2010 should explicitly consider limit control rules with that planning evaluation.
>
> **Timescale:** Appropriate limit and target reference points enacted within one year of certification.

c) Cognisance needed to be taken of the continuing development of MSC conditions for certification. In future re-certification processes these may well include requirements along the lines of:
   i) a high probability of being above the abundance where recruitment success may be impaired (essentially synonymous with the limit reference point concept), and
   ii) where the resource is below its MSYL, recovery to MSYL should be targeted for a multiple (possibly a number in the range [2; 3]) of the time it would take to reach that level in the absence of any catches.

10.2 Operational Objectives

The MSC's particular focus has been on the status of *M. paradoxus* in terms of abundance. The following Reference Points (defined in terms of the RSa set of operating models) were therefore included in the operational objectives:

- Target Reference Point: B^{sp}_{MSY}
- Limit Reference Point: B^{sp}_{2007} (a low point on the past abundance trajectory)

The following operational objectives were used for guidance in developing CMPs to replace OMP-2007.

a) *M. paradoxus* recovery to the Maximum Sustainable Yield (MSY) level (in terms of the median under the Reference Set of operating models) should be no slower than intended under OMP-2007, and ideally should occur within a period of 2 to 3 times what would be realised in the absence of any exploitation (this MSY level - B^{sp}_{MSY} - is the Target Reference Point required to be specified under the MSC re-certification).

b) The lower 2.5%ile for the spawning biomass of *M. paradoxus* should not decrease below the 2007 level estimated by the Reference Set of models (B^{sp}_{2007} - this is the Limit Reference Point required by the MSC re-certification).

c) The lower 2.5%ile for the lowest TAC anticipated should be as high as possible for socio-economic reasons.

d) Inter-annual increases in TAC should not exceed 10% while decreases should not exceed 5% (to facilitate stability in the industry), except in circumstances where catch rates fall below specified threshold levels.

10.3 Candidate Management Procedures Testing Methodology

CMP testing is based on the simulated application of some feedback harvest control rule to different Operating Models (OMs) of the resource. It requires projections of the resource's dynamics into the future, so as to be able to simulate the impact of alternative series of future catches on the resource. Details of the projection methodology applied are provided in Appendix 10.I. The performance statistics used to compare the different CMPs are also listed in this Appendix, together with the data available to the CMPs.

10.4 Candidate Management Procedures investigated

A variety of Candidate Management Procedures (CMPs) has been considered. Appendix 10.II provides detailed technical specifications. All the CMPs tested have been of the "empirical" type – they use the resource monitoring data directly as input to simple formulae to provide TAC recommendations, rather than the “model-based” type which first filter these data through a (usually relatively simple) population dynamics model. Empirical procedures have been preferred, primarily because of their simplicity, which enhances the transparency and saleability of the MP (Butterworth 2008).

Results are given here only for a limited set of CMPs for illustrative purposes, although a large number of CMPs were investigated during the development of OMP-2011. Table 10.1a, lists the set of CMPs presented, with their control parameter values given in Table 10.1b. A series of steps and factors investigated in the process of selecting OMP-2011 are described below, with results for the illustrative CMPs under the Reference Set shown in Table 10.2.

10.4.1 Continuation of the existing OMP-2007

One option for OMP-2011 was to retain OMP-2007 for a further four years. OMP-2007 is described in detail in Chapter 5.

10.4.2 Simple CMPs based on abundance index trends

In the first step, simple CMPs based on abundance index trends were developed from a simplified version of OMP-2007. In CMPa132, the λ parameter which multiples the average trend value is not time dependent, though the target increase rate parameter T is decreased linearly to zero from 2020 to 2023 and fixed at zero thereafter, where 2020 is roughly the time by which MSYL for *M. paradoxus* has been reached so that TACs can be increased as production need no longer be set aside for resource growth. Other differences from OMP-2007 are the relative weightings of the CPUE and survey series in calculating average trends across abundance indices (see Section 10.4.2 below), and the use of coast-specific rather than coast-combined CPUE indices. The maximal +-10% TAC inter-annual change constraint of OMP-2007 is retained.

Results are shown in Table 10.2 and Figure 10.1 for a tuning to a median average TAC over 2011-2020 under RSa of 132 thousand tons. Figure 10.1 plots median and lower 2.5%ile projections for the TAC and for spawning biomass relative to the 2010 estimate for *M. paradoxus* for RSa, and for *M. capensis* for RSb. Table 10.3 lists the years in which each CMP sees MSYL reached. It indicates that OMP-2007 reaches MSYL (in median terms) for *M. paradoxus* in 2016, eight years earlier than estimated in 2006, which is a consequence of changed assumptions in the updated assessment together with improved survey and CPUE results over the past four years. CMPa132 also reaches MSYL at 2016, i.e. within two times the three years that would be taken if all fishing was immediately suspended. This falls within the range under consideration for possible future MSC certification requirements.

10.4.3 Alternative relative weightings of CPUE and survey information

OMP-2007 gave equal weighting to CPUE and survey-based abundance indices when averaging over the recent trends indicated by each to compute the trend parameter s_y^{spp} to input to its TAC formula. Table 10.4 lists the weight given to the trend estimate for each abundance index in the case of equal weighting, exact inverse variance weighting and "mid-way" weighting. Inverse variance weighting relates to the precision of the trend estimates from past values of the index concerned – the caption to Table 10.4 specifies exactly how this was computed. The “mid-way” weighting is an intermediate weighting between these two “extremes”.

Three CMPs using either equal, inverse variance or "mid-way" weighting but otherwise equivalent were tuned to give the same median average annual TAC over the next decade. Of interest is the behaviour of the risk statistics, "low para" for RSa and "low cap" for RSb: an approach that sees these as high as possible would be preferred. Performance of these three CMPs under the RS (see Table 10.5) showed that the "mid-way" weighting outperforms equal weighting in terms of risk statistics ("low para"). Although inverse variance weighting performed better still, "mid-way" weighting has been chosen to be used in all other CMPs. Why not opt for inverse variance weighting? The concern is that for various reasons CPUE may not provide an exactly comparable index of abundance over time. The three CMPs have also been applied to robustness test Rob35 for which the future CPUE data generated incorporate an undetected 2% annual increase in catchability and so provide positively biased estimates of trends in abundance. Under this scenario equal weighting provides a lower risk than mid-way weighting, for which risk is in turn less than for inverse variance weighting. Considering results for both the RS and Rob35 in combination, mid-way weighting seems to provide a reasonable compromise.

10.4.4 Include adjustments based on a target CPUE and survey value

A modification to the structure of the TAC formula for OMP-2007 and CMPa132 was investigated where in addition to recent trends in indices of abundance, the TAC is also varied in relation to how CPUE and surveys averaged over three recent years compare to a target CPUE and survey level. For CMPb132, the TAC is then adjusted up or down by an amount proportional to how far the recent abundance indices are above or below the chosen target level (see equation App.10.II.3).

Tables 10.2 and 10.3 as well as Figure 10.1 show results for CMPb132, with the tuning to a median average catch of 132 thousand tons over the next decade under RSa, as for CMPa132.

The attractive feature of CMPb132 results is the reduced range of TAC values to be expected (see Figure 10.1). Thus comparing CMPa132 and CMPb132, the latter reflects a lower 2.5%ile for the annual TAC that is more than 10 thousand tons greater than for the former. Risk in terms of “low para” under RSa is also slightly reduced (Table 10.2). However, these desirable features are achieved at the expense of a likely lesser increase and further a substantial probability of an appreciable decrease in the TAC over the next few years (Figure 10.1), which are not an attractive prospect for industry.

CMPc132 is an amalgamation of CMPa132 ("slope only") and CMPb132 ("slope+target") which seeks to retain the desirable but exclude the less desirable features of the two approaches by using the first for the first two years and then phasing linearly to the second over the next three.

Results for this phasing approach are shown in Table 10.2 and Figure 10.1, and indicate that it has eliminated the undesirable features of CMPa132’s and CMPb132’s behaviours.

10.4.5 Further penalty

Although the final one or two CMPs are checked on the complete suite of robustness tests, only a selected subset of robustness tests were used to test the CMPs routinely. To reduce the number of robustness tests to be run routinely for the CMPs, the ones that appear under constant catch projections to present the greatest challenges from a resource conservation perspective were selected to form a key set of robustness tests. A projected constant catch of 150 000t was chosen as this is more informative (in terms of the poor resource conservation performers) than a constant catch set at the current TAC.

In terms of the tests related to *M. paradoxus*, the following robustness tests were retained: for changes in the past: robustness tests Rob5 (true Ricker), Rob13 (decrease in *K*), Rob17 (start in 1978) and Rob25 (lower steepness *h*) and for changes in the future robustness tests Rob31f (case of no future surveys and an undetected catchability trend for CPUE), Rob35 (undetected catchability trend for CPUE) and Rob37 (decrease in *K*). With the exception of tests Rob31f and Rob35 for which constant catch trials do not provide a test of the variation involved, the reason for these selections is inadequate increase of spawning biomass towards its MSY level.

Robustness tests are also needed for the case when the extent of *M. capensis* depletion is estimated to be relatively high (RSb) and four robustness tests were selected to be run on RS11 (on of the RSb OMs). For changes in the past, three of the four robustness tests selected for *M. paradoxus* testing above were chosen (Rob5, Rob13 and Rob25, but not Rob17 which is of a different nature and does not show *M. capensis* to be heavily depleted), and for changes in the future, Rob37 (decrease in *K*) was selected.

This key set of more severe robustness tests were run under CMPc132, with the results shown in Table 10.6. Because this CMP does not perform well in some of these tests, an extra "safeguard" rule was added if the CPUE and surveys fall below a fixed level. Specifically the TAC is further reduced by a penalty if recent average biomass indices falls below their average value over 2006-2008, with the size of the reduction related to the magnitude of the shortfall (see Appendix 10.II for details). Furthermore, the constraint on the maximum inter-annual TAC change is loosened if the biomass indices fall too low. This is in the spirit of a limit reference point approach where additional conservation measures are taken if resource abundance drops below a specified threshold, and was investigated here as a response to the MSC's re-certification condition 7. The CMP with these further penalties is referred to as CMPd132.

The values of the control parameters (p^{spp} and Q_{min} - see Appendix 10.II) were chosen to secure a minimal effect on performance under the RS, with their impacts coming into play only at CPUE and survey values below the range expected under the RS.

Figure 10.2 focuses on test Rob13 (decrease in *K* in the past) which led to the worst performance of all in terms to *M. paradoxus* depletion under CMPc132. The lower 2.5%ile envelope for *M. paradoxus* spawning biomass, which shows continuous decline under CMPc132, has this decline reversed under CMPd132. As also evident from these same Tables and Figure, these modifications to CMPc132 hardly alter its performance under RSa, as intended.

For the other more severe robustness tests for *M. paradoxus*, changing from CMPc132 to CMPd132 improves the depletion level for *M. paradoxus* for Rob17 (start in 1978) and for Rob25 (lower steepness *h*), and also improves performance for Rob37 (future decrease in *K*) (see Table 10.6). It has little impact on Rob31f (no future surveys and an undetected catchability trend for CPUE in the future), which is not too surprising as in the absence of future surveys, the misleading upward bias in CPUE prevents the adjustment of equation App.10.II.3 coming into play.

This change from CMPc132 to CMPd132 also secures some improvement in risk-related statistics for *M. capensis* for more severe robustness tests related to RSb (see Table 10.6b).

10.4.6 TAC inter-annual change constraints

Table 10.2 shows results for CMPe132 which decreases the downward TAC change constraint to 5% (from 10%). The upward constraint remains unchanged and the loosening of the constraints if the CPUE falls too low (described above) is retained. These results indicate that the restriction of annual TAC downward changes to 10% could be reduced to 5% without compromising resource risk.

10.4.7 Tuning

To illustrate the medium-term catch *vs* recovery trade-off, three tunings were selected corresponding to median average annual TACs over the next 10 years of 127, 132 and 137 000t, corresponding in Table 10.2 to CMPe127, CMPe132 and CMPe137 respectively. Note that continued application of the existing OMP-2007 would achieve a median average annual catch of 127.4 thousand tons over the next decade (see Table 10.2).

10.4.8 Other options explored

The effect of an increase in the λ parameter multiplying average trend values in the TAC formula was investigated. The risk to the resource increased together with a substantial rise in the average annual TAC variation, so that this option was not considered further.

In the CMPs described above, the next year's TAC is based on the previous year's TAC. This approach was compared to basing next year's TAC on the average TAC over the last five years instead. Although this approach offered some advantages in terms of raising the lower 2.5%ile for future TACs (reducing variability), this was more than offset by higher risk, coupled to a median TAC trajectory that first increased and then declined over the next few years.

The imposition of a TAC cap of 160 000t was also considered but it did not provide any further risk benefits, so that this option was not pursued further.

10.5 Final OMP-2011 selection

The development of OMP-2011 involved regular consultation with stakeholders, including scientists, resource managers, industry representatives, as well as representatives of the Marine Stewardship Council. From the wide range of CMPs tested and described above, a final set of six CMPs was selected, varying along two axes: a) the level of inter-annual TAC change constraints (+10%/-10% and +10%/-5%; i.e. CMPd *vs* CMPe) and b) the median projected TAC over the next decade (127, 132 and 137 000t; i.e. CMPd/e127 *vs* 132 *vs* 137). These two axes summarise two trade-offs: the trade-off between higher TACs and higher risk of *M. paradoxus* depletion, and the trade-off in relation to inter-annual TAC variation.

10.5.1 Reference Set

Results for these six final CMPs are given in Table 10.2 for the RS. Medians and lower 2.5%iles for the TAC and for B^{sp}/B^{sp}_{2010} for *M. paradoxus* under RSa are compared in Figure 10.2. Figures 10.3a-f plot a large number of projection statistics for each of the six CMPs, with Figure 10.3g contrasting the levels of inter-annual TAC variation to be expected under the six CMPs.

Figure 10.4 plots medians and lower 2.5%iles of $B^{sp}/B^{sp}_{\mathrm{MSY}}$ for *M. paradoxus* under RSa of which consideration needs to be taken in the context of satisfying MSC-related recovery requirements. Figure 10.5 compares medians and 95%iles for a series of performance statistics under the six CMPs for the RS.

10.5.2 Robustness tests

The full set of robustness tests are listed in Chapter 9. Results for CMPe137 under this full set are given in Table 10.7, and medians and 95%iles for a series of performance statistics are plotted in Figure 10.6. Only the least conservative of the six CMPs (CMPe137) has been tested against the full set, because the other candidates would show better risk-related performances. What stands out from the comparisons in Figure 10.6 for RSa-related tests is that the risk in terms of unintended depletion of *M. paradoxus* to a low spawning biomass is much higher for test Rob13 (a decrease in *K* in the past) than for any of the other tests. This is confirmed in the Figure 7 plots of medians and lower 2.5%iles for the TAC and for B^{sp}/B^{sp}_{2010} for *M. paradoxus* for the seven most difficult of these tests based on the RC. It is only for Rob13 that there is any appreciable reduction at the lower 2.5%ile below the 2007 minimum spawning biomass for *M. paradoxus*.

For the RSb-related robustness tests (*M. capensis* in need of rebuilding) for which medians and lower 2.5%iles for the TAC and for B^{sp}/B^{sp}_{2010} for *M. capensis* are shown in Figure 10.8, median recovery rates for *M. capensis* are slow, but perhaps of most importance is that again there is scarcely any probability at the lower 2.5%ile of dropping below the 2007 spawning biomass minimum.

10.5.3 OMP-2011

In term of the inter-annual TAC variations, the stakeholders agreed on the 5% maximum downward inter-annual TAC constraint option, except in circumstances where the relevant composite biomass index falls below a threshold level in which case this maximum downward constraint could be as high as 25%. Results were judged to indicate that the larger downward constraint of 10% offered no real benefits to the resource in conservation terms, while exposing industry to greater potential socio-economic instability.

The trade-off between higher TACs and higher risk of *M. paradoxus* depletion is illustrated in Figure 10.1c at the lower 2.5%ile in relation to the *M. paradoxus* spawning biomass dropping below its current 2010 level under the RS. Figure 10.4 shows similar plots in terms of recovery to the MSY level for spawning biomass. The stakeholders agreed that the least conservative option (a median projected TAC of 137 000t over the next decade) showed inadequate recovery of *M. paradoxus* in the context of satisfying MSC-related recovery requirements for certification.

CMPe132, with a median projected TAC of 132 000 tons over the next decade, was accepted for recommendation as OMP-2011 as it was seen to reflect an appropriate compromise between speed of recovery and utilisation of the resource during that recovery period.

10.5.4 Exceptional Circumstances

Implicit in the OMP development process is the adoption of an "Exceptional Circumstances" protocol to cover situations outside the range for which the OMP was simulation tested. This document, developed by the Demersal Scientific Working Group, is reproduced in Appendix 10.III.

Unless an Exceptional Circumstance is triggered, the application of OMP-2011 will provide TAC recommendations for the period 2011-2014.

10.5.5 2011 TAC Recommendation

The 2011 TAC recommendation for the South African hake resource was computed in terms of the OMP-2011 (Appendix 10.II) as follows:

$$C_y^{spp} = w_y C_{y-1}^{*spp}\left[1+\lambda_{up/down}\left(s_y^{spp}-T_y^{spp}\right)\right]+\left(1-w_y\right)\left[a^{spp}+b^{spp}\left(J_y^{spp}-1\right)-Pen_y^{spp}\right]$$

(10.1)

The computations input a TAC of 119 800 thousand tons for 2010. As specified in the OMP, this is disaggregated by species assuming the 2009 species-split of the catches, i.e. 80.12% (95 985 tons) *M. paradoxus* and 19.88% (23 815 tons) *M. capensis* to provide the C_{y-1}^{*spp} values for equation (10.1).

The GLM-standardised CPUE series (Glazer 2010) and survey biomass abundance estimates (Fairweather and Sithole 2010) used as inputs to the OMP are shown in Table 10.7 and the resulting trends in Figure 10.10. Note that the results from surveys carried out with the *Africana* with new gear have been rescaled to take the calibration factor into account (this involves dividing new gear estimates by 0.95 for *M. paradoxus* and 0.80 for *M. capensis*), as specified in the OMP.

The recent annual trend, s_y, computed from a specified weighted average of the CPUE and survey slopes, is 10.98 % for *M. paradoxus* and 8.68% for *M. capensis*. Since $w_{2011} = 1$ and $T_{2011}^{para} = 0.75\%$, the *M. paradoxus* contribution to the TAC is:

$$C_{2012}^{para} = 95985t\left[1 + 1.25\left(10.98\% - 0.75\%\right)\right] = 108258t$$

and the *M. capensis* contribution:

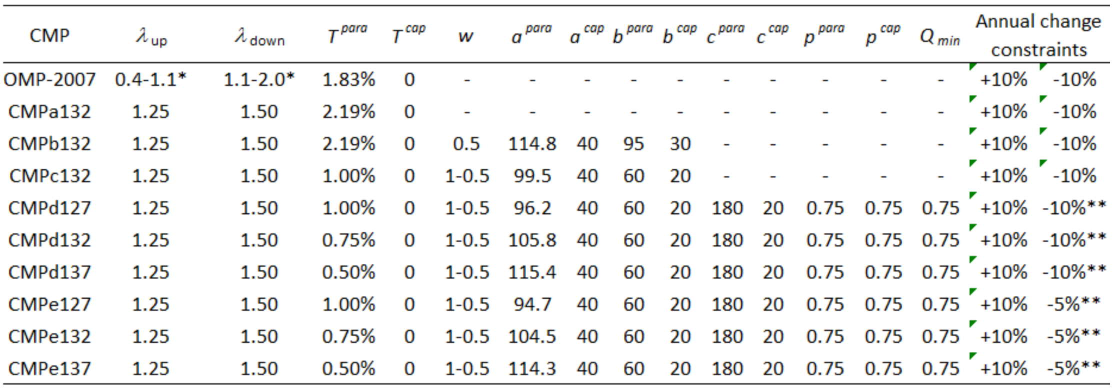
$$C_{2010}^{cap} = 23815t\left[1 + 1.25\left(8.68\% - 0\%\right)\right] = 26400t$$

The resulting value from these computations is a TAC of 134 658 tons. Due to the constraint that the TAC cannot increase by more than 10% from one year to the next, the final TAC that was recommended for 2011 was 131 780 (i.e. an increase of 10% from the 2010 level of 119 800t).

Table 10.1a: Summary of an illustrative set of CMPs.

CMP	Description	Tuned to average catch over 2011-2020	Inter-annual change constraints
OMP-2007	Slope-based only, see Appendix 5.I for details		
CMPa132	Slope-based only	132 000t	10%-10%
CMPb132	Slope- + target-based	132 000t	10%-10%
CMPc132	Phasing from slope-based only to slop- + target-based	132 000t	10%-10%
CMPd127	As CMPc132 but with extra penalty	127 000t	10%-10%
CMPd132	As CMPc132 but with extra penalty	132 000t	10%-10%
CMPd137	As CMPc132 but with extra penalty	137 000t	10%-10%
CMPe127	As CMPd132	127 000t	10%-5%
CMPe132	As CMPd132	132 000t	10%-5%
CMPe137	As CMPd132	137 000t	10%-5%

Table 10.1b: Tuning parameter values for each CMP for which performance statistics are presented. T^{para} applies up to the year 2015 and then declines linearly to zero in year 2018, except for OMP-2007, for which T^{para} applies to the whole projection period.



CMP	λ_{up}	λ_{down}	T^{para}	T^{cap}	w	a^{para}	a^{cap}	b^{para}	b^{cap}	c^{para}	c^{cap}	p^{para}	p^{cap}	Q_{min}	Annual change constraints	
OMP-2007	0.4-1.1*	1.1-2.0*	1.83%	0	-	-	-	-	-	-	-	-	-	-	+10%	-10%
CMPa132	1.25	1.50	2.19%	0	-	-	-	-	-	-	-	-	-	-	+10%	-10%
CMPb132	1.25	1.50	2.19%	0	0.5	114.8	40	95	30	-	-	-	-	-	+10%	-10%
CMPc132	1.25	1.50	1.00%	0	1-0.5	99.5	40	60	20	-	-	-	-	-	+10%	-10%
CMPd127	1.25	1.50	1.00%	0	1-0.5	96.2	40	60	20	180	20	0.75	0.75	0.75	+10%	-10%**
CMPd132	1.25	1.50	0.75%	0	1-0.5	105.8	40	60	20	180	20	0.75	0.75	0.75	+10%	-10%**
CMPd137	1.25	1.50	0.50%	0	1-0.5	115.4	40	60	20	180	20	0.75	0.75	0.75	+10%	-10%**
CMPe127	1.25	1.50	1.00%	0	1-0.5	94.7	40	60	20	180	20	0.75	0.75	0.75	+10%	-5%**
CMPe132	1.25	1.50	0.75%	0	1-0.5	104.5	40	60	20	180	20	0.75	0.75	0.75	+10%	-5%**
CMPe137	1.25	1.50	0.50%	0	1-0.5	114.3	40	60	20	180	20	0.75	0.75	0.75	+10%	-5%**

* see Appendix 5.I for details.

** can change up to -25% following equation App.10.II.12.

Table 10.2: Projections results (either median, lower or upper 2.5%ile) for a series of performance statistics for an illustrative set of CMPs under the RS. Catch units are thousand tons. The "low para $B^{sp}_{low}/B^{sp}_{2010}$" cells are shaded if values are less than 0.76 (the 2007 level); the "lowest TAC (2011-2030)" cells are shaded if less than 95 (thousand tons).

		RSa	OMP-2007	CMPa132	CMPb132	CMPc132	CMPd127	CMPd132	CMPd137	CMPe127	CMPe132	CMPe137
median	BS	avC: 2011-2020	127.4	132.0	132.0	132.0	127.0	132.0	137.0	127.0	132.0	137.0
low	para	$B^{sp}_{low}/B^{sp}_{2010}$	0.72	0.72	0.75	0.73	0.73	0.72	0.71	0.73	0.72	0.71
low	cap	$B^{sp}_{low}/B^{sp}_{2010}$	0.72	0.73	0.71	0.76	0.78	0.78	0.77	0.78	0.77	0.75
median	para	B^{sp}_{2020}/B_{MSY}	1.30	1.19	1.20	1.18	1.29	1.19	1.10	1.29	1.20	1.11
median	cap	B^{sp}_{2020}/B_{MSY}	2.93	2.91	2.91	2.90	2.93	2.89	2.87	2.93	2.90	2.87
median	BS	AAV	4.2	4.6	4.2	3.4	3.7	3.7	3.8	3.5	3.5	3.6
low	BS	lowest TAC (2011-2030)	88.7	86.6	98.4	101.0	89.7	94.9	99.7	87.8	91.9	94.5
	BS	Prob decl >20% (2011-2013)	2.6	1.6	0.4	0.9	0.2	0.2	0.1	1.5	1.5	1.3
	BS	Prob decl >20% (2012-2014)	4.4	5.0	0.0	0.6	1.1	1.2	1.0	1.6	1.4	1.4
median	BS	Pdecl>20% (2011-2028)	0.0	5.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
high	BS	Pdecl>20% (2011-2028)	16.7	27.8	16.7	11.1	0.0	0.1	5.6	5.6	5.6	5.6
		RSb										
median	BS	avC: 2011-2015	122.0	125.1	126.3	126.8	121.8	126.7	131.6	120.6	125.6	130.5
low	para	$B^{sp}_{low}/B^{sp}_{2010}$	0.95	0.94	0.95	0.93	0.93	0.93	0.93	0.93	0.93	0.93
low	cap	$B^{sp}_{low}/B^{sp}_{2010}$	0.88	0.85	0.88	0.84	0.87	0.84	0.80	0.87	0.85	0.80
median	para	B^{sp}_{2020}/B_{MSY}	1.04	0.97	1.00	0.94	1.00	0.95	0.88	1.04	0.96	0.89
median	cap	B^{sp}_{2020}/B_{MSY}	0.60	0.58	0.58	0.56	0.58	0.56	0.54	0.60	0.57	0.55
median	BS	AAV	4.3	4.3	3.9	3.2	3.6	3.4	3.4	3.6	3.4	3.5
low	BS	lowest TAC (2011-2030)	87.1	88.8	97.5	100.0	84.2	87.7	99.4	75.3	84.5	86.1
	BS	Prob decl >20% (2011-2013)	3.0	2.5	1.0	1.0	1.0	0.0	0.0	3.5	3.5	3.0
	BS	Prob decl >20% (2012-2014)	10.5	10.0	0.0	2.5	2.0	2.0	2.0	9.0	7.0	3.0
median	BS	Pdecl>20% (2011-2028)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
high	BS	Pdecl>20% (2011-2028)	16.7	22.2	16.7	11.1	5.6	5.6	5.6	11.1	11.1	5.6

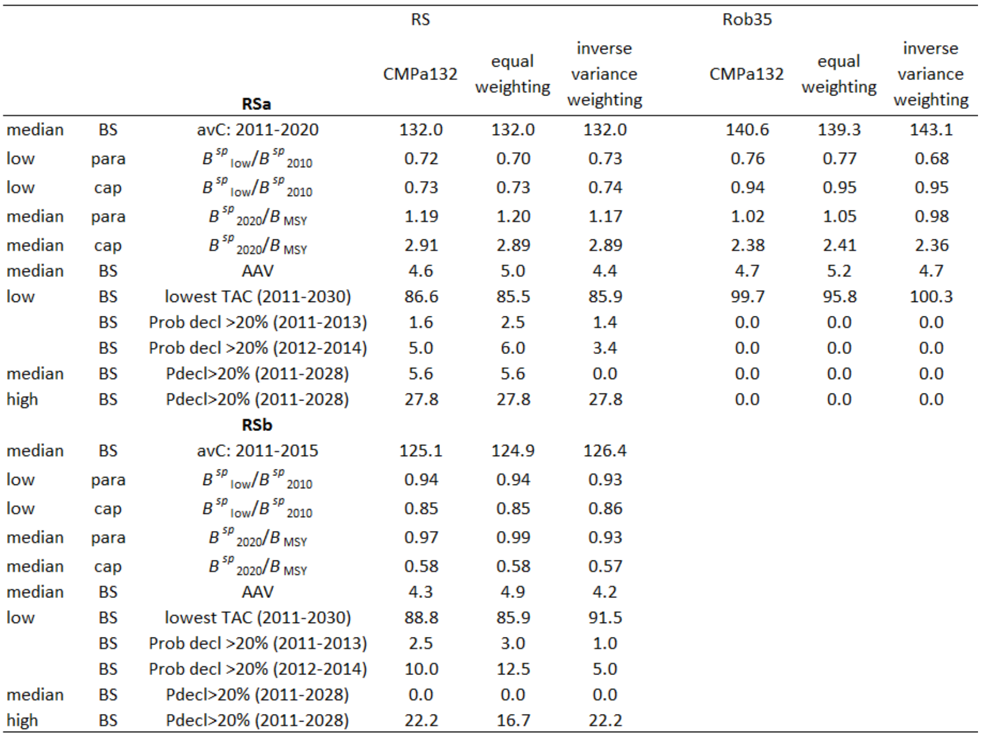
Table 10.3: Year in which the *M. paradoxus* spawning biomass is expected (in median terms) to first exceed B_{MSY} for a catch of zero and a series of CMPs for RSa. OMP-2007* is as applied in 2006 (i.e. to the 2006 RS), while OMP-2007 has been run under the current RSa.

CMP	Year *M. paradoxus* spawning biomass > B_{MSY}
Catch = 0	2013
OMP-2007*	2024
OMP-2007	2016
CMPa132	2016
CMPb132	2015
CMPc132	2015
CMPd132	2017
CMPe127	2016
CMPe132	2017
CMPe137	2017

Table 10.4: Weighting of the CPUE and survey series when computing s_y^{spp}, the measure of immediate past trend in the abundance indices. The variances for the various trend estimates were obtained from empirical estimates of variance for the slope in the log-linear fit of a trend to five successive points of the series in question. An average was taken over five such estimates: that for the most recent 5 years, and for CPUE those for such periods set earlier by one, two, three of four years. For surveys the set back was only up to three years for the West Coast, and two years for the South Coast, because of years without *Africana* surveys in the early 2000s.

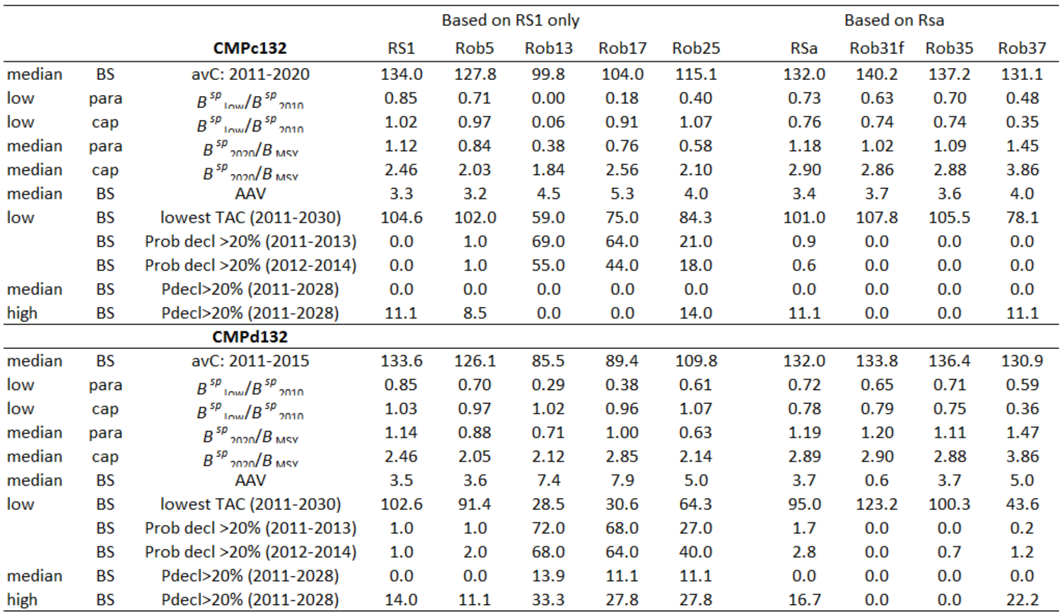
		Equal Weigthing	Inverse variance weighting	Mid-way weighting
CPUE				
M. paradoxus	WC	1.00	1.00	1.00
	SC	1.00	0.40	0.75
M. capensis	WC	1.00	1.00	1.00
	SC	1.00	0.40	0.75
Survey				
M. paradoxus	WC	1.00	0.20	0.50
	SC	1.00	0.02	0.25
M. capensis	WC	1.00	0.20	0.50
	SC	1.00	1.00	1.00

Table 10.5: Projection results for a series of performance statistics for CMPa132, CMPa132 with equal weighting of the CPUE and survey series in the slope calculation ("equal weighting") and CMPa132 with exact inverse variance weighting ("inverse variance weighting"). These results are presented for the RS and Rob35 (undetected 2% p.a. increase in catchability related to CPUE in the future).



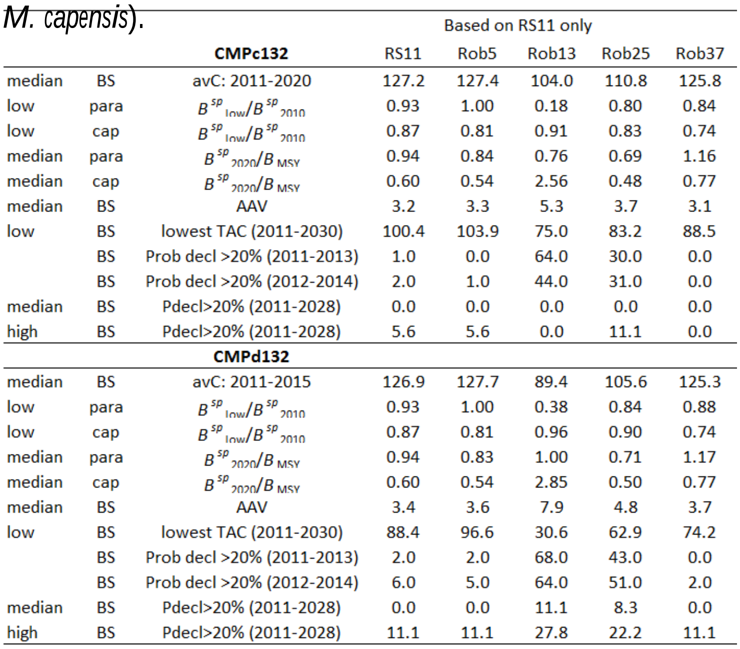
			RS			Rob35		
		RSa	CMPa132	equal weighting	inverse variance weighting	CMPa132	equal weighting	inverse variance weighting
median	BS	avC: 2011-2020	132.0	132.0	132.0	140.6	139.3	143.1
low	para	$B^{sp}_{low}/B^{sp}_{2010}$	0.72	0.70	0.73	0.76	0.77	0.68
low	cap	$B^{sp}_{low}/B^{sp}_{2010}$	0.73	0.73	0.74	0.94	0.95	0.95
median	para	B^{sp}_{2020}/B_{MSY}	1.19	1.20	1.17	1.02	1.05	0.98
median	cap	B^{sp}_{2020}/B_{MSY}	2.91	2.89	2.89	2.38	2.41	2.36
median	BS	AAV	4.6	5.0	4.4	4.7	5.2	4.7
low	BS	lowest TAC (2011-2030)	86.6	85.5	85.9	99.7	95.8	100.3
	BS	Prob decl >20% (2011-2013)	1.6	2.5	1.4	0.0	0.0	0.0
	BS	Prob decl >20% (2012-2014)	5.0	6.0	3.4	0.0	0.0	0.0
median	BS	Pdecl>20% (2011-2028)	5.6	5.6	0.0	0.0	0.0	0.0
high	BS	Pdecl>20% (2011-2028)	27.8	27.8	27.8	0.0	0.0	0.0
		RSb						
median	BS	avC: 2011-2015	125.1	124.9	126.4			
low	para	$B^{sp}_{low}/B^{sp}_{2010}$	0.94	0.94	0.93			
low	cap	$B^{sp}_{low}/B^{sp}_{2010}$	0.85	0.85	0.86			
median	para	B^{sp}_{2020}/B_{MSY}	0.97	0.99	0.93			
median	cap	B^{sp}_{2020}/B_{MSY}	0.58	0.58	0.57			
median	BS	AAV	4.3	4.9	4.2			
low	BS	lowest TAC (2011-2030)	88.8	85.9	91.5			
	BS	Prob decl >20% (2011-2013)	2.5	3.0	1.0			
	BS	Prob decl >20% (2012-2014)	10.0	12.5	5.0			
median	BS	Pdecl>20% (2011-2028)	0.0	0.0	0.0			
high	BS	Pdecl>20% (2011-2028)	22.2	16.7	22.2			

Table 10.6a: Projections results (either median or lower 2.5%ile: “low”) for a series of performance statistics for CMPc132 and CMPd132 for a series of more severe robustness tests related to *M. paradoxus* (Rob5 (true Ricker), Rob13 (decrease in *K* in the past), Rob17 (start in 1978), Rob25 (lower steepness *h*), Rob31f (case of no survey and an undetected catchability trend for CPUE in the future - the surveys are used in the computation of the slope until more than two data points (out of six) are missing for the regression.), Rob35 (undetected catchability trend for CPUE in the future) and Rob37 (future decrease in *K*)) under RS1 and RSa.



			Based on RS1 only					Based on Rsa			
		CMPc132	RS1	Rob5	Rob13	Rob17	Rob25	RSa	Rob31f	Rob35	Rob37
median	BS	avC: 2011-2020	134.0	127.8	99.8	104.0	115.1	132.0	140.2	137.2	131.1
low	para	$B^{sp}_{low}/B^{sp}_{2010}$	0.85	0.71	0.00	0.18	0.40	0.73	0.63	0.70	0.48
low	cap	$B^{sp}_{low}/B^{sp}_{2010}$	1.02	0.97	0.06	0.91	1.07	0.76	0.74	0.74	0.35
median	para	B^{sp}_{2020}/B_{MSY}	1.12	0.84	0.38	0.76	0.58	1.18	1.02	1.09	1.45
median	cap	B^{sp}_{2020}/B_{MSY}	2.46	2.03	1.84	2.56	2.10	2.90	2.86	2.88	3.86
median	BS	AAV	3.3	3.2	4.5	5.3	4.0	3.4	3.7	3.6	4.0
low	BS	lowest TAC (2011-2030)	104.6	102.0	59.0	75.0	84.3	101.0	107.8	105.5	78.1
	BS	Prob decl >20% (2011-2013)	0.0	1.0	69.0	64.0	21.0	0.9	0.0	0.0	0.0
	BS	Prob decl >20% (2012-2014)	0.0	1.0	55.0	44.0	18.0	0.6	0.0	0.0	0.0
median	BS	Pdecl>20% (2011-2028)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
high	BS	Pdecl>20% (2011-2028)	11.1	8.5	0.0	0.0	14.0	11.1	0.0	0.0	11.1
		CMPd132									
median	BS	avC: 2011-2015	133.6	126.1	85.5	89.4	109.8	132.0	133.8	136.4	130.9
low	para	$B^{sp}_{low}/B^{sp}_{2010}$	0.85	0.70	0.29	0.38	0.61	0.72	0.65	0.71	0.59
low	cap	$B^{sp}_{low}/B^{sp}_{2010}$	1.03	0.97	1.02	0.96	1.07	0.78	0.79	0.75	0.36
median	para	B^{sp}_{2020}/B_{MSY}	1.14	0.88	0.71	1.00	0.63	1.19	1.20	1.11	1.47
median	cap	B^{sp}_{2020}/B_{MSY}	2.46	2.05	2.12	2.85	2.14	2.89	2.90	2.88	3.86
median	BS	AAV	3.5	3.6	7.4	7.9	5.0	3.7	0.6	3.7	5.0
low	BS	lowest TAC (2011-2030)	102.6	91.4	28.5	30.6	64.3	95.0	123.2	100.3	43.6
	BS	Prob decl >20% (2011-2013)	1.0	1.0	72.0	68.0	27.0	1.7	0.0	0.0	0.2
	BS	Prob decl >20% (2012-2014)	1.0	2.0	68.0	64.0	40.0	2.8	0.0	0.7	1.2
median	BS	Pdecl>20% (2011-2028)	0.0	0.0	13.9	11.1	11.1	0.0	0.0	0.0	0.0
high	BS	Pdecl>20% (2011-2028)	14.0	11.1	33.3	27.8	27.8	16.7	0.0	0.0	22.2

Table 10.6b: Projections results (either median or lower 2.5%ile) for a series of performance statistics for a series of more severe robustness tests under RS11 (related to *M. capensis*).



			Based on RS11 only				
		CMPc132	RS11	Rob5	Rob13	Rob25	Rob37
median	BS	avC: 2011-2020	127.2	127.4	104.0	110.8	125.8
low	para	$B^{sp}_{low}/B^{sp}_{2010}$	0.93	1.00	0.18	0.80	0.84
low	cap	$B^{sp}_{low}/B^{sp}_{2010}$	0.87	0.81	0.91	0.83	0.74
median	para	B^{sp}_{2020}/B_{MSY}	0.94	0.84	0.76	0.69	1.16
median	cap	B^{sp}_{2020}/B_{MSY}	0.60	0.54	2.56	0.48	0.77
median	BS	AAV	3.2	3.3	5.3	3.7	3.1
low	BS	lowest TAC (2011-2030)	100.4	103.9	75.0	83.2	88.5
	BS	Prob decl >20% (2011-2013)	1.0	0.0	64.0	30.0	0.0
	BS	Prob decl >20% (2012-2014)	2.0	1.0	44.0	31.0	0.0
median	BS	Pdecl>20% (2011-2028)	0.0	0.0	0.0	0.0	0.0
high	BS	Pdecl>20% (2011-2028)	5.6	5.6	0.0	11.1	0.0
		CMPd132					
median	BS	avC: 2011-2015	126.9	127.7	89.4	105.6	125.3
low	para	$B^{sp}_{low}/B^{sp}_{2010}$	0.93	1.00	0.38	0.84	0.88
low	cap	$B^{sp}_{low}/B^{sp}_{2010}$	0.87	0.81	0.96	0.90	0.74
median	para	B^{sp}_{2020}/B_{MSY}	0.94	0.83	1.00	0.71	1.17
median	cap	B^{sp}_{2020}/B_{MSY}	0.60	0.54	2.85	0.50	0.77
median	BS	AAV	3.4	3.6	7.9	4.8	3.7
low	BS	lowest TAC (2011-2030)	88.4	96.6	30.6	62.9	74.2
	BS	Prob decl >20% (2011-2013)	2.0	2.0	68.0	43.0	0.0
	BS	Prob decl >20% (2012-2014)	6.0	5.0	64.0	51.0	2.0
median	BS	Pdecl>20% (2011-2028)	0.0	0.0	11.1	8.3	0.0
high	BS	Pdecl>20% (2011-2028)	11.1	11.1	27.8	22.2	11.1

Table 10.7a: Projections results (either median, lower or upper “high” 2.5%ile) for a series of performance statistics for CMPe137 under the full set of robustness tests based on the RC. The "low para $B^{sp}_{low}/B^{sp}_{2010}$" cells are shaded if values are less than 0.7 (the 2007 level); the "lowest TAC (2011-2030)" cells are shaded if less than 95 (thousand tons).

			RS1	Rob1	Rob2	Rob3	Rob4	Rob5	Rob6	Rob7	Rob8	Rob9
median	BS	avC: 2011-2020	138.2	131.0	131.4	133.3	141.1	130.9	138.2	141.1	146.2	159.3
low	para	$B^{sp}_{low}/B^{sp}_{2010}$	0.83	0.92	0.59	0.85	1.01	0.69	0.95	0.86	0.89	0.84
low	cap	$B^{sp}_{low}/B^{sp}_{2010}$	0.98	1.02	1.01	1.00	1.03	0.96	0.93	0.99	0.80	0.82
median	para	B^{sp}_{2020}/B_{MSY}	1.05	1.58	1.00	2.21	0.82	0.80	1.06	1.10	0.75	0.70
median	cap	B^{sp}_{2020}/B_{MSY}	2.41	5.32	4.13	4.41	2.43	2.00	2.32	2.36	2.34	1.95
median	BS	AAV	3.5	3.7	3.6	3.6	3.4	3.5	3.3	3.6	4.2	4.6
low	BS	lowest TAC (2011-2030)	105.6	92.1	97.4	100.4	116.3	97.1	111.3	112.6	107.4	117.2
	BS	Prob decl >20% (2011-2013)	0.0	4.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0
	BS	Prob decl >20% (2012-2014)	0.0	3.0	2.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0
median	BS	Pdecl>20% (2011-2028)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
high	BS	Pdecl>20% (2011-2028)	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1

			RS1	Rob10	Rob11	Rob12a	Rob12b	Rob12c	Rob12d	Rob13	Rob14	Rob15
median	BS	avC: 2011-2020	138.2	142.3	139.8	135.9	137.6	139.6	137.8	87.9	150.7	131.0
low	para	$B^{sp}_{low}/B^{sp}_{2010}$	0.83	0.75	0.88	0.87	0.85	0.76	0.80	0.26	0.80	0.69
low	cap	$B^{sp}_{low}/B^{sp}_{2010}$	0.98	0.59	1.03	0.94	0.92	0.80	0.93	1.02	0.83	0.88
median	para	B^{sp}_{2020}/B_{MSY}	1.05	1.12	1.04	1.06	1.12	1.01	0.99	0.72	1.15	1.07
median	cap	B^{sp}_{2020}/B_{MSY}	2.41	1.11	2.64	1.82	1.90	2.13	2.38	2.11	1.92	2.03
median	BS	AAV	3.5	3.9	3.5	3.6	3.6	3.5	3.5	7.6	4.0	3.5
low	BS	lowest TAC (2011-2030)	105.6	93.9	109.0	99.7	102.6	109.1	106.3	31.4	113.0	96.3
	BS	Prob decl >20% (2011-2013)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	71.0	0.0	0.0
	BS	Prob decl >20% (2012-2014)	0.0	0.0	0.0	1.0	0.0	0.0	0.0	66.0	0.0	0.0
median	BS	Pdecl>20% (2011-2028)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0
high	BS	Pdecl>20% (2011-2028)	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.3	0.1	0.0

			RS1	Rob16	Rob17	Rob18	Rob19a	Rob19b	Rob19c	Rob20a	Rob20b	Rob20c
median	BS	avC: 2011-2020	138.2	142.7	155.2	145.1	145.2	145.6	133.5	138.6	137.4	138.7
low	para	$B^{sp}_{low}/B^{sp}_{2010}$	0.83	1.00	0.80	0.79	0.83	0.78	0.87	0.83	0.83	0.79
low	cap	$B^{sp}_{low}/B^{sp}_{2010}$	0.98	1.05	0.82	0.94	1.00	0.88	1.02	0.98	0.97	0.98
median	para	B^{sp}_{2020}/B_{MSY}	1.05	0.85	1.06	1.33	1.03	0.97	1.27	1.05	1.06	0.96
median	cap	B^{sp}_{2020}/B_{MSY}	2.41	3.76	1.90	2.12	1.99	1.84	2.52	2.42	2.38	2.41
median	BS	AAV	3.5	3.4	4.3	3.7	3.6	3.8	3.5	3.5	3.6	3.6
low	BS	lowest TAC (2011-2030)	105.6	117.2	119.3	113.3	118.9	115.8	90.8	106.4	103.9	105.5
	BS	Prob decl >20% (2011-2013)	0.0	0.0	0.0	0.0	0.0	0.0	5.0	0.0	0.0	0.0
	BS	Prob decl >20% (2012-2014)	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0	1.0	0.0
median	BS	Pdecl>20% (2011-2028)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
high	BS	Pdecl>20% (2011-2028)	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0

			RS1	Rob21	Rob22	Rob23	Rob24a	Rob24b	Rob25	Rob26	Rob27	Rob28
median	BS	avC: 2011-2020	138.2	141.4	152.6	136.6	138.0	138.3	115.2	153.5	140.2	146.1
low	para	$B^{sp}_{low}/B^{sp}_{2010}$	0.83	0.78	0.62	0.86	0.84	0.82	0.53	0.74	0.84	0.87
low	cap	$B^{sp}_{low}/B^{sp}_{2010}$	0.98	0.89	0.79	1.00	0.98	0.98	1.07	1.00	0.97	0.94
median	para	B^{sp}_{2020}/B_{MSY}	1.05	1.06	0.83	1.10	1.05	1.05	0.58	1.23	1.14	1.14
median	cap	B^{sp}_{2020}/B_{MSY}	2.41	1.60	1.15	1.92	2.35	2.48	2.11	2.47	2.55	1.85
median	BS	AAV	3.5	3.8	4.3	3.5	3.5	3.6	4.5	4.0	3.6	3.9
low	BS	lowest TAC (2011-2030)	105.6	101.5	114.8	103.1	105.3	105.8	69.4	122.1	110.0	117.9
	BS	Prob decl >20% (2011-2013)	0.0	0.0	0.0	0.0	0.0	0.0	6.0	0.0	0.0	0.0
	BS	Prob decl >20% (2012-2014)	0.0	0.0	0.0	0.0	0.0	0.0	8.0	0.0	0.0	0.0
median	BS	Pdecl>20% (2011-2028)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
high	BS	Pdecl>20% (2011-2028)	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.0

			RS1	Rob29	Rob34a	Rob34b	Rob35	Rob36a	Rob36b	Rob36c	Rob37	Rob38
median	BS	avC: 2011-2020	138.2	139.4	138.0	138.6	142.5	142.4	139.3	140.8	137.3	138.2
low	para	$B^{sp}_{low}/B^{sp}_{2010}$	0.83	0.80	0.82	0.84	0.74	0.93	0.85	0.88	0.52	0.83
low	cap	$B^{sp}_{low}/B^{sp}_{2010}$	0.98	1.04	1.00	0.96	0.95	1.06	1.01	1.03	0.49	0.98
median	para	B^{sp}_{2020}/B_{MSY}	1.05	0.98	1.02	1.09	0.97	1.25	1.11	1.18	1.31	1.05
median	cap	B^{sp}_{2020}/B_{MSY}	2.41	2.53	2.46	2.34	2.37	2.75	2.60	2.67	3.12	2.41
median	BS	AAV	3.5	3.6	3.6	3.5	3.6	3.6	3.6	3.6	6.0	3.5
low	BS	lowest TAC (2011-2030)	105.6	106.0	105.4	105.9	115.0	113.1	107.2	109.8	45.2	105.6
	BS	Prob decl >20% (2011-2013)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	BS	Prob decl >20% (2012-2014)	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
median	BS	Pdecl>20% (2011-2028)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
high	BS	Pdecl>20% (2011-2028)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0

Table 10.7b: Projections results (either median, lower or upper 2.5%ile) for a series of performance statistics for CMPe137 under the full set of robustness tests based on RS11 (*M. capensis* in need of rebuilding). The "low para $B^{sp}_{low}/B^{sp}_{2010}$" cells are shaded if values are less than 0.7 (the 2007 level); the "lowest TAC (2011-2030)" cells are shaded if less than 95 (thousand tons).

			RS11	Rob5	Rob13	Rob25	Rob37
median	BS	avC: 2011-2020	130.6	132.0	90.0	128.9	128.9
low	para	$B^{sp}_{low}/B^{sp}_{2010}$	0.93	1.00	0.38	0.78	0.78
low	cap	$B^{sp}_{low}/B^{sp}_{2010}$	0.84	0.75	0.92	0.69	0.69
median	para	B^{sp}_{2020}/B_{MSY}	0.89	0.78	0.99	1.10	1.10
median	cap	B^{sp}_{2020}/B_{MSY}	0.58	0.52	2.85	0.74	0.74
median	BS	AAV	3.5	3.4	8.2	4.4	4.4
low	BS	lowest TAC (2011-2030)	87.2	96.0	36.5	61.5	61.5

Table 10.8: GLM-standardised CPUE series (Glazer 2010) and survey abundance estimates (Fairweather and Sithole 2010) used as input in the 2011 TAC computation. The abundance estimates shaded are for surveys that have been conducted with the new gear on the *F.R.S. Africana*.

	M. paradoxus				*M. capensis*			
	West Coast CPUE	South Coast CPUE	West coast summer survey	South Coast autumn survey	West Coast CPUE	South Coast CPUE	West coast summer survey	South Coast autumn survey
2004	2.0610	1.3252			0.8383	1.9092		
2005	2.2117	1.3150	286.42	26.61	0.4944	1.5028	70.98	76.93
2006	2.3641	1.3678	315.31	34.80	0.5640	1.1991	88.42	130.90
2007	2.7567	1.4412	392.81	129.65	0.5972	1.0488	82.27	70.94
2008	3.4236	1.3913	246.54	39.51	0.5028	1.6515	50.88	108.20
2009	3.6006	1.6309	330.24	102.83	1.0335	3.0417	175.29	124.00
2010			592.57	169.56			164.66	184.96

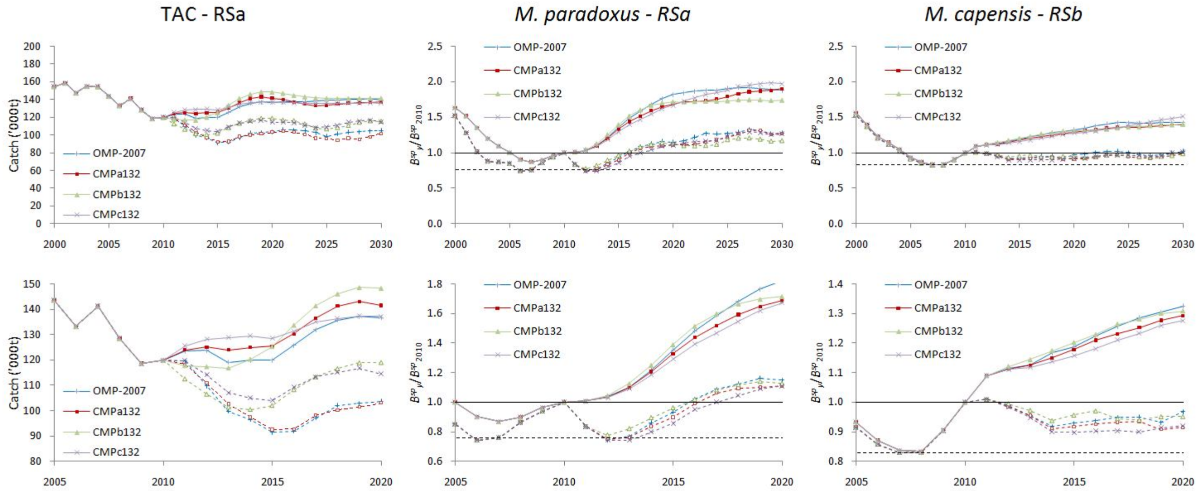


Figure 10.1a: Median (full lines) and lower 2.5%iles (dashed lines) TAC (RSa) and spawning biomass (in terms of 2010 level) for *M. paradoxus* (RSa) and *M. capensis* (RSb) for OMP-2007, CMPa132, CMPb132 and CMPc132. The horizontal dashed line shows the 2007 level. Here and in plots below, the bottom row repeats the top row, but with different scales for improved discrimination.

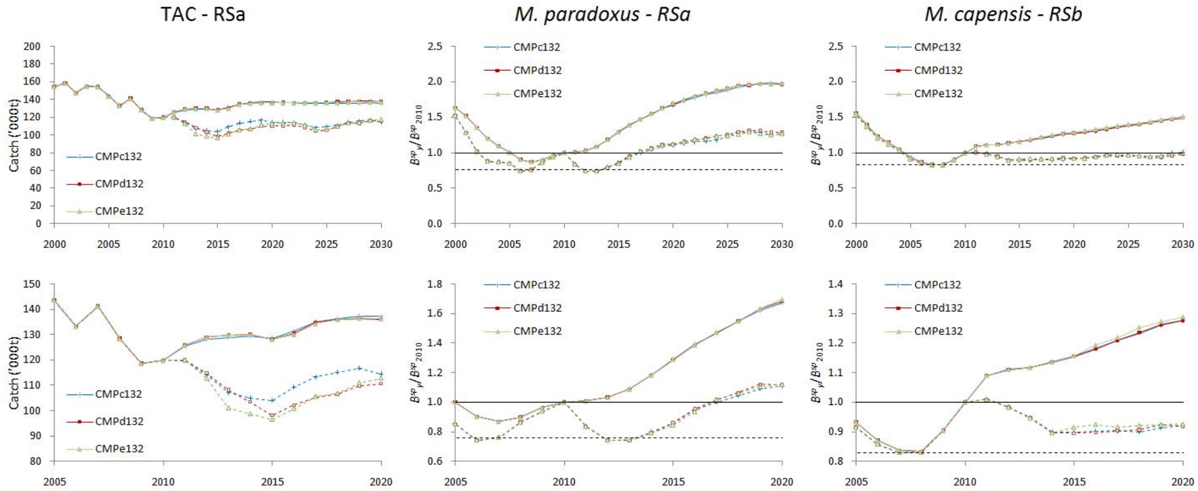


Figure 10.1b: Median (full lines) and lower 2.5%iles (dashed lines) TAC (RSa) and spawning biomass (in terms of 2010 level) for *M. paradoxus* (RSa) and *M. capensis* (RSb) for CMPc132, CMPd132 and CMPe132. The horizontal dashed line shows the 2007 level.

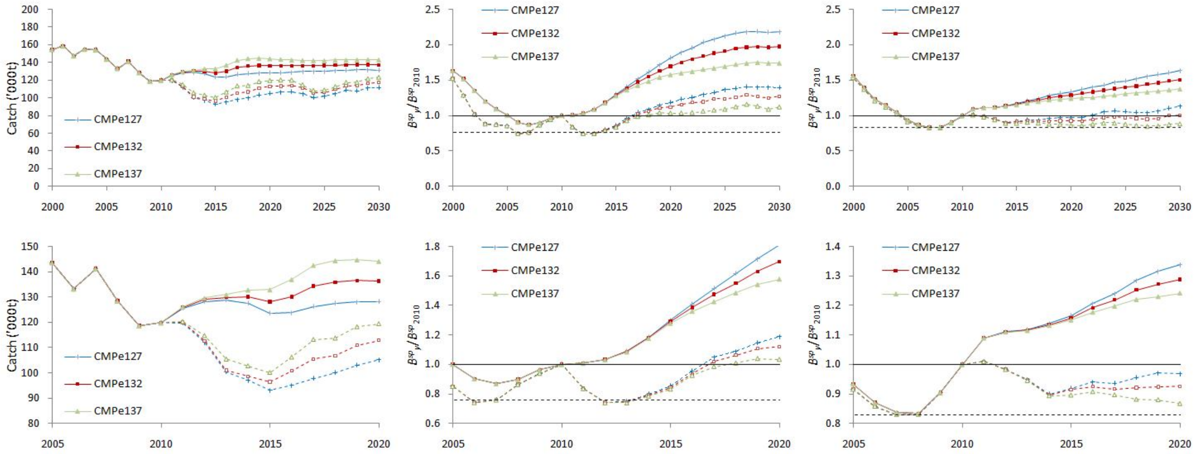


Figure 10.1c: Median (full lines) and lower 2.5%iles (dashed lines) TAC (RSa) and spawning biomass (in terms of 2010 level) for *M. paradoxus* (RSa) and *M. capensis* (RSb) for CMPe127, CMPe132 and CMPe137. The horizontal dashed line shows the 2007 level.

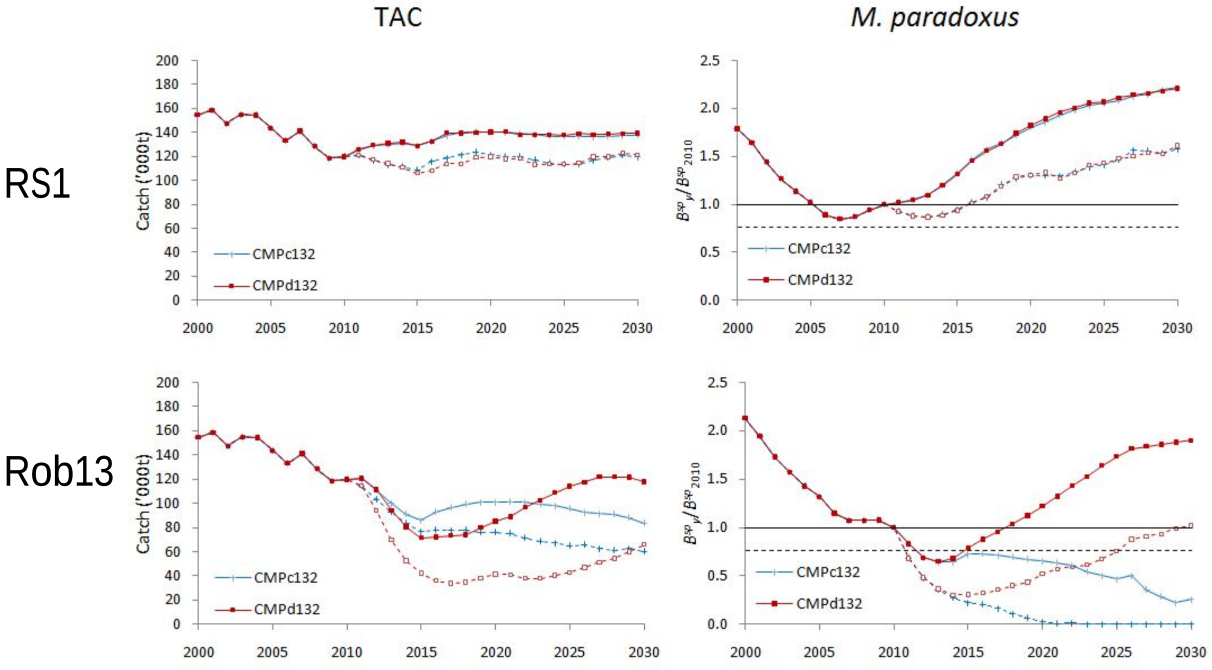


Figure 10.2: Median (full lines) and lower 2.5%iles (dashed lines) TAC and spawning biomass (in terms of 2010 level) for *M. paradoxus* for CMPc132 (no extra penalty) and CMPd132 (with extra penalty) under RS1 and the most severe robustness test, also based on RS1, Rob13 (decrease in *K* in the past).

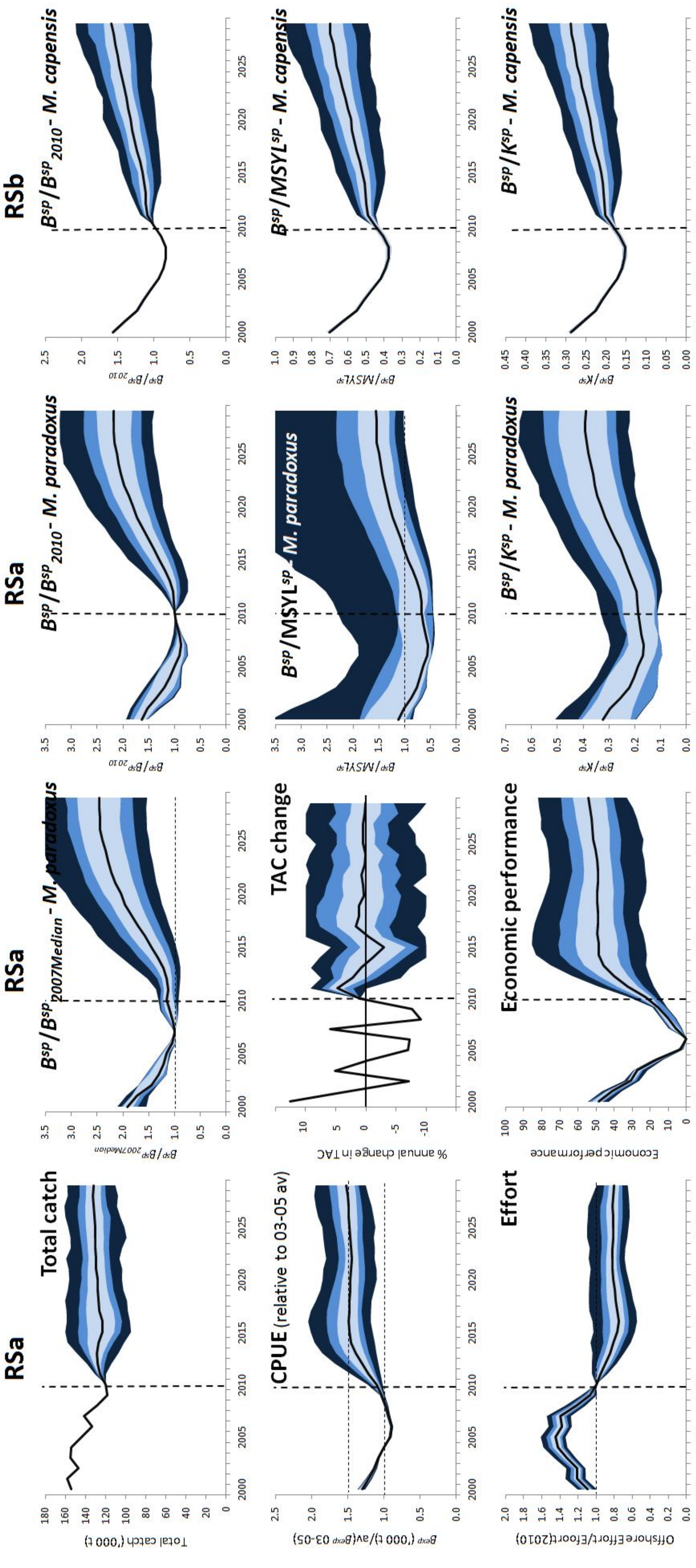
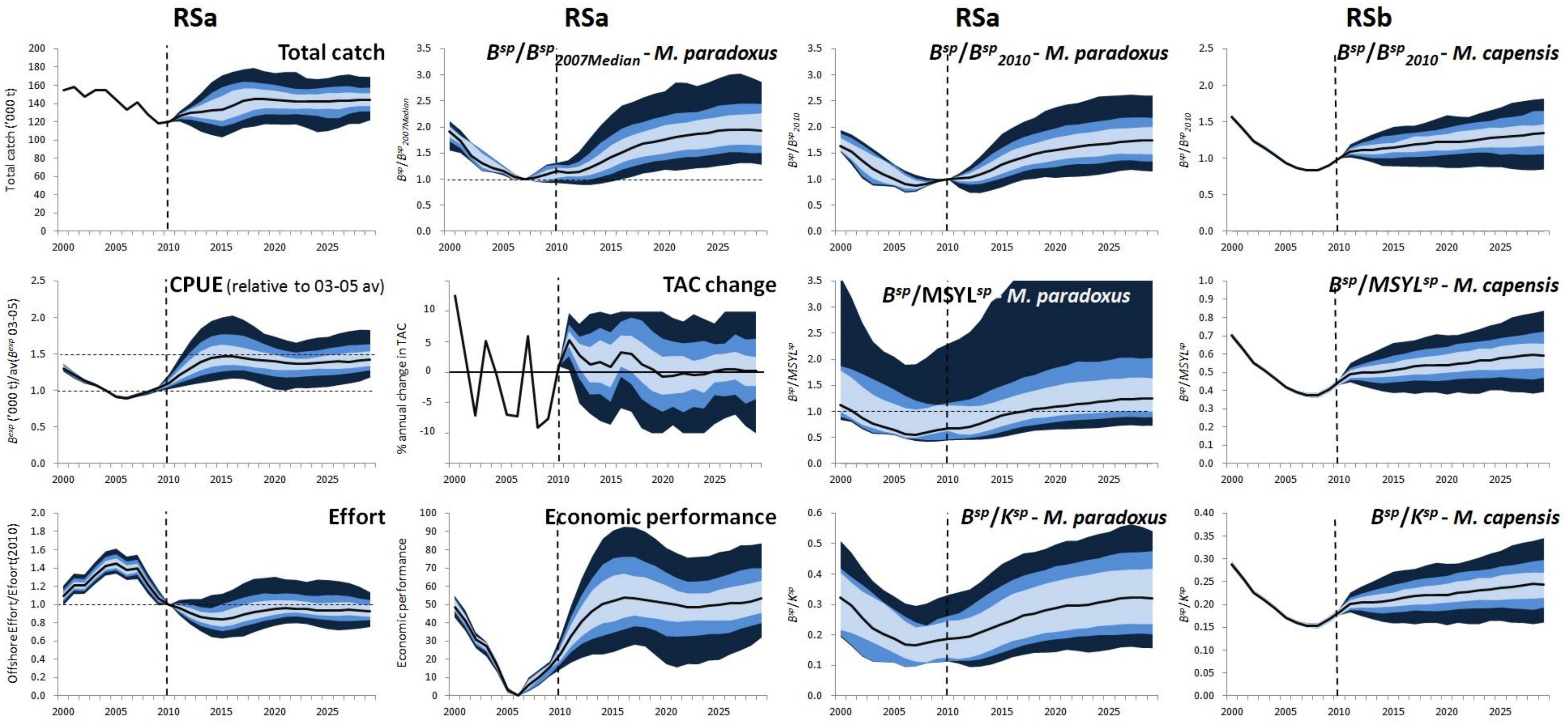


Figure 10.3a: 95, 75, 50% PI and median for a series of performance statistics for **CMPd127**.

Figure 10.3b: 95, 75, 50% PI and median for a series of performance statistics for **CMPd132**.



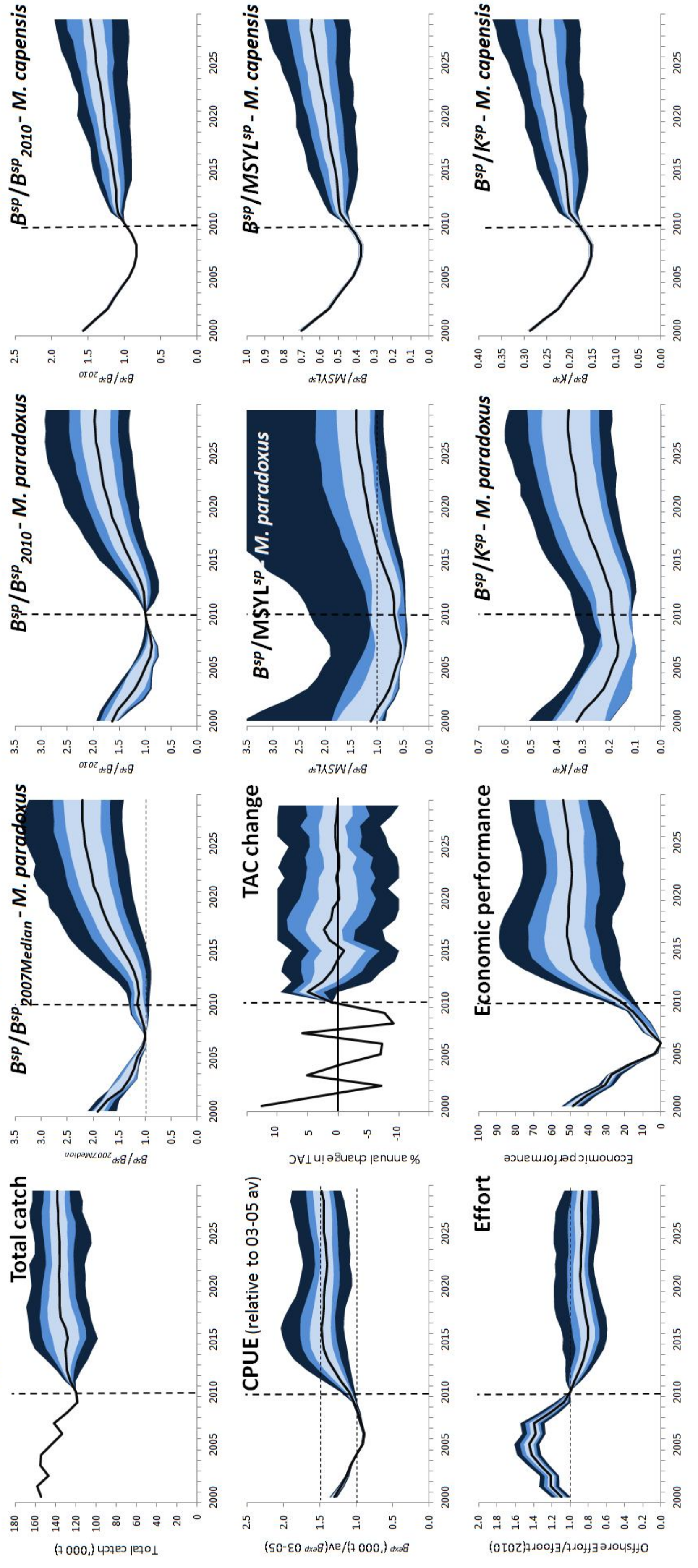


Figure 10.3c: 95, 75, 50% PI envelopes and medians for a series of performance statistics for **CMPd137**.

Figure 10.3d: 95, 75, 50% PI envelopes and medians for a series of performance statistics for **CMPe127**.

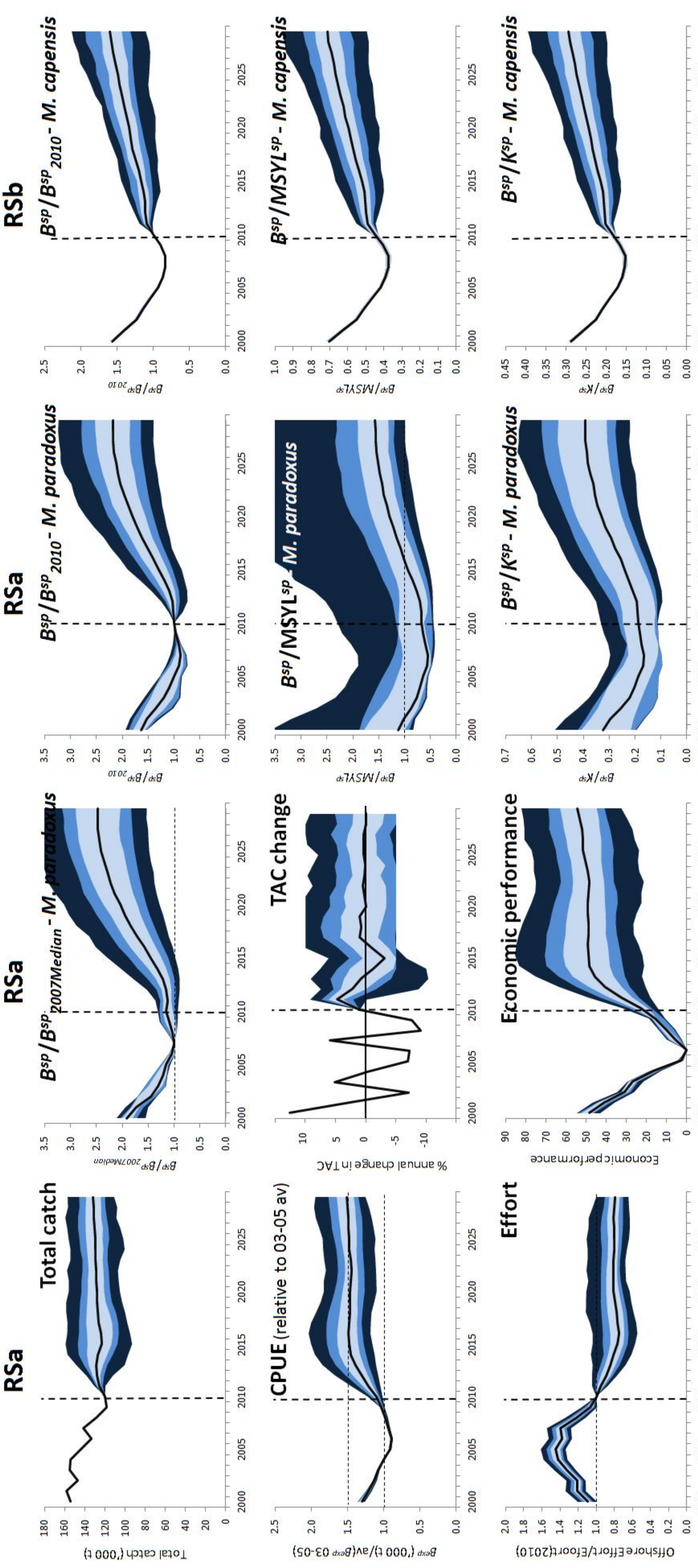


Figure 10.3e: 95, 75, 50% PI envelopes and medians for a series of performance statistics for **CMPe132**.

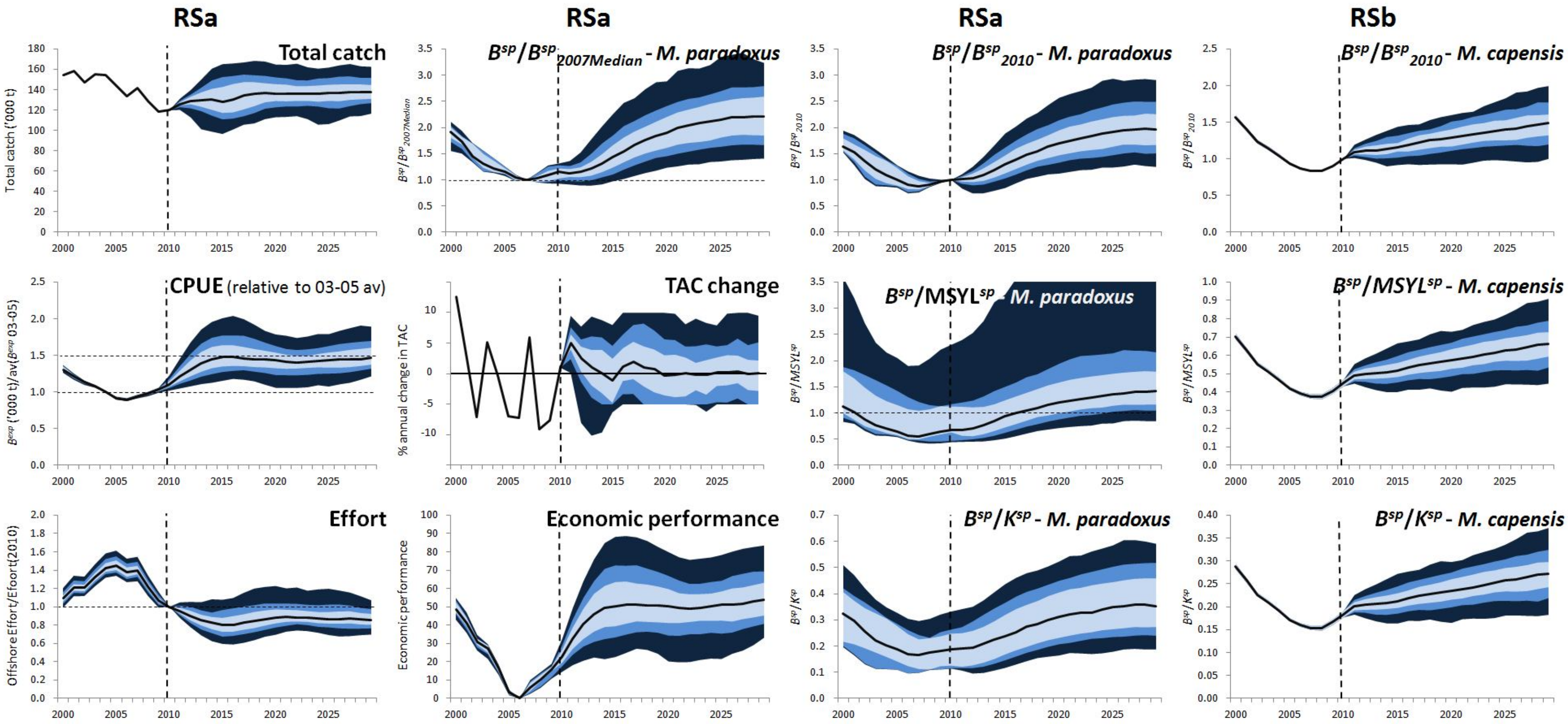
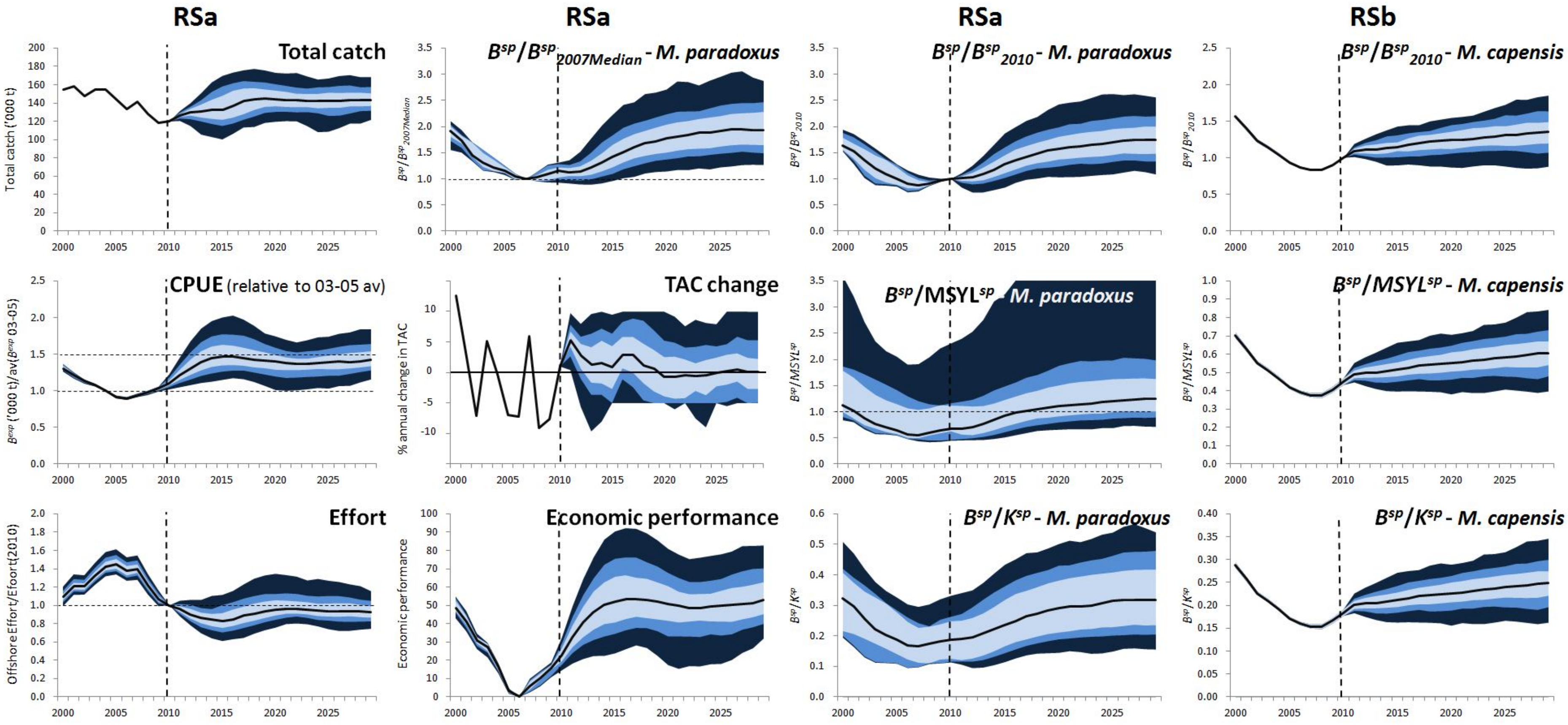


Figure 10.3f: 95, 75, 50% PI envelopes and medians for a series of performance statistics for **CMPe137**.



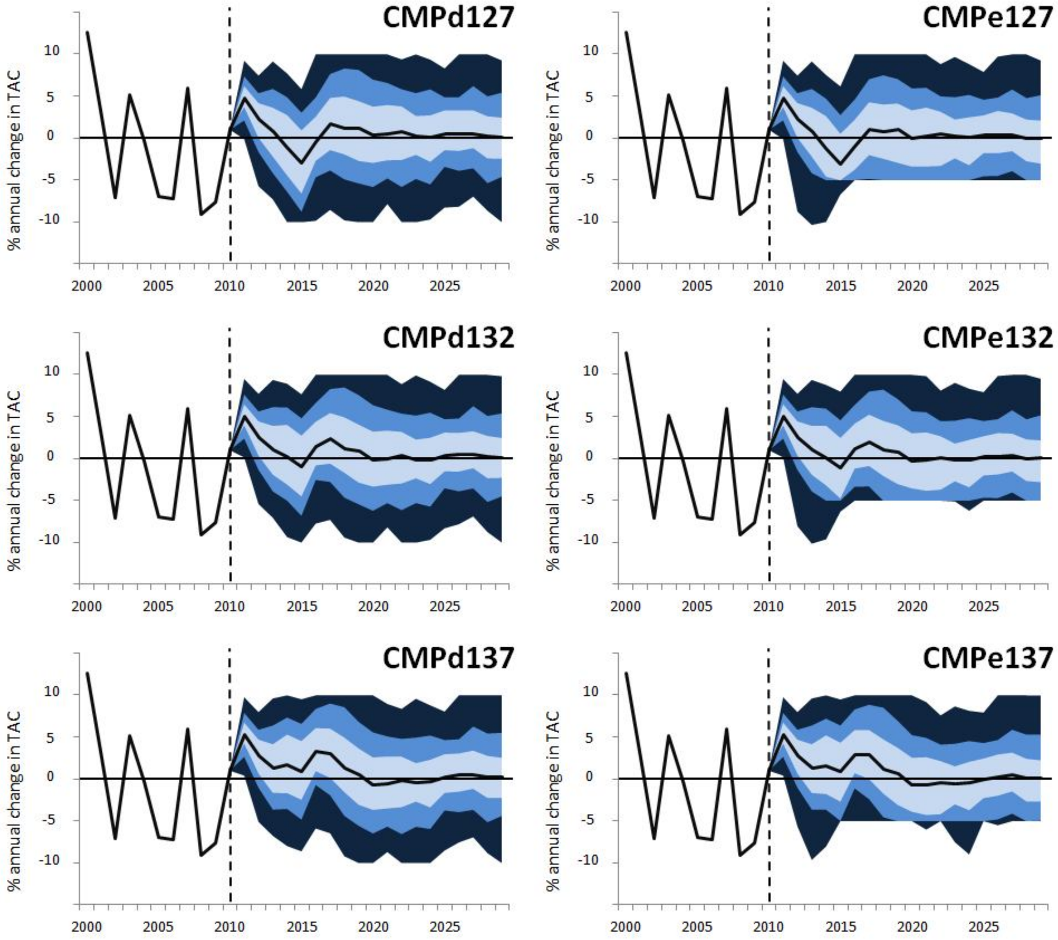


Figure 10.3g: 95, 75, 50% PI envelopes and medians for the percentage annual change in TAC for each of the six final CMPs.

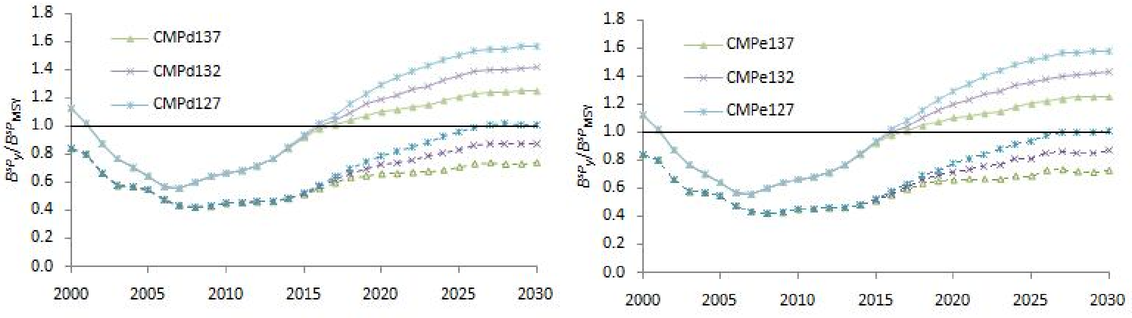


Figure 10.4: Median (full lines) and lower 2.5%iles (dashed lines) for spawning biomass (in terms of B^{sp}_{MSY}) for *M. paradoxus* for the final set of CMPs based on RSa.

Figure 10.5: Performance statistics (medians) under the final set of CMPs for the RS. The bars show the 95% PIs.

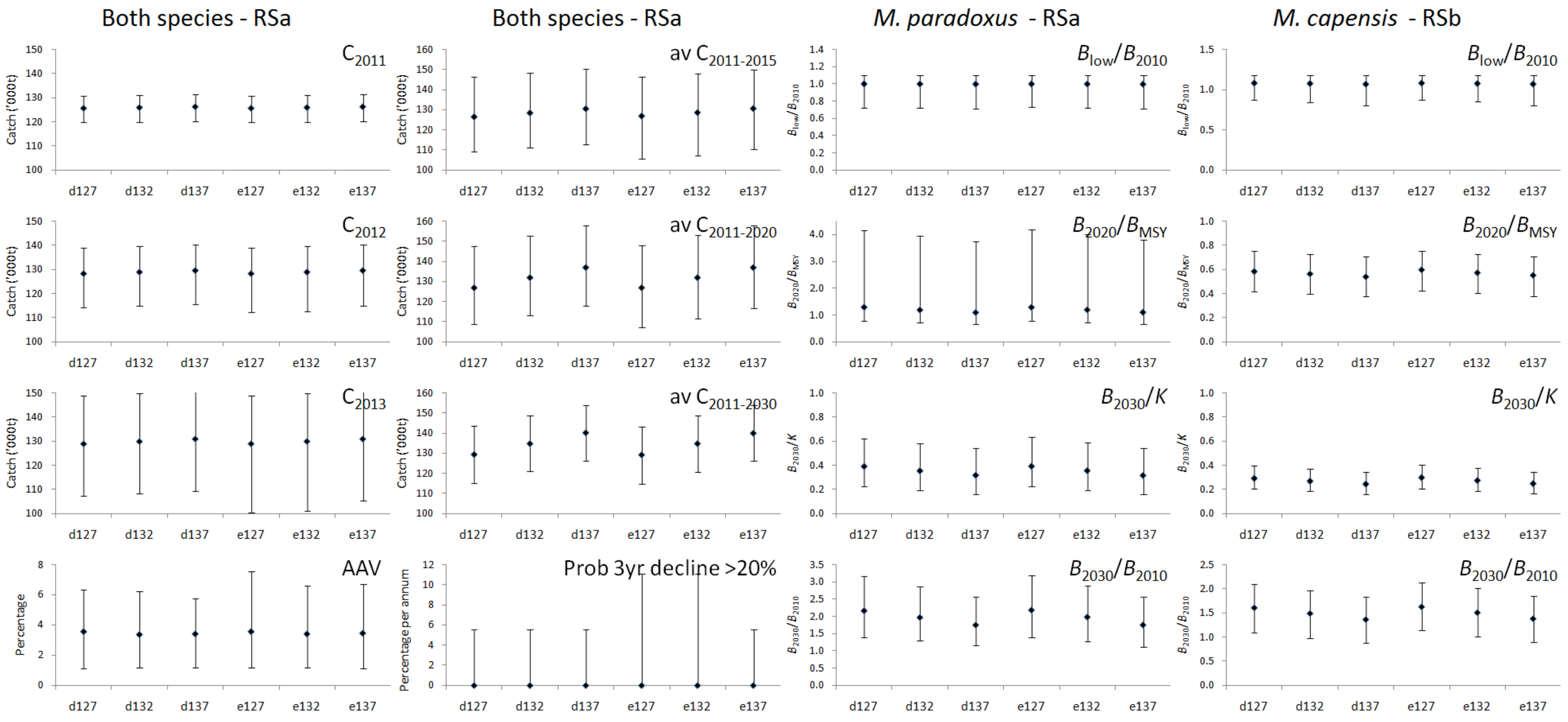
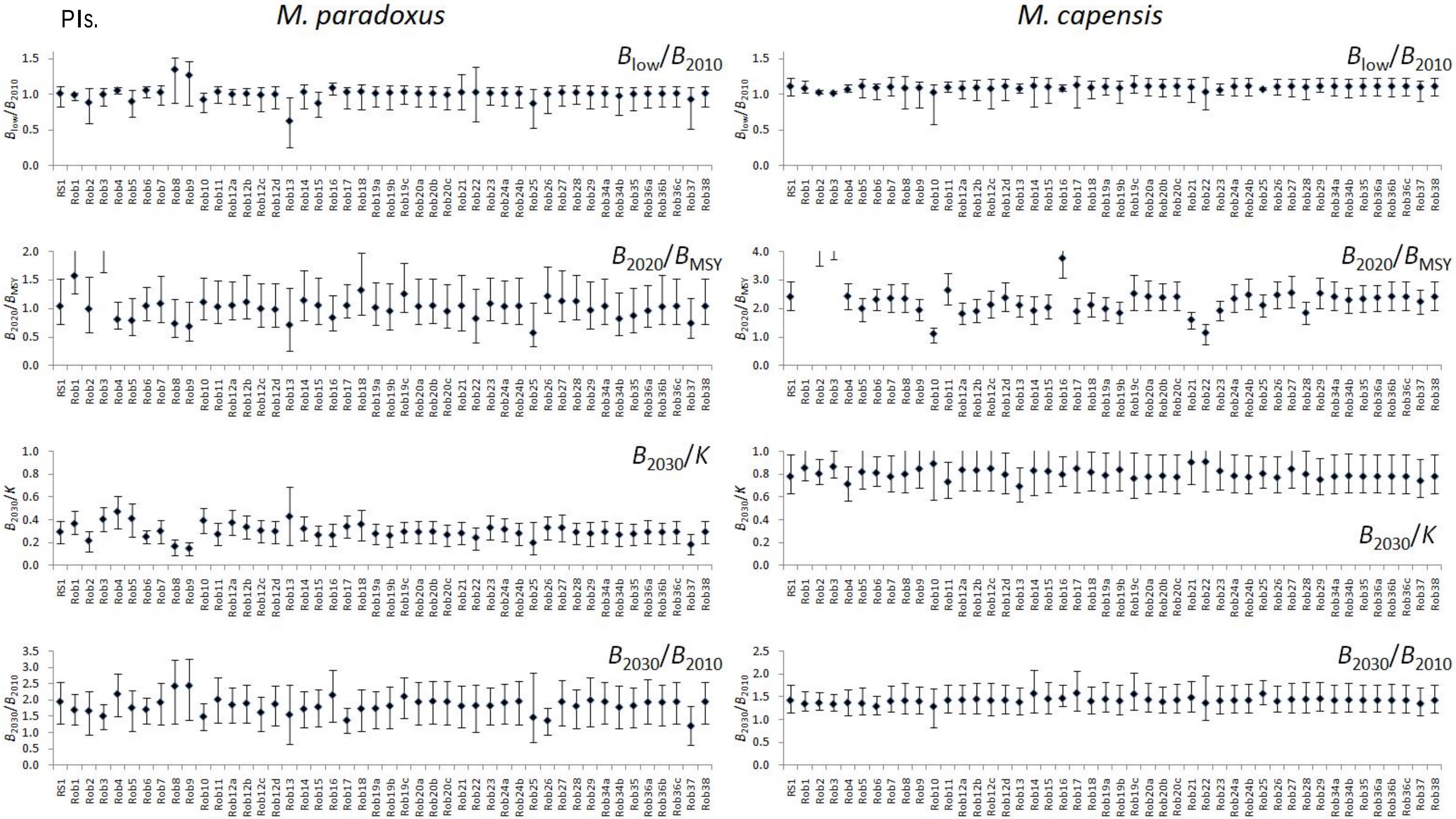


Figure 10.6: Performance statistics (medians) under CMPe137 for the full set of robustness tests. The bars show the 95% PIs.



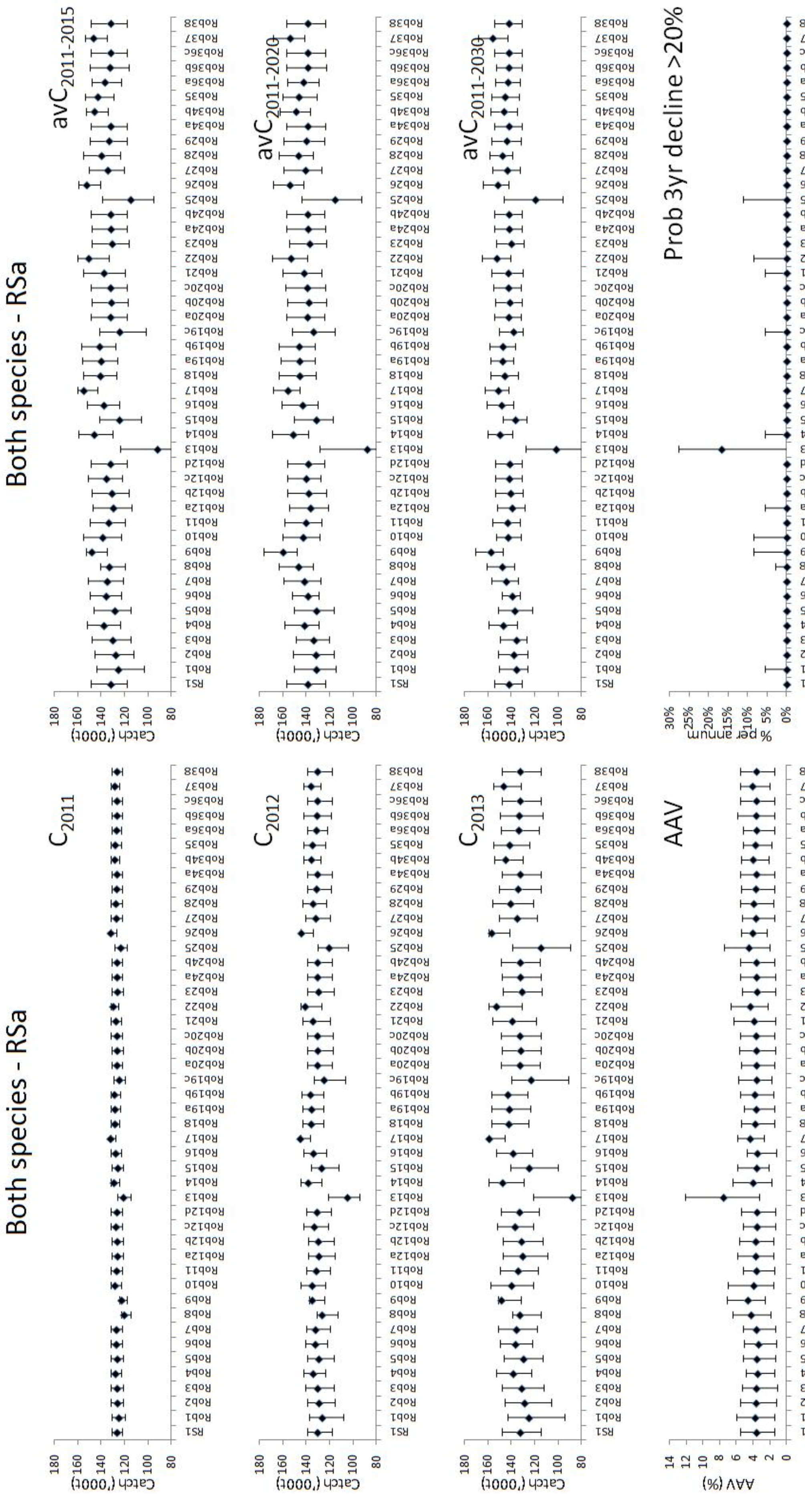


Figure 10.6: continued

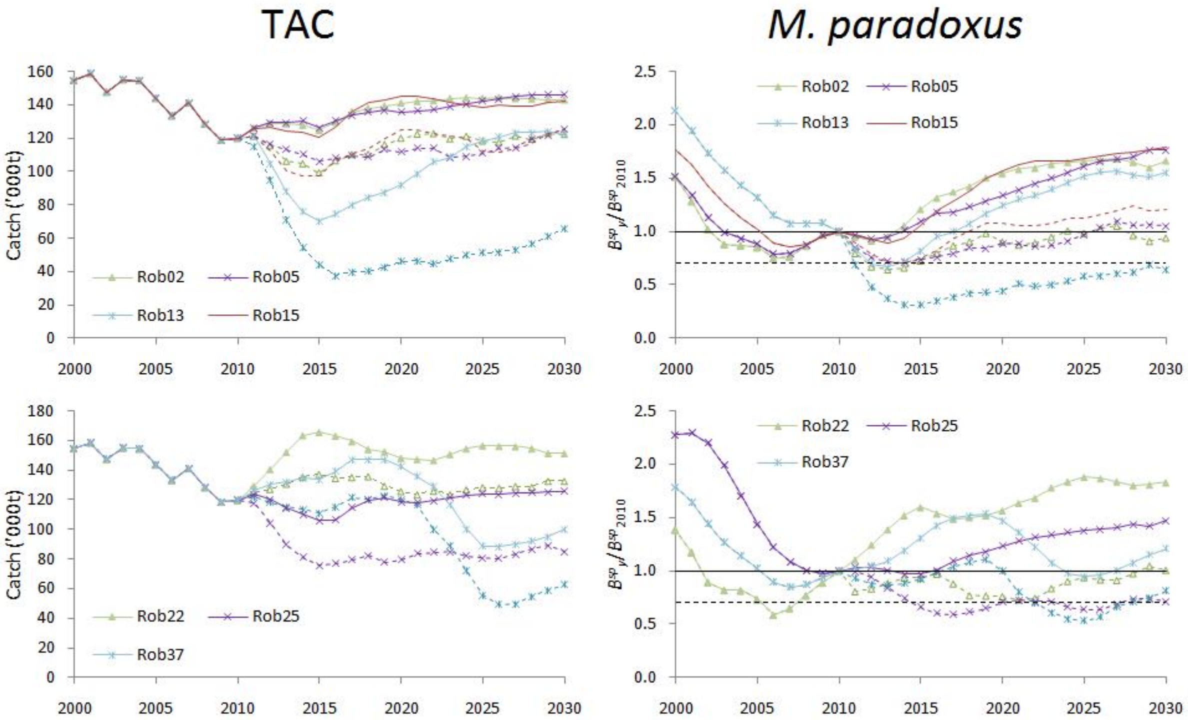


Figure 10.7: Median (full lines) and lower 2.5%iles (dashed lines) TAC and spawning biomass (in terms of 2010 level) for *M. paradoxus* for the more difficult robustness tests based on the RC, under CMPe137. The horizontal dashed line shows the 2007 level. The robustness tests are:

Rob02: BH est., shift center in 1950, paradoxus: M_{2-}=0.9, M_{5+}=0.5, capensis: M_{2-}=0.6, M_{5+}=0.5;

Rob05: True Ricker, shift center in 1950, both species: M_{2-}=0.9, M_{5+}=0.5;

Rob13: Decrease in *K* in the past;

Rob15: No shrinking of recent recruitment towards the stock-recruitment relationship predicted;

Rob22: Ageing of both species to be halved;

Rob25: Alternative maturity-at-length with fixed lower *h* value;

Rob37: Decrease in *K* in the future.

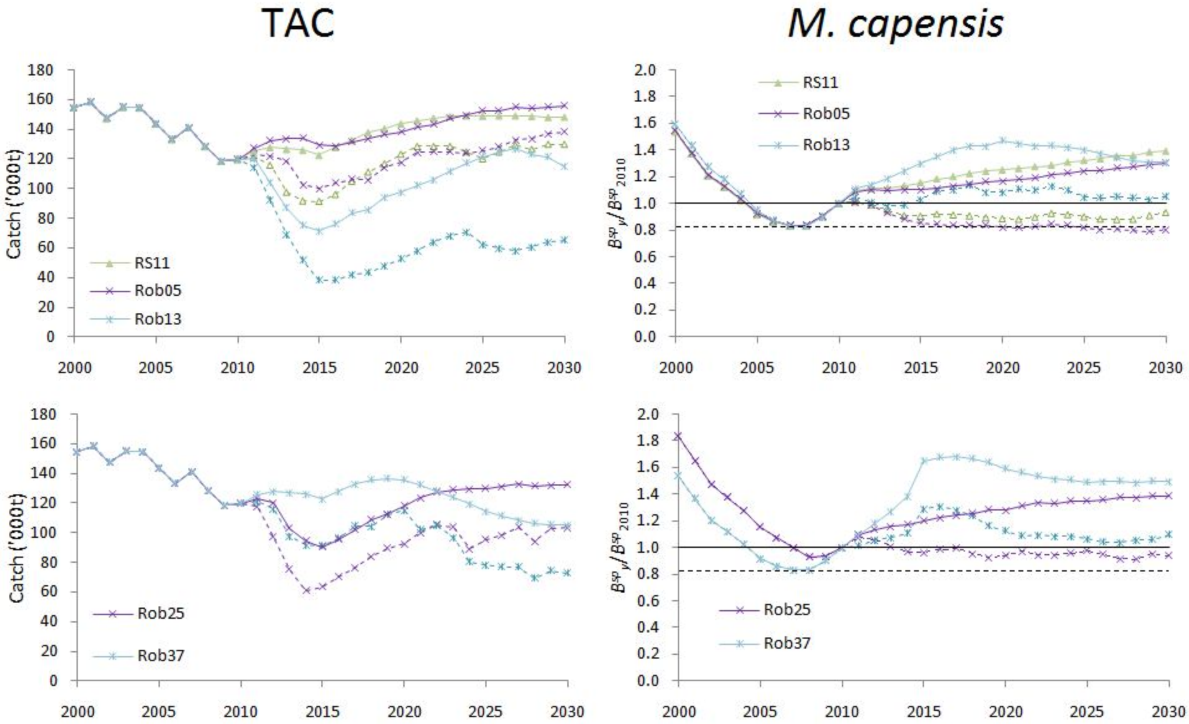


Figure 10.8: Median (full lines) and lower 2.5%iles (dashed lines) TAC and spawning biomass (in terms of 2010 level) for *M. paradoxus* for the robustness tests based on RS11 (*M. capensis* in need of rebuilding), under CMPe137. The horizontal dashed line shows the 2007 level. The robustness tests are:

Rob05: True Ricker, shift center in 1950, both species: M_{2-}=0.9, M_{5+}=0.5;

Rob13: Decrease in *K* in the past;

Rob25: Alternative maturity-at-length with fixed lower *h* value;

Rob37: Decrease in *K* in the future.

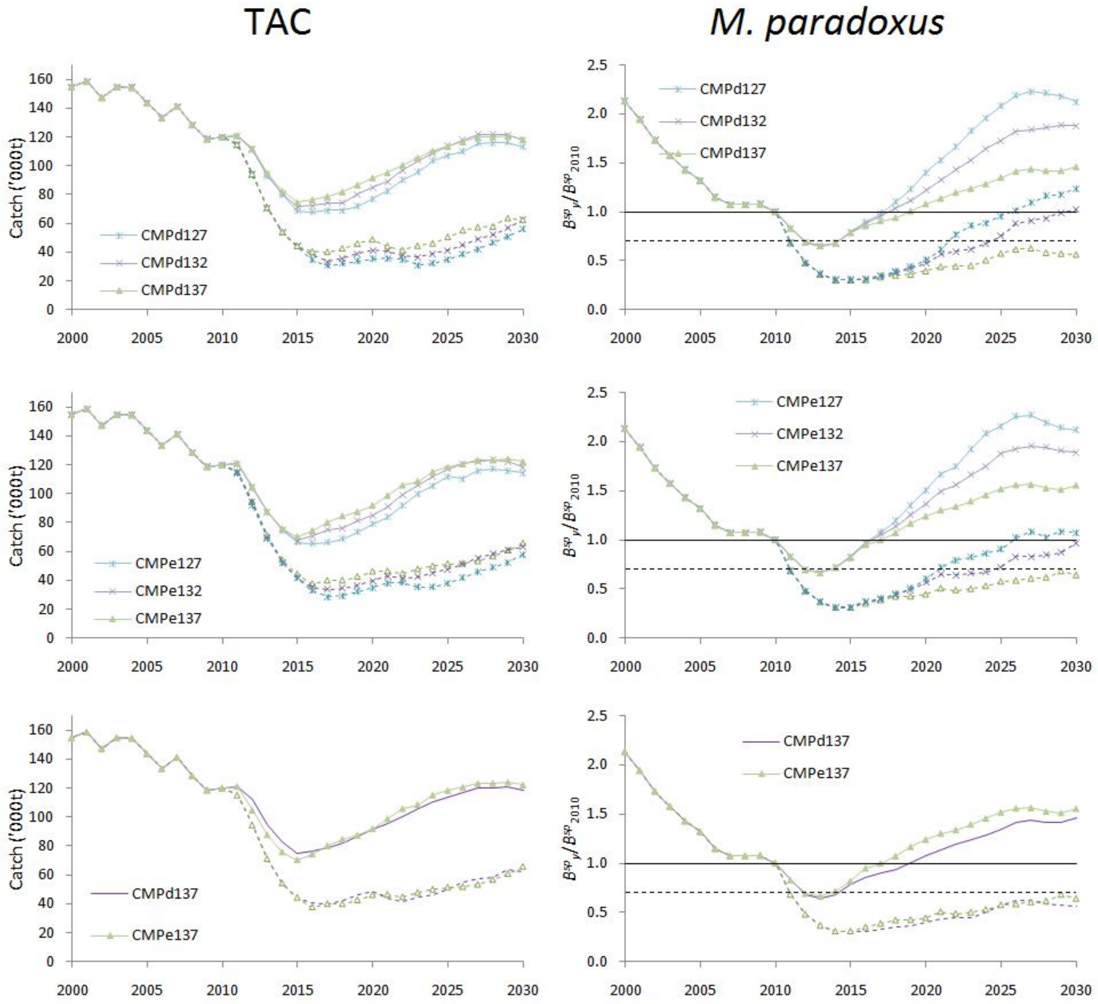


Figure 10.9: Median (full lines) and lower 2.5%iles (dashed lines) TAC and spawning biomass (in terms of 2010 level) for *M. paradoxus* for the final set of CMPs based on Rob13 (decrease in *K* in the past). The horizontal dashed line shows the 2007 level.

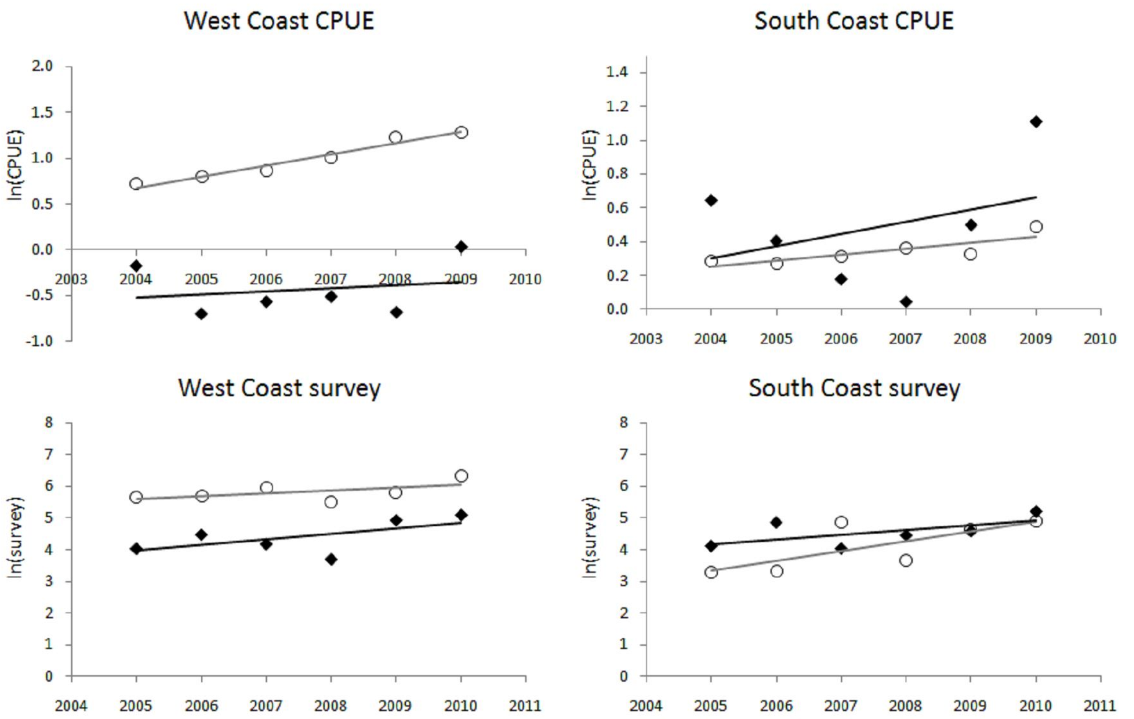


Figure 10.10: Recent trends in the GLM-standardised CPUE and survey abundance indices for *M. paradoxus* (open circles) and *M. capensis* (filled diamonds) which are used in the TAC computation. The survey abundance estimates shown include the calibration factors specified in the OMP for the years in which the new gear was used on the *F.R.S. Africana*.

APPENDIX 10.I

Candidate Management Procedures Testing Methodology

10.I.1 Projection Methodology

Projections into the future under a specific Candidate Management Procedure (CMP) are evaluated using the following steps for the Operating Model (OM) under consideration.

Step 1: Begin-year numbers at age

The components of the numbers-at-age vector for each gender and species at the start of 2010 ($N^g_{2010,a}$: a = 1,…, m – here and below the species superscript has been omitted for ease of reading) are obtained from the MLE of an assessment of the resource, assuming a total catch in 2009 equal to the TAC set for that year and split between species, coast and fleet using the 2008 catch ratio.

Error is included for ages 0 to 3 because these are poorly estimated in the assessment given limited information on these year-classes, i.e.: $N^g_{2010,a} \rightarrow N^g_{2010,a}e^{\varepsilon_a}$

$$\varepsilon_a \text{ from } N\left(0,\left(\sigma_R\right)^2\right) \qquad \text{(App.10.I.1)}$$

where σ_R is the standard deviation of the stock-recruitment residuals estimated by the OM for the years 1985 to 2005 (the last year before shrinking of SR residuals). Note that the residuals each year are assumed to be gender-independent. Equation App.10.I.1 is approximate in that it omits to adjust for past catches from the year-class concerned, but these are so small that the differential effect is negligible.

Step 2: Catch

These numbers-at-age are projected one year forward at a time given a catch for the year concerned. C_y is as specified by the CMP.

This requires specification of how the catch is disaggregated by species, fleet, gender and age to obtain C^g_{fya}, and of how future recruitments are generated.

Step 3: Catch-at-age by species, gender and fleet

Catch by species:

Although the annual catch (TAC) generated by the CMP can be species-disaggregated, the TAC recommended by the MP will be an overall figure for the two species combined given the difficulties that would be encountered in trying to set species-specific hake TACs. To disaggregate the total catch by species, previous practice when projecting forward was to assume for each fleet that the ratio of the fishing mortality (F) for the two species (F_{para}/F_{cap}) remains the same, i.e. that the current pattern of fishing remains approximately unchanged over the projection period — although some robustness tests explored sensitivity to this). Figure App.10.I.1 shows plots of estimates of this ratio for the three fleets concerned, together with averages over recent periods, for the central OM within the Reference Set (the OM RS1). The averages over the last five years (2005–2009) might be used for this purpose; however given that there is variability from year to year evident in these plots, instead in each future year the ratio is drawn from a Normal distribution with mean and variance as estimated from the values over the last five years, except that these distributions are truncated at +2 and -2 standard deviations to avoid generation of outlying values.

Catch by gender:

The fishing mortality on males and females is assumed to be equal for each species and fleet, as assumed in the assessment, except for the South Coast offshore fishery for which the female downscaling factor estimated in the OM is used in the projection.

Catch by fleet:

The total TAC recommended by the CMP is divided in fixed proportions among the various fleets, with the following values used for the sector allocations as in the last rights re-allocation process for the fishery: offshore trawl — 84%, inshore trawl — 6%, longline — 7% and handline — 3%. The offshore trawl and longline fleet catches are further split between the West and South Coasts using the average proportion over the last five years data (2004-2008) (see Figure App.10.I:2). This should differ little from what happens in practice as the stocks each cover both coasts.

Catch by age:

C^g_{fya} is obtained by assuming that S^g_{fyl}, $P^g_{a+1/2,l}$ and $\tilde{w}^g_{a+1/2}$ stay constant in the future as estimated in the OM, and therefore that:

$$S^g_{fya} = \sum_l S^g_{fyl} P^g_{a+1/2,l} \qquad \text{(App.10.I.2)}$$

the commercial selectivity functions, also stay constant in the projections.

The matrix *P* is calculated under the assumption that length-at-age is log-normally distributed about a mean given by the von Bertalanffy equation, i.e.:

$$l_a \sim N\left[\ln(l_\infty\left(1-e^{-\kappa(a-t_0)}\right));\left(\frac{\theta_a}{l_\infty\left(1-e^{-\kappa(a-t_0)}\right)}\right)^2\right] \qquad \text{(App.10.I.3)}$$

where θ_a, l_∞, t_0 and κ are as estimated in the OM for each species and gender.

From this it follows that:

$$C_{fy} = \sum_g \sum_{a=0}^{m} \tilde{w}^g_{fya+1/2}\, C^g_{fya} = \sum_g \sum_{a=0}^{m} \tilde{w}^g_{fya+1/2}\, N^g_{ya} e^{-M^g_a/2} F_{fy} S^g_{fya} \qquad \text{(App.10.I.4)}$$

$\tilde{w}^g_{fy,a+1/2}$ is the selectivity-weighted mid-year weight-at-age *a* of gender *g* for fleet *f* and year *y* (see equation App.8.11.9);

$$F_{fy}^{cap} = \frac{C_{fy}^{tot}}{\left[F_{ratio} \sum_{g} \sum_{a=0}^{m} \tilde{w}_{fya+1/2}^{para,g} \ N_{ya}^{para,g} e^{-M_a^{para,g}/2} S_{fya}^{para,g} + \sum_{g} \sum_{a=0}^{m} \tilde{w}_{fya+1/2}^{cap,g} \ N_{ya}^{cap,g} e^{-M_a^{cap,g}/2} S_{fya}^{cap,g} \right]}$$

(App.10.I.5)

$$F_{fy}^{para} = F_{fy}^{cap} F_{ratio}$$

and hence that:

$$C_{fya}^{g} = N_{ya}^{g} e^{-M_a^g/2} F_{fy} S_{fya}^{g} \qquad \text{(App.10.I.6)}$$

The numbers-at-age can then be computed for the beginning of the following year (y+1):

$$N_{y+1,0}^{g} = R_{y+1}^{g} \qquad \text{(App.10.I.7)}$$

$$N_{y+1,a+1}^{g} = \left(N_{ya}^{g} e^{-M_a^g/2} - \sum_{f} C_{fya}^{g} \right) e^{-M_a^g/2} \qquad \text{for } 0 \le a \le m - 2 \qquad \text{(App.10.I.8)}$$

$$N_{y+1,m}^{g} = \left(N_{y,m-1}^{g} e^{-M_{m-1}^g/2} - \sum_{f} C_{f,y,m-1}^{g} \right) e^{-M_{m-1}^g/2} + \left(N_{ym}^{g} e^{-M_m^g/2} - \sum_{f} C_{fym}^{g} \right) e^{-M_m^g/2}$$

(App.10.I.9)

The procedure above can however lead to problems in situations where the catch specified is not small relative to the resource abundance, and may lead to certain numbers-at-age going negative. To avoid such a situation arising, and indeed further to ensure that in any one year no more than 90% of any cohort can be taken by the fishery as a whole (as this would require an unrealistically large level of effort), the following procedure is then followed. First to see whether this situation has arisen, for each species and age, check that:

$$\left[N_{ya}^{g} e^{-M_a^g/2} - \sum_{f} C_{fya}^{g} \right] \ge \left[0.1 N_{ya}^{g} e^{-M_a^g/2} \right] \qquad \text{(App.10.I.10)}$$

if $\left[N^g_{ya}e^{-M^g_a/2}-\sum_f C^g_{fya}\right]<\left[0.1N^g_{ya}e^{-M^g_a/2}\right]$ for any age *a* then:

$$N^{*g}_{y,a}=N^g_{y*a}e^{-M^g_a/2} \qquad \text{(App.10.I.11)}$$

For each fleet in the following order: West Coast longline, South Coast longline, West Coast offshore, South Coast offshore, South Coast inshore and South Coast handline, go through equations App.10.I.12 to App.10.I.18:

A]. if $F^{para}_{fy}>0.9$ and $F^{cap}_{fy}\le 0.9$, otherwise go to **B**]

$$F^{'para}_{fy}=0.9 \qquad \text{(App.10.I.12)}$$

$$F^{'cap}_{fy}=\frac{C_{fy}-0.9\sum_g\sum_{a=0}^{m}\tilde{w}^{para,g}_{fy,a+1/2}N^{*para,g}_{ya}S^{para,g}_{fya}}{\sum_g\sum_{a=0}^{m}\tilde{w}^{cap,g}_{fy,a+1/2}N^{*cap,g}_{ya}S^{cap,g}_{fya}} \qquad \text{(App.10.I.13)}$$

if $F^{'cap}_{fy}>0.9$ then go to **C**].

B] if $F^{cap}_{fy}>0.9$ and $F^{para}_{fy}\le 0.9$

$$F^{'cap}_{fy}=0.9 \qquad \text{(App.10.I.4)}$$

$$F^{'para}_{fy}=\frac{C_{fy}-0.9\sum_g\sum_{a=0}^{m}\tilde{w}^{cap,g}_{fy,a+1/2}N^{*cap,g}_{ya}S^{cap,g}_{fya}}{\sum_g\sum_{a=0}^{m}\tilde{w}^{para,g}_{fy,a+1/2}N^{*para,g}_{ya}S^{para,g}_{fya}} \qquad \text{(App.10.I.15)}$$

if $F^{'para}_{fy}>0.9$ then go to **C**].

C] if $F^{para}_{fy}>0.9$ and $F^{cap}_{fy}>0.9$

$$F_{fy}^{'para} = 0.9 \text{ and } F_{fy}^{'cap} = 0.9 \qquad \text{(App.10.I.16)}$$

$$C_{fya}^{g} = N_{ya}^{*g} F_{fy}^{'} S_{fya}^{g} \qquad \text{(App.10.I.17)}$$

$$N_{y,a}^{'g} = N_{ya}^{*g} - C_{fya}^{g} \qquad \text{(App.10.I.18)}$$

In equations App.10.I.13, App.10.I.15 and App.10.I.17, $N_{y,a}^{*g}$ is replaced by $N_{y,a}^{'g}$.

Move to the next fleet and continue through all the fleets.

$$N_{y+1,a+1}^{g} = N_{ya}^{'g} e^{-M_a^g/2} \qquad \text{for } 0 \le a \le m-2 \qquad \text{(App.10.I.19)}$$

$$N_{y+1,m}^{g} = N_{y,m-1}^{'g} e^{-M_{m-1}^g/2} + N_{y,m}^{'g} e^{-M_m^g/2} \qquad \text{(App.10.I.20)}$$

Step 4: Recruitment

Future recruitments are provided by a Beverton-Holt or a modified (generalised) form of the Ricker stock-recruitment relationship, as specified for the OM and assuming a 50:50 sex-split at recruitment.

$$R_y^g = \frac{4hR_0 B_y^{\text{♀},sp}}{K^{\text{♀},sp}(1-h) + (5h-1)B_y^{\text{♀},sp}} e^{(\varsigma_y - \sigma_R^2/2)} \qquad \text{(App.10.I.21)}$$

for the Beverton-Holt stock-recruitment relationship and

$$R_y^g = \alpha B_y^{\text{♀},sp} \exp\left(-\beta\left(B_y^{\text{♀},sp}\right)^{\gamma}\right) e^{(\varsigma_y - \sigma_R^2/2)} \qquad \text{(App.10.I.22)}$$

with

$$\alpha = R_0 \exp\left(\beta\left(K^{\text{♀},sp}\right)^{\gamma}\right) \qquad \text{and} \qquad \beta = \frac{\ln(5h)}{\left(K^{\text{♀},sp}\right)^{\gamma}\left(1-5^{-\gamma}\right)}$$

for the modified Ricker relationship.

Log-normal fluctuations are introduced by generating ς_y factors from $N\left(0,\sigma_R^2\right)$ where σ_R is estimated from the residuals of the model fit for years 1985 to 2004. K^{sp}, *h* (and γ with the modified Ricker) are as estimated for that OM.

$B_y^{♀sp}$ is the female spawning biomass at the start of year *y*, computed as:

$$B_y^{♀,sp} = \sum_{a=1}^{m} f_a^{♀} w_a^{♀} N_{ya}^{♀} \qquad \text{(App.10.I.23)}$$

Step5:

The information obtained in Steps 1 to 4 is used to generate values of the abundance indices in the form of species-disaggregated CPUE series (one for each coast and species) and survey indices of abundance (one for each coast and species). These abundance indices (CPUE and surveys) are generated from the OM, assuming the same error structures as in the past, as follows:

(a) Coast- and species-disaggregated CPUE series are generated from model estimates for corresponding mid-year exploitable biomass and catchability coefficients, with multiplicative lognormal errors incorporated where the associated variance is estimated within the OM concerned from past data. When computing the TAC for year *y*+1, such data are available to year *y*–1.

$$I_y^i = \hat{q}^i \hat{B}_{fy}^{ex} e^{\varepsilon_y^i} \qquad \text{(App.10.I.24)}$$

where

$$B_{fy}^{ex} = \sum_g \sum_{a=0}^{m} \tilde{w}_{fy,a+1/2}^{g} S_{fya}^{g} N_{ya}^{g} e^{-M_a^g/2} \left(1 - \sum_f S_{fya}^{g} F_{fy} \Big/ 2 \right) \qquad \text{(App.10.I.25)}$$

$$\hat{\sigma}^i = \sqrt{1/n_i \sum_{y=1978}^{2008} \left(\ell\text{n}(I_y^i) - \ell\text{n}(\hat{I}_y^i) \right)^2} \qquad \text{and} \qquad \text{(App.10.I.26)}$$

$$\ell n\,\hat{q}^i = \frac{\sum_{y=1978}^{2008}\left(\ell n I_y^i - \ell n \hat{B}_{fy}^{ex}\right)}{\sum_{y=1978}^{2008} 1} \qquad \text{(App.10.I.27)}$$

$$\varepsilon_y^i \quad \text{from } N\left(0,\left(\sigma^i\right)^2\right) \qquad \text{(App.10.I.28)}$$

(b) Species-disaggregated biomass estimates from the West Coast summer and South Coast autumn surveys are generated from model estimates of mid-year survey biomass. Because the research survey vessel, the RV *Africana*, used new gear commencing in 2003/2004, estimates from that date are adjusted by a multiplicative bias when the new gear is used. For future projections it is assumed that each year the new gear is used (this is no restriction is practice, because even if gear is varied in future, a calibration factor assumed to be known exactly would be applied). Lognormal error variance includes the survey sampling variance with the CV set equal to the average historical value, plus survey additional variance (the variability that is not accounted for by sampling variability) as estimated within the OM concerned from past data. For the TAC for year *y*+1, such data are available for year *y*.

$$I_y^i = \hat{q}^i \hat{B}_{fy}^{surv} e^{\varepsilon_y^i} \qquad \text{(App.10.I.29)}$$

$$B_y^{surv} = \sum_g \sum_{a=0}^{m} \tilde{w}_a^{g,sum} S_a^{g,sum} N_{ya}^g \qquad \text{(App.10.I.30)}$$

for begin-year (summer) surveys, and

$$B_y^{surv} = \sum_g \sum_{a=0}^{m} \tilde{w}_{a+1/2}^{g,win} S_a^{g,win} N_{ya}^g e^{-M_a^g/2}\left(1-\sum_f S_{fya}^g F_{fy} \Big/ 2\right) \qquad \text{(App.10.I.31)}$$

for mid-year (spring, winter and autumn) surveys,

$\tilde{w}_a^{g,i}$ is the survey selectivity-weighted weight-at-age *a* of gender *g* for survey *i*, computed in the same manner as for the commercial selectivity-weight-at-age (equation

App.II.9) and taking account of the begin-year ($\tilde{w}^{g,sum}_{y,a}$ from $P^{g}_{a,l}$) or mid-year ($\tilde{w}^{g,win}_{y,a+1/2}$ from $P^{g}_{a+1/2,l}$) nature of the surveys.

ε^{i}_{y} from $N\left(0,\left(\sigma^{i}\right)^{2}\right)$ (App.10.I.32)

where

$$\sigma^{i}=\sqrt{\ln(1+\overline{CV^{i}}^{2})+\sigma^{2}_{a}} \qquad \text{(App.10.I.33)}$$

The survey specific average CV ($\overline{CV^{i}}$) is computed over all the years available for that survey as:

$$\overline{CV^{i}}=\frac{\sum\limits_{y} se^{i}_{y}\big/I^{i}_{y}}{\sum\limits_{y} 1} \qquad \text{(App.10.I.34)}$$

For *M. paradoxus*, $\overline{CV^{i}}$ is 0.185 and 0.372 for the West Coast summer and South Coast autumn surveys respectively, and for *M. capensis*, $\overline{CV^{i}}$ is similarly 0.178 and 0.112.

The reason for this difference in periods for which data are available is that the recommendation for a TAC, which applies over a calendar year (*y*+1), is required by October of the preceding year (*y*). By that time the results of the surveys conducted during year *y* will be available, but not for CPUE which pertains to the full calendar year *y*. Thus, care is taken in developing and testing the OMP that only data that would actually be available at the time a TAC recommendation is required are used. Furthermore, in order to project the resource biomass trajectory forward, the TAC needs to be disaggregated by species and by fleet.

As for the commercial selectivity, the survey selectivities are obtained under the assumption that the selectivity functions estimated for that OM remain constant.

Step 6:

Given the new CPUE indices I_{y-1}^{i} and the new survey indices I_{y}^{i} compute TAC_{y+1} using the CMP.

Step 7:

Steps 1-6 are repeated for each future year in turn for as long a period as desired, and at the end of that period the performance of the candidate MP under review is assessed by considering statistics such as the average catch taken over the period and the final spawning biomass of the resource.

10.I.2 Performance Statistics

The following performance statistics, related to the objectives above, are computed for the CMP tested. Projections are conducted over 20 years.

Utilisation-related

- The median of the medium term average TAC: $\frac{1}{10}\sum_{y=2011}^{2020} C_y$ (for both species combined).
- The 2.5% PI of the lowest expected TAC (for both species combined) during the projection period.

TAC variability

- The median Average Annual Variation in TAC: $AAV = \frac{1}{20}\sum_{y=2011}^{2030} \left|C_y - C_{y-1}\right| / C_{y-1}$.
- The probability of a decline in the TAC greater than 20% over the 2011-2013 period.
- The probability of a decline in the TAC greater than 20% over the 2012-2014 period.
- The median and 97.5% PI probability of a decline in the TAC greater than 20% over any consecutive three years for such periods commencing 2011-2028.

Resource status-related

- The 2.5% PI of $B_{low}^{sp}/B_{2010}^{sp}$: for each species, the lowest expected female spawning biomass during the projection period, relative to current (2010) level.
- The median of $B_{2020}^{sp}/B_{MSY}^{sp}$: for each species, the expected female spawning biomass in 2020, relative to the Maximum Sustainable Yield level.

In addition, time trajectories are plotted for certain outputs from the projections, such as C_y and B_y^{sp}.

10.I.3 Summary of data available to CMPs

The data available to a CMP to provide a TAC recommendation for year *y*+1 are**:**

- Catch data by species to year *y*-1
- CPUE indices by coast and species to year *y*-1
- Survey abundance estimates by coast and species to year *y*.

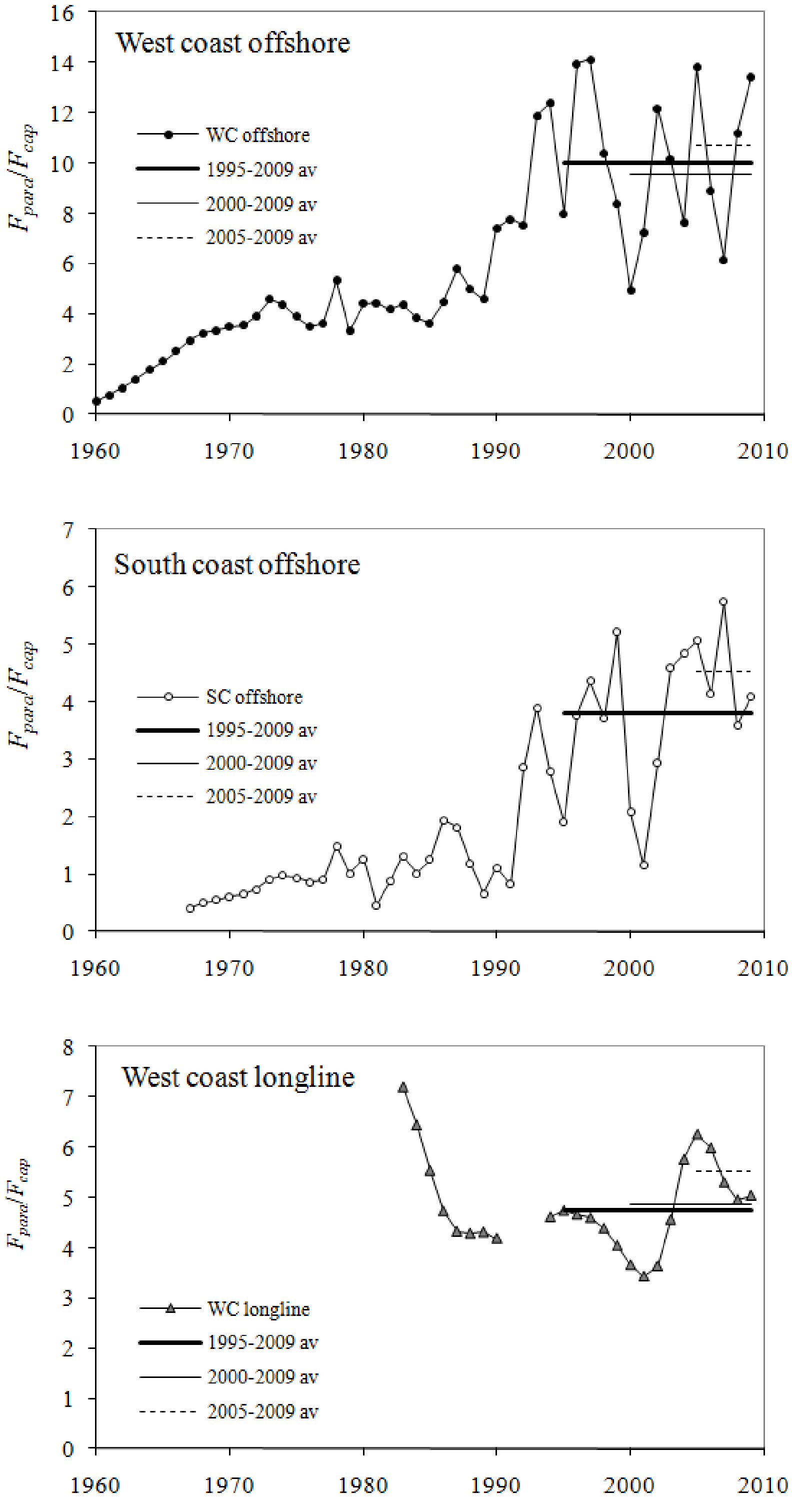


Figure App.10.I.1: Trends in past F_{ratio} (F_{para}/F_{cap}) for the West and South Coast offshore trawl and West Coast longline fleet for the Reference Case assessment (RS1) within the Reference Set. The averages over1995-2009, 2000-2009 and 2005-2009 are also shown.

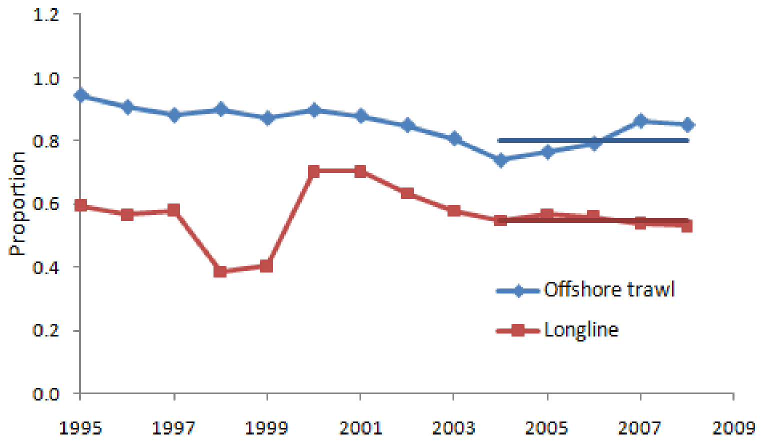


Figure App.10.I.2: Proportion of the species combined offshore trawl and longline catches taken on the West Coast. The averages over the last five years are also shown.

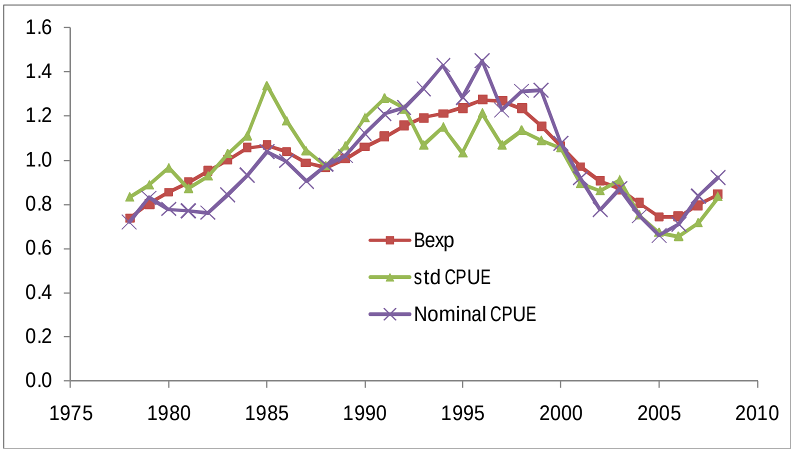


Figure App.10.I.3: Comparison of nominal CPUE (aggregated over species, gender and coasts), CPUE GLM-standardised as for coast- and species-specific data, and offshore trawl species- and coast-combined exploitable biomass in the past as estimated for the Reference Case assessment..

APPENDIX 10.II

2010 Operational Management Procedure Specifications

10.II.1 Introduction

The algorithm for OMP-2011 to provide TAC recommendations for the South African *Merluccius paradoxus* and *M. capensis* resources is empirical. It combines an increase or decrease of the TAC in relation to a) the magnitude of recent trends in CPUE and survey abundance estimates for both species and b) the relative level of recent CPUE and survey abundance estimates compared to a target level. The basis for the associated computations is set out below, with the tuning parameters given in Table App.10.II.1.

10.II.2 The 2011 OMP

The formula for computing the TAC recommendation is as follows:

$$TAC_y = C_y^{para} + C_y^{cap} \qquad \text{(App.10.II.1)}$$

with

$$C_y^{spp} = w_y C_{y-1}^{*spp}\left[1 + \lambda_{up/down}\left(s_y^{spp} - T_y^{spp}\right)\right] + \left(1 - w_y\right)\left[a^{spp} + b^{spp}\left(J_y^{spp} - 1\right) - Pen_y^{spp}\right] \qquad \text{(App.10.II.2)}$$

where

TAC_y is the total TAC recommended for year *y*,

C_y^{spp} is the intended species-disaggregated TAC for year *y*,

C_{y-1}^{*spp} is the achieved catch[14] of species *spp* in year *y*-1,

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[14] Implemented by applying the species ratio of the catch in year *y*-2 to the TAC for year *y*-1, as the species ratio for year *y*-1 would not yet be known by the time at which a recommendation for the TAC for year *y* would be required.

w_y is a year-dependent tuning parameter,

$\lambda_{up/down}$ are tuning parameters; λ_{up} is used if $s_y^{spp} \geq 0$ and λ_{down} is used if $s_y^{spp} < 0$,

T_y^{spp} is the year-dependant target rate of increase for species *spp*,

s_y^{spp} is a measure of the immediate past trend in the abundance indices for species *spp* as available to use for calculations for year *y*,

a^{spp}, b^{spp}, c^{spp} and p^{spp} are tuning parameters, and

$$Pen_y^{spp} = \begin{cases} 0 & \text{if } J_y^{spp} \geq p^{spp} \\ c^{spp}\left(J_y^{spp} - p^{spp}\right)^2 & \text{if } J_y^{spp} < p^{spp} \end{cases} \qquad \text{(App.10.II.3)}$$

where

J_y^{spp} is a measure of the immediate past level in the abundance indices for species *spp* as available to use for calculations for year *y.*

10.II.2.1 Measure of recent trend

The trend measure s_y^{spp} is computed as follows from the species- and coasts-disaggregated GLM-CPUE ($I_y^{WC\_CPUE,spp}$ and $I_y^{SC\_CPUE,spp}$), West Coast summer survey ($I_y^{WC\_surv,spp}$) and South Coast autumn survey ($I_y^{SC\_surv,spp}$) indices:

- linearly regress $\ln I_y^{WC\_CPUE,spp}$ and $\ln I_y^{SC\_CPUE,spp}$ *vs* year *y*' for $y' = y - p - 1$ to $y' = y - 2$, to yield two regression slope values $s_y^{WC\_CPUE,spp}$ and $s_y^{SC\_CPUE,spp}$,
- linearly regress $\ln I_y^{WC\_surv,spp}$ and $\ln I_y^{SC\_surv,spp}$ *vs* year *y*' for $y' = y - p$ to $y' = y - 1$, to yield two regression slope values $s_y^{WC\_surv,spp}$ and $s_y^{SC\_surv,spp}$,

where *p*=6 is the length of the periods considered for these regressions. Note that the reason the trend for surveys is calculated for a period moved one year later than for CPUE is that by the time of year that the TAC recommendation would be computed for the following year, survey results for the current year would be known, but not CPUE as fishing for the year would not yet have been completed. Note also that surveys carried out using the old gear are made comparable to those carried out using the new gear by multiplying them by a species specific calibration factor (0.95 for *M. paradoxus* and 0.8 for *M. capensis*).

Then:

$$s_y^{para} = \left(s_y^{WC\_CPUE,para} + 0.75 s_y^{SC\_CPUE,para} + 0.5 s_y^{WC\_surv,para} + 0.25 s_y^{SC\_surv,para}\right)\Big/2.5$$

(App.10.II.4)

$$s_y^{cap} = \left(s_y^{WC\_CPUE,cap} + 0.75 s_y^{SC\_CPUE,cap} + 0.5 s_y^{WC\_surv,cap} + s_y^{SC\_surv,cap}\right)\Big/3.25$$

(App.10.II.5)

10.II.2.2 Measure of recent level

The measure of the immediate past level J_y^{spp} in the abundance indices is computed as follows:

$$J_y^{para} = \frac{1.0 J_y^{WC\_CPUE,para} + 0.75 J_y^{SC\_CPUE,para} + 0.5 J_y^{WC\_surv,para} + 0.25 J_y^{SC\_surv,para}}{2.5}$$

(App.10.II.6)

$$J_y^{cap} = \frac{1.0 J_y^{WC\_CPUE,cap} + 0.75 J_y^{SC\_CPUE,cap} + 0.5 J_y^{WC\_surv,cap} + 1.0 J_y^{SC\_surv,cap}}{3.25}$$

(App.10.II.7)

with

$$J_y^{WC\_CPUE,spp} = \frac{\sum\limits_{y'=y-4}^{y-2} I_y^{WC\_CPUE,spp}}{\theta^{spp} \sum\limits_{y=2006}^{2008} I_y^{WC\_CPUE,spp}}$$

(App.10.II.8)

$$J_y^{SC\_CPUE,spp} = \frac{\sum\limits_{y'=y-4}^{y-2} I_y^{SC\_CPUE,spp}}{\theta^{spp} \sum\limits_{y=2006}^{2008} I_y^{SC\_CPUE,spp}}$$

(App.10.II.9)

$$J_y^{WC\_surv,spp} = \frac{\sum_{y'=y-3}^{y-1} I_y^{WC\_surv,spp}}{\theta^{spp} \sum_{y=2007}^{2009} I_y^{WC\_surv,spp}}$$ and (App.10.II.10)

$$J_y^{SC\_surv,spp} = \frac{\sum_{y'=y-3}^{y-1} I_y^{SC\_surv,spp}}{\theta^{spp} \sum_{y=2007}^{2009} I_y^{SC\_surv,spp}}$$ (App.10.II.11)

with

θ^{para}= 1.67 and θ^{cap} = 1.50.

10.II.2.3 Maximum allowable change in TAC

While the maximum allowable annual increase in TAC is 10%, the maximum allowable decrease in TAC from one year to the next is:

$$MaxDecr_y = \begin{cases} 5\% & \text{if } J_y > Q_{\min} \\ \text{linear between 5\% and 25\%} & \text{if } Q_{\min} - 0.2 \le J_y \le Q_{\min} \\ 25\% & \text{if } J_y < Q_{\min} - 0.2 \end{cases}$$ (App.10.II.12)

where

$$J_y = \frac{J_y^{para} + J_y^{cap}}{2}$$ (App.10.II.13)

and

$Q_{\min}$ is a tuning parameter.

10.II.3 Procedure in event of missing data

10.II.3.1 CPUE data

Non-availability of data to compute the GLM-standardised CPUE series for each species is not anticipated.

10.II.3.2 Survey data

a) If at most two of the four survey estimates are not available in a given year, the computations continue as indicated, with the missing data omitted from the regression estimates of *slope*.

b) If more than two such estimates are missing, or if for more than one survey two years have been missed, computations will continue on the basis in a), but an OMP review will commence immediately.

Table App.10.II.1: Tuning parameters for OMP-2011

	M. paradoxus	*M. capensis*
λ_{up}	1.25	
λ_{down}	1.50	
T_y^{spp}	$\begin{cases} 0.75\% & \text{if } y < 2015 \\ \text{linear between } 0.75\% \text{ and } 0\% & 2015 \le y \le 2018 \\ 0\% & \text{if } y \ge 2019 \end{cases}$	0%
w_y	$\begin{cases} 1 & \text{if } y \le 2011 \\ \text{linear between } 1 \text{ and } 0.5 & 2012 \le y \le 2015 \\ 0.5 & \text{if } y \ge 2016 \end{cases}$	
a^{spp}	104.5	40
b^{spp}	60	20
c^{spp}	180	20
p^{spp}	0.75	0.75
$Q_{\min}$	0.75	

APPENDIX 10.III

Procedures for deviating from OMP output for the recommendation for a TAC, and for initiating an OMP review

10.III.1. Metarule Process

Metarules can be thought of as "rules" which pre-specify what should happen in unlikely, Exceptional Circumstances when application of the TAC generated by the OMP is considered to be highly risky or highly inappropriate. Metarules are not a mechanism for making small adjustments, or 'tinkering' with the TAC from the OMP. It is difficult to provide firm definitions of, and to be sure of including all possible, Exceptional Circumstances. Instead, a process for determining whether Exceptional Circumstances exist is described below (see Figure App.10.III.1). The need for invoking a metarule should be evaluated by the relevant DAFF Scientific Working Group (hereafter indicated by SWG), but only provided that appropriate supporting information is presented so that it can be reviewed at a SWG meeting.

10.III.1.1 Description of Process to Determine Whether Exceptional Circumstances Exist

While the broad circumstances that may invoke the metarule process can be identified, it is not always possible to pre-specify the data that may trigger a metarule. If a SWG Member or Observer, or DAFF Management, is to propose an Exceptional Circumstances review, then such person(s) must outline in writing the reasons why they consider that Exceptional Circumstances exist, and must either indicate where the data, information or analyses are to be found supporting the review, or must supply those data, information or analyses in advance of the SWG meeting at which their proposal is to be considered.

Every year the SWG will:

- Review population and fishery indicators, and any other relevant data or information on the population, fishery and ecosystem, and conduct a simple routine updated assessment (likely no more than core reference set models used in the OMP testing refitted taking a further year's data into account).
- On the basis of this, determine whether there is evidence for Exceptional Circumstances.

Examples of what might constitute an exceptional circumstance in the case of hake include, but are not necessarily limited to:

- Survey estimates of abundance that are appreciably outside the bounds predicted in the OMP testing.
- Standardized CPUE trends that are appreciably outside the bounds predicted in the OMP testing.
- Catch species composition in major components of the fishery or surveys that differ markedly from previous patterns (and so may reflect appreciable changes in selectivity).

Every two years the SWG will:

- Conduct an in depth stock assessment (more intensive than the annual process above, and in particular including the conduct of a range of sensitivity tests).
- On the basis of the assessment, indicators and any other relevant information, determine whether there is evidence for Exceptional Circumstances.

The primary focus for concluding that Exceptional Circumstances exist is if the population assessment/indicator review process provides results appreciably outside the range of simulated population and/other other indicator trajectories considered in OMP evaluations. This includes the core (Reference case or set of) operating models used for these evaluations, and likely also (though subject to discussion) the operating models for the robustness tests for which the OMP was considered to have shown adequate performance. Similarly, if the review process noted regulatory changes likely to effect appreciable modifications to outcomes predicted in terms of the assumptions used for projections in the OMP evaluations (e.g. as a result, perhaps, of size limit changes or closure of areas), or changes to the nature of the data collected for input to the OMP beyond those for which allowance may have been made in those evaluations, this would constitute grounds for concluding that Exceptional Circumstances exist in the context of continued application of the current OMP.

Every year, IF the SWG concludes that there is no or insufficient evidence for Exceptional Circumstances, the SWG will:

- Report to the Director Resources Research, DAFF that Exceptional Circumstances do not exist.

IF the SWG has agreed that Exceptional Circumstances exist, the SWG will:

- Determine the severity of the Exceptional Circumstances.
- Follow the “Process for Action” described below.

10.III.1.2 Specific issues that will be considered annually (regarding Underlying Assumptions of the Operating Models (OMs) for the OMP Testing Process)

The following critical aspects of assumptions underlying the OMs for hake need to be monitored after OMP implementation. Any appreciable deviation from these underlying assumptions may constitute an exceptional circumstance (i.e. potential metarule invocation) and will require a review, and possible revision, of the OMP:

- Whether over recent years the species splits of catches from the major fisheries differ substantially from the species splits considered in projections in the OMP testing.
- Whether selectivities-at-length for the major fisheries differ substantially from assumptions made to generate operating model projections.
- Whether standardised CPUE and survey abundance estimates are within the bounds indicated in operating model projections, where bounds here and in similar cases following shall be taken to be the 2.5%ile and 97.5%ile of projections under the Reference Set a (RSa) of operating models.

- Whether future recruitment levels are within the bounds projected by the RS1 operating models.
- Whether new data suggest appreciably increased plausibility of the RSb scenarios which reflect a much more depleted *M. capensis* population than is the case under RSa.
- Whether the "survey-standardised-CPUE discrepancy statistic" defined below for each species as:

  $$D_y^{WC\_surv,spp} = \Delta I_y^{WC\_surv,spp} - \frac{\left(\Delta I_y^{WC\_CPUE,spp} + \Delta I_y^{SC\_CPUE,spp}\right)}{2}$$

  $$D_y^{SC\_surv,spp} = \Delta I_y^{SC\_surv,spp} - \frac{\left(\Delta I_y^{WC\_CPUE,spp} + \Delta I_y^{SC\_CPUE,spp}\right)}{2}$$

  where

  $$\Delta I_y^i = \frac{\left(I_{y+1}^i - I_y^i\right)}{I_y^i}$$

  falls outside the bounds indicating in the OMP testing.
- Whether updates of major data sets or ageing practices indicate substantial differences from what were used to condition the operating models for the OMP testing.
- Whether there have been a series of substantial differences between TACs allocated and the catches subsequently made.
- Whether fishing regulations and/or strategies have changed substantially, and in a manner such that continuing use of the agreed GLM-standardisation procedures would likely introduce substantial bias in resource abundance trend estimates based on CPUE indices.
- Whether new data or information suggest a substantial revision of estimates of stock status or of the spawning biomass at MSY which is the target reference point for the fishery.
- Whether updated assessments suggest that the spawning biomass for the *M. paradoxus* population has fallen below its 2007 level, which will be considered a limit reference point for the fishery. Given that the OMP intends recovery of this population, an

upward revision of this reference point will be considered at the next four-yearly OMP review.

A guide as to what constitutes "substantial" is a change that would alter the recommended TAC by more than 3%.]

10.III.1.3 Description of Process for Action

If making a determination that there is evidence of Exceptional Circumstances, the WG will with due promptness:

- Consider the severity of the Exceptional Circumstances (for example, how severely "out of bounds" are the recent CPUEs and survey abundance estimates or recruitment estimates).
- Follow the principles for action (see examples below).
- Formulate advice on the action required (this could include an immediate change in TAC, a review of the OMP, the relatively urgent collection of ancillary data, or conduct of analyses to be reviewed at a further SWG meeting in the near future).
- Report to the Director Resources Research, DAFF that Exceptional Circumstances exist and provide advice on the action to take.

The Director Resources Research, DAFF will:

- Consider the advice from the SWG.
- Decide on the action to take, or recommendations to make to his/her principals.

10.III.1.4 Examples of 'Principles for Action'

If the risk is to the resource, or to dependent or related components of the ecosystem, principles may be:

- The OMP-derived TAC should be an upper bound.
- Action should be at least an x% decrease in the TAC output by the OMP, depending on severity.

If the risk is to socio-economic opportunities within the fishery, principles may be:

- The OMP-derived TAC should be a minimum.
- Action should be at least a y% increase in the TAC output by the OMP, depending on severity.

For certain categories of Exceptional Circumstances, specific metarules may be developed and pre-agreed for implementation should the associated circumstances arise (for example, as has been the case for OMP's for the sardine-anchovy fishery where specific modified TAC algorithms come into play if abundance estimates from surveys fall below pre-specified thresholds). Where such development is possible, it is preferable that it be pursued.

10.III.2. Regular OMP Review and Revision Process

The procedure for regular review and potential revision of the OMP is the process for updating and incorporating new data, new information and knowledge into the management procedure, including the operating models (OMs) used for testing the procedure. This process should happen on a relatively long time-scale to avoid jeopardising the performance of the OMP, but can be initiated at any time if the SWG considers that there is sufficient reason for this, and that the effect of the revision would be substantial. During the revision process the OMP should still be used to generate TAC recommendations unless a metarule is invoked.

10.III.2.1 Description of Process for Regular Review (see Figure App.10.III.2)

Every year the SWG will:

- Consider whether the procedure for Metarule Process has triggered a review/revision of the OMP. Note that if proposals by a SWG Member or Observer, or DAFF Management, for an Exceptional Circumstances review include suggestions for an OMP review and possible revision, they must outline in writing the reasons why they consider this necessary, and must either indicate where the data, information or analyses are to be found supporting their proposed review, or must supply those data or analyses in advance of the SWG meeting at which their proposal is to be considered.

This includes the possibility of a suggested improvement in the manner in which the OMP calculates catch limitation recommendations; this would need to be motivated by reporting results for this amended OMP when subjected to the same set of trials as were used in the selection of the existing OMP, and arguing that improvements in anticipated performance were evident.

Every two years the SWG will:

- Conduct an in depth stock assessment and review population, fishery and related ecosystem indicators, and any other relevant data or information on the population, fishery and ecosystem.
- On the basis of this, determine whether the assessment (or other) results are outside the ranges for which the OMP was tested (note that evaluation for Exceptional Circumstances would be carried out in parallel with this process; see procedures for the Metarule Process), and whether this is sufficient to trigger a review/revision of the OMP.
- Consider whether the procedure for the Metarule Process triggered a review / revision of the OMP.

Every four years since the last revision of the OMP the SWG will:

- Review whether enough has been learnt to appreciably improve/change the operating models (OMs), or to improve the performance of the OMP, or to provide new advice on tuning level (chosen to aim to achieve management objectives).

On the basis of this, determine whether the new information is sufficient to trigger a review/revision of the OMP.

In any year, IF the SWG concludes that there is sufficient new information to trigger a review/revision of the OMP, the SWG will:

- Outline the work plan and timeline (e.g. over a period of one year) envisaged for conducting a review.
- Report to the Director Resources Research, DAFF that a review/revision of the OMP is required, giving details of the proposed work plan and timeline.

- Advise the Director Resources Research, DAFF that the OMP can still be applied while the revision process is being completed (unless Exceptional Circumstances have been determined to apply and a metarule invoked).

In any year, IF the SWG concludes that there is no need to commence a review/revision of the OMP, the SWG will:

Report to the Director Resources Research, DAFF that a review/revision of the OMP is not yet required.

The Director Resources Research, DAFF will:

- Review the report from the SWG.
- Decide whether to initiate the review/revision process.

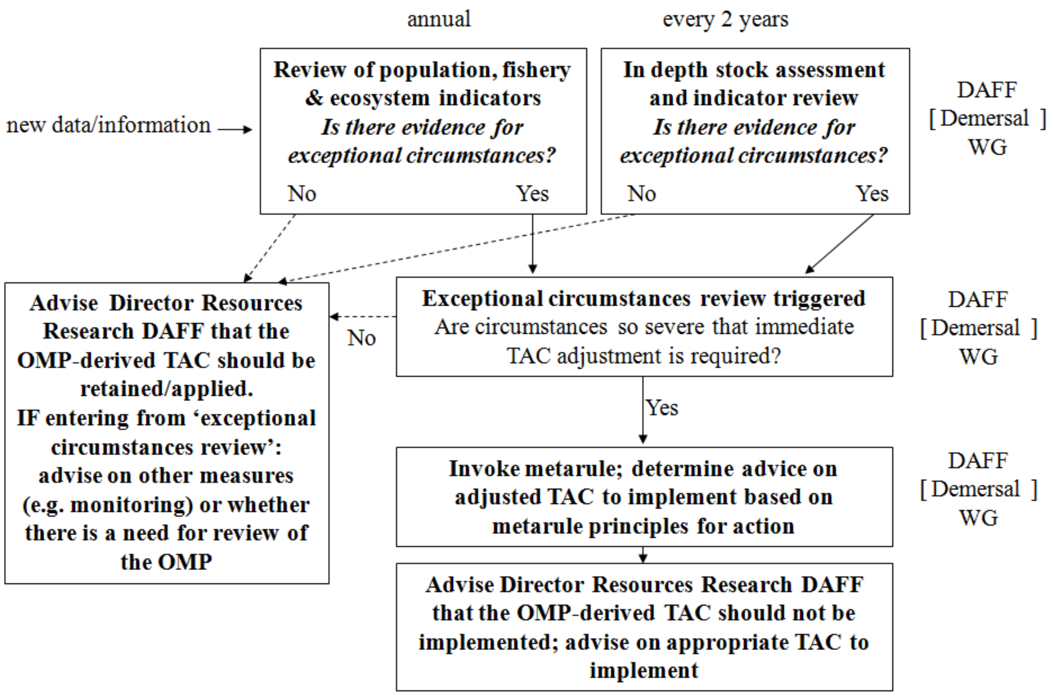

Figure App.10.III.1: Flowchart for Metarules Process

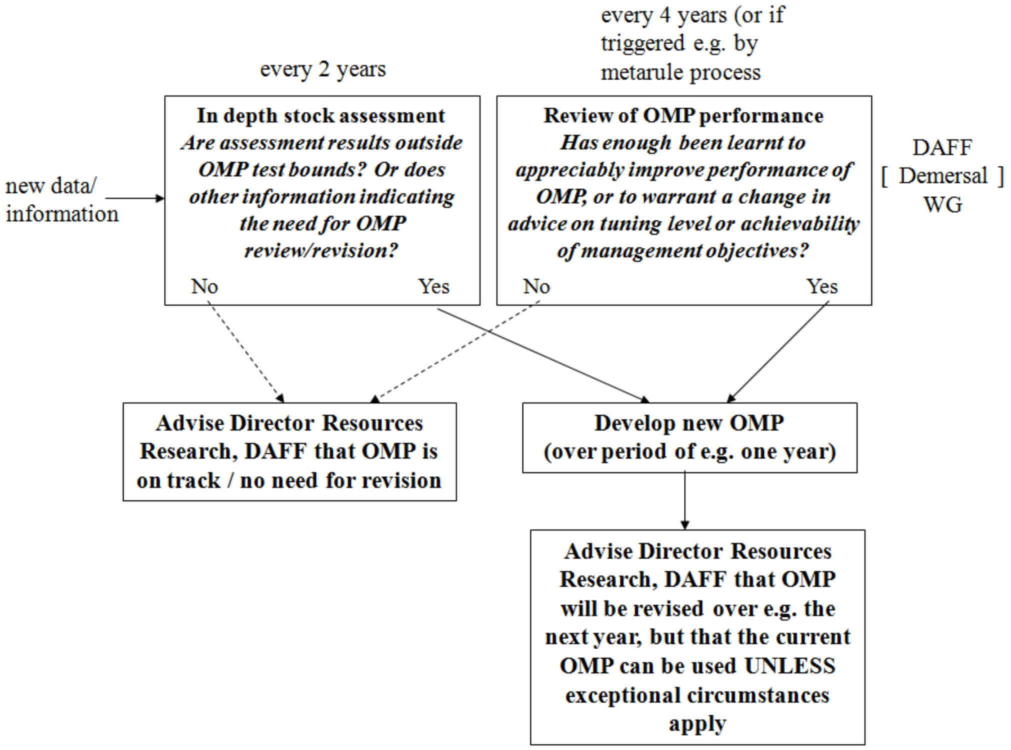

Figure App.10.III.2: Flowchart for Regular Review and Revision Process.

Chapter 11

Future work and overall conclusions

11.1 Future work

The current assessment and OMP for the South African hake provide a sound basis to manage this resource for the near future, and certainly until the next OMP review scheduled for 2014. The OMP basis used to provide TAC recommendations for this resource over recent years has demonstrated its intended adaptive behaviour in responding to trends in resource abundance indicated by new data forthcoming over time. However, some important questions have also been raised, which future research will need to attempt to solve. Some recommendations to address these problems, as well as suggestions to improve the current assessments and management of the resource are listed below.

11.1.1 Assessment

11.1.1.1 Changing selectivity-at-length over time

To date, only simple deterministic changes or trends in selectivity have been included in the South African hake assessments. Alterations in the selectivity of the offshore trawl fleet are modelled in a simple manner, being taken to differ over three fixed periods to take account of the change in the proportion of younger ages over time in the commercial catches (likely due to the phasing out of the (illegal) use of netliners to enhance catch rates) with linear trends between these periods. Future assessments should allow for variation in the behaviour of the fishers over time, for marketing and other reasons, which will be reflected by changes in selectivity.

Butterworth *et al*. (2003) present a time-series methodology to incorporate a temporal variability in the selectivity-at-age (which could equally be used for selectivity-at-length) in statistical catch-at-age analyses. This approach, in which age-specific selectivity is allowed to change over time within the bounds of some statistical distribution, would allow a more objective basis for accounting for selectivity changes, where at the moment, the choices of periods for constant and then linearly changing selectivity are somewhat arbitrary. Similarly, Nielsen (2011) describes a fully stochastic State-space Assessment Model (SAM) that allows selectivity (modelled as a random effect) to vary gradually with time. These approaches can be implemented using the ADMB package (Fournier *et al*. 2011).

11.1.1.2 Include additional CPUE information

South African hake assessment models are at present fitted to CPUE information from the offshore trawl fishery only (which accounts for about 90% of the total catch). Consideration needs to be given to the possibilities of using CPUE data for the trawl fleet operating inshore on the South Coast, as well as such data for the longline fleet on both the South and West Coasts. It is possible that these series will give a different perspective on the status of the resource, since different fleets have different selectivities and target different areas (such as untrawlable rocky ground in the case of longliners) where the species and age distribution of the hake may differ from those for the hake available to the offshore trawlers.

It has been shown in this thesis that the extent of *M. capensis* depletion is sensitive to a potential bias in the GLM-standardised CPUE series (Chapter 7). The possibility that factors responsible for an increase in catching efficiency may have been omitted from GLM standardisation needs to be investigated.

11.1.1.3 Species differentiation of the catch

The species-disaggregated estimates of annual catch used in the current hake assessments are computed from survey-based species proportion-by-depth relationships. This splitting algorithm assumes unchanging species ratios at depth for relatively long periods, but if *M. paradoxus* and *M. capensis* are changing in abundance at different rates, these ratios would change over time, giving biased estimates of species-disaggregated catches. On-board sampling by observers should be analysed regularly to validate the species-splitting.

11.1.1.4 Include discard information

The estimates of annual catch used in the current hake assessment are based on landed values, ignoring the practice of discarding small fish. As a consequence total removals are under-estimated, particularly for the younger age classes. To take this bias into account, catches prior to 1972 were increased by 39% (ICSEAF 1978). It is not clear how this figure of 39% was chosen and, if this increase was applied to compensate for all discarding, why no correction was applied post-1972. Discarding practices have undoubtedly changed over time and it has been suggested that, because of a lesser demand for fish and a greater availability of large fish in earlier years, the minimum size of fish retained prior to 1972 was somewhat larger than post-1972.

Although the effect of different discarding rates has been investigated through robustness tests (see Chapter 4), an analysis of all existing observer length-frequency data needs to be initiated to improve estimation of plausible discard rates so that this information can be included in future assessments of the resource. One way to model discarding of non-marketable fish would be to parameterize a "retention curve", by length, based on actual gear selectivity relative to what was marketed.

11.1.1.5 Temporal changes in somatic growth

For some species, the weight-at-age relationship can vary considerably from one cohort to the next. Sampling data from the surveys and the various commercial fisheries for hake need to be examined to check whether it is justified to assume (as for existing assessments) that the somatic growth curve is constant over time. If the results indicate that the level of variability is of sufficient magnitude to make an appreciable impact on the assessment results, this will have to be taken into account in future assessments.

11.1.1.6 Movement model

The next step in the assessment process needs to involve explicit spatial disaggregation by distinguishing different areas by depth and longshore coordinates, and estimating age-specific movement rates between these areas explicitly (instead of using selectivity-at-age or –at-length to mimic this).

From catch-at-length information, it is clear that the two hake species are not distributed evenly in terms of age/length in different areas. *M. capensis* is usually found in depths of less than 400 m, with the largest biomass in the 100-200 m depth range, while the distribution of *M. paradoxus* is mainly between 150 m and 500 m. There is also a tendency for hake to move offshore into deeper water as they grow older. Age information from the surveys furthermore suggests that young (up to age 3) *M. capensis* are primarily restricted to the West Coast (Le Clus 2005). At intermediate ages, a large proportion of these fish move to the South Coast. However, for the oldest fish (ages 6+), there is some movement back to the West Coast. Similarly for *M. paradoxus*, the smaller fish tend to be found more on the West Coast.

The current assessment of the resource treats each hake species as if it were homogeneously distributed throughout the whole region, and reflects the different age/length structure on the West and South coasts by assuming different fishing selectivities-at-age or -at-length for the commercial and survey fleets (so selectivity here combines both gear and availability effects). In the spatial model suggested above however, the survey and commercial fishing selectivities-at-age will separately be taken to be the same across all regions (i.e. reflecting gear effects only). The regional differences in the age/length distributions of the catches will therefore be explained instead by the different proportions of each age class in each region. Hake movement will be modelled using movement matrices, which reflect the probability that a fish of a particular age in region *r*' at the start of the year, moves to region *r* at the end of the year (e.g. Fournier *et al*. 1998). Plans are that this model will initially comprise nine regions, following the present survey area stratifications, so that all the survey data are readily available in this format. These regions include five depth zones on the West Coast and four on the South Coast.

11.1.1.7 Incorporating cannibalism and multi-species predation effects

The most important form of predation on Cape hakes is inter-specific (hake-on-hake) predation and to a lesser extent cannibalism (see for example Punt *et al*. 1992). Inter- and intra-specific predation are thus likely to be very important factors in regulating hake abundance off South Africa. A multi-species model-estimation procedure which takes explicit account of the high levels of inter-specific predation and cannibalism should be developed, perhaps by updating and extending models of the type developed by Punt and Hilborn (1994), and by Punt and Butterworth (1995) that explicitly incorporated feeding interactions amongst the two hake species and seals. The aims of such a model would be a clearer understanding of the population dynamics of the two hake species and a basis for future Operating Models (OMs) used to test Candidate Management Procedures (CMPs).

Smith *et al*. (2011) recommend that such a model starts simple and increases in complexity as needed. The model should fit to catch-at-age, catch-at-length and diet data (see, for example, Kinzey and Punt 2009) and attempt to estimate daily ration for the two hake species directly, rather than relying only on results for similar species elsewhere. Sufficient diet composition data (proportion of species/length eaten by predator length-class) to attempt this are available for hake on the South African West Coast. They recommend that the model should initially be based on a simple (e.g. Holling Type II) feeding functional relationship before examining the implications of alternative relationships.

11.1.2 Management Procedures

11.1.2.1 Incorporating environmental factors into survey biomass estimates

Consideration should be given to including environmental variables (such as wind speed, water colour and dissolved oxygen) when standardizing the survey catch rate data, focusing on those environmental parameters that can be linked to hake catchability. This would hopefully reduce the variance of the survey biomass estimates and hence lead to their being given greater weight in future assessments and OMPs.

As stressed in Chapter 6, including environmental data in the survey standardisation should not however be confused with some sort of "quality control" on the surveys, in which for example certain environmental conditions (such as "green water") would be avoided in conducting tows. If such avoidance behaviour were to take place in the future, when it did not in the past, the future survey series would then become non-comparable with the past and further calibration would be needed before the data could be used as input to any OMP.

11.1.2.2 Pseudo-species-specific management

Although the last two OMPs developed for South African hake have been species-split, the recommended TACs are still species-aggregated. Thus separate TACs for each species could be specified, but how practical would that be to implement? It would be very difficult, if not impossible, to manage the fishery using such separate TACs because this would require accurate species splits of the hake caught on every vessel-trip. However, "pseudo species-specific" management could be implemented by balancing allocation among sectors with the productivity of the component of the resource which they target or by broadly regulating the depths at which fishing takes place. Since the statuses of two species are estimated to differ considerably, with *M. paradoxus* below B_{MSY} and *M. capensis* well above, higher catches could be achieved. Towards this end, the effects of greater flexibility in implementation, such as allowing TACs each year to be over- or under-caught by up to some small percentage, should be investigated. Also, consideration should be given to the extent to which monitoring data on the catch species-composition (from on-board observers) should be used as an input to the OMPs.

11.1.2.3 Incorporate socio-economic factors

The comparison of alternative CMPs for scientific advice for the management of the South African hake resource is in terms of performance statistics. These performance statistics have principally been based on biological and 'operational' measures, such as expected catches, projected depletion levels and TAC variability from year to year. Although some simple economic parameters have been computed (e.g. a measure of economic performance and trends in effort), these have not been used in making the choice between CMPs. If pertinent quantitative inputs could be determined (which may prove difficult because economic conditions can change rapidly, particularly for export markets), it would be useful and straightforward to include economic considerations into the OMP selection process. Examples of economic factors that could be taken into consideration include the proportion of the TAC caught by trawling *vs* longlining, and the number of vessels in the fishery. Experience elsewhere has shown that, whilst challenging, incorporation of economic factors can be very valuable (e.g. Dichmont *et al*. 2010).

11.1.3 Ecosystem Approach to Fisheries

Over the last 20 years or so, there has been a worldwide call to move from traditional fisheries management practices, which largely depend on single-species assessment and management approaches, to the implementation of a more holistic ecosystem approach to fisheries (EAF) (Garcia *et al*. 2003). EAF is neither inconsistent with, nor a replacement for conventional target-species fisheries management, and is likely to be adopted as an incremental extension of current fisheries management approaches. In the Gulf of Alaska for example, measures taken include setting a cap on total groundfish yields which is less than the sum of the potential individual Allowable Biological Catches, prohibiting fishing in Stellar sea lion foraging areas and establishing a minimum biomass threshold for sea lion prey, as well as prohibiting bottom trawling on large areas of the continental shelf, e.g. to protect deep-water corals, while developing and monitoring various ecosystem status indicators (Witherell *et al*. 2000).

South Africa is committed to the EAF management ethos. For example in the purse-seine fishery for anchovy and sardine, increased attention is being given to the possibility that these fisheries may be negatively impacting the dynamics of land-breeding predator species such as the African penguin *Spheniscus demersus* (Crawford *et al*. 2006; Cunningham and Butterworth 2006). Furthermore the recent introduction of tori lines has proved successful in appreciably reducing the numbers of birds killed in the demersal trawl fishery. Other aspects which are within the ability of fisheries management to implement in an EAF context for hake include those described below.

11.1.3.1 Multispecies models

An obvious step in an EAF context in modelling the hake resource is to include multispecies interactions. To contribute to practical management advice, a multispecies modelling approach should provide at least qualitative and ideally defensible quantitative guidance as to the management of marine natural resources (Plagányi 2007).

Section 11.1.1.7 above describes future plans for the incorporation of cannibalism and intra-specific (hake-on-hake) predation effects into the modelling of the hake dynamics. The immediate suggestion in an EAF context is to extend this model to consider interactions with other components of the ecosystem, most notably Cape fur seals (*Arctocephalus pusillus pusillus*), in an incremental fashion, building on Punt and Butterworth (1995). Their analysis, defined as a Minimum Realistic Model (MRM), needs to be updated to take account of changes in and extensions to the data used as inputs, as well as the improved understanding since 1995 of the distribution and dynamics of the species involved.

Modelling approaches other than MRM should also be considered in addressing interactions of the hake resource with other components of the ecosystem. The Globally applicable Area Disaggregated General Ecosystem Toolbox (GADGET, Begley and Howell 2004) shows potential to contribute to practical fisheries management advice, with its rigorous statistical framework and being capable of detailed sensitivity in investigating alternative growth, consumption, movement and recruitment formulations (Plagányi 2007).

Nevertheless, while these multi-species models can provide useful insight and inform broad utilisation strategy, uncertainties about key components of the models (e.g. feeding functional relationships) which can have major quantitative impacts means that the tactical use of these models for computing specific harvest limits still seems some time off.

11.1.3.2 Marine Protected Areas

Marine Protected Areas (MPAs) fit well into an ecosystem approach because of their potential to address multiple objectives, such as fisheries management and habitat conservation. In South Africa, however, the implications for local fisheries are unclear, reflecting current controversy regarding the effectiveness of MPAs as fishery management tools (Hilborn *et al*. 2004, Walters *et al*. 2007). If MPAs are to be advanced on the basis of their proposed fishery benefits, then it is important that their implications for the fishery are quantitatively assessed (e.g. Walters *et al*. 2007, Holland 2000).

A spatial, age-structure population model of the South African hake resource, fitting to available data, has been developed by Edwards *et al*. (2009) to investigate the potential fishery consequences of an area closure within a realistic framework. The results show that for the model considered, although protected populations are likely to recover at low movement rates, the net benefit to the resource as a whole, and hence to the fishery, of MPA implementation is negligible for a relatively mobile species such as hake. This work merits further development, such as by modelling increased recruitment within the MPA zone, so that its conclusions could be made more general. This model might also be used to examine whether the impact of trawling on the benthos has had a detrimental impact on population productivity.

11.1.3.3 *Include ecosystem considerations into future MP*

MPs provide a strategic and practical framework for developing an operational EAF. Several ecosystem models for potential use as OMs within MP (and MSE) frameworks have recently been developed. For instance, the Atlantis modelling framework (Fulton *et al*. 2005) has been closely aligned to efforts to evaluate ecosystem indicators using a MSE approach. Atlantis can be configured flexibly to many different degrees of process detail for simulating “real world” dynamics, and an Atlantis model including hake is currently under construction (Smith and Fulton 2011).

In general, the level of development of ecosystem models can seldom provide quantitatively reliable predictions. Therefore, their implementation in MP evaluation exercises generally has been implicit only, by means of interim approaches/solutions. Rather than developing complicated multispecies testing models to contribute to their revised MP development process, IWC (1989) adopted a simpler method through allowing for time dependence in the intrinsic growth rate and carrying capacity parameters of a simple single-species OM. This served to mimic the typical impacts on the population modelled of changing levels of predator and prey species. Similarly, MP testing procedures for the South African hake resource have used changes in single-species parameters (such as carrying capacity, *K*) as a surrogate for ecosystem effects (Chapters 5 and 9). Attempts to incorporate bycatch, stock structure, and spatial aspects are increasingly being documented elsewhere (e.g. Punt *et al*. 2002; Dichmont *et al*. 2005).

11.1.4 Joint Management with Namibia

Justification for a joint management approach between Namibia and South Africa of the hake resources of the region needs a demonstration of reasonable plausibility that one or more stocks are shared. It also requires an evaluation of the consequences (for stock status and fishery performance) of alternative management arrangements under different scenarios pertaining to the extent of stock sharing.

If there is little or no sharing of stocks, separate management is quite adequate, and there are no adverse implications for either country arising from the actions or management success of the other. It is only in the case of substantial sharing of stocks (e.g. a single stock fished in both countries) that negative consequences can arise for one country from excessive fishing of the stock by the other. Such negative consequences can be avoided by joint management (such as agreed objectives and bases to divide allowable catches, and adequate catch controls in both countries). However joint management comes at an additional cost in terms of coordination. If there is little or no sharing of stocks, this additional cost represents a negative consequence of joint management.

A flexible model is needed to evaluate alternative stock structure hypotheses, and model selection techniques could be used to help discriminate between alternative stock structure hypotheses by examining fits of alternative models (embodying the hypotheses) to data. Simulations to evaluate the effects of various degrees of stock sharing and of different options for cooperative management responses are also required to evaluate the risks of not cooperating in management of a resource that is shared, and the benefits of cooperative management of a shared resource. Conducting simulations on alternate sharing hypotheses can be an important aid to understanding the benefits of cooperative management, and promoting common understanding of these benefits.

A spatial model (with explicit modelling of movement) as discussed in Section 11.1.1.6 would provide a suitable framework for a proper examination of the hypotheses of some actual stock overlap and/or movement across the border and their implications for management. This further model development is essential if joint management with Namibia is to be considered, as the selectivity-surrogate approach used in the current South African hake assessment would not be able to capture the implications of imbalanced catches in the different regions appropriately.

Some of the problems identified in the current South African assessments, such as low recruitment variability and high estimated natural mortality when this parameter is unconstrained, could be a result of model misspecification in terms of stock-structure, and so might be resolved by an extension of the assessment to include hake in Namibia.

More information is however needed before agreement can be obtained on the degree of sharing of the two hake species between Namibia and South Africa. Information of particular interest includes: spatial and temporal distribution of hake spawning, distribution and abundance of various life stages, examination of both commercial and research based data sets including biomass estimates, age and growth and length frequency data, genetics, morphometrics and other data relating to stock differentiation. Tagging could also provide important information to discriminate between alternative migration hypotheses, but innovative methods will need to be applied as generally barotrauma results in mortality of hake captured.

11.2 Overall conclusions

This Section summarises the major findings of and benefits arising from and the work accomplished, both scientifically and towards improved hake management.

11.2.1 Assessment

11.2.1.1 Improvements

Species-disaggregation: Until the late-1990s on the South Coast and early 2000s on the West Coast, the assessment methods treated the two hake species as one. This approach is unsatisfactory since the two species clearly present different population characteristics (such as growth rates, maturity-at-age, etc.) and particularly since the advent of longlining have been fished differently, with different age/length-selectivity patterns. Furthermore, the species composition of the fishery has changed over time with the catches having switched from consisting almost entirely of shallow-water hake to comprise principally deep-water hake later. Therefore, the development of a fully species-disaggregated assessment of the South African hake resource (Chapter 4) has been a major improvement in terms of representing the actual dynamics of the two populations and shedding more clarity on the status of the two stocks.

Gender-disaggregation and other demographic aspects: Given the gender-specific differences in somatic growth as well as in the longline fishery, a move towards a gender-disaggregated assessment as described in Chapter 8 is certainly the correct approach to take. Possibly because of insufficient gender-disaggregated data available, this step did not however seem to have a large impact on the results. The natural mortalities are still estimated to be surprisingly high for both species, and although the estimated recruitment variation has increased a little it remains very low compared to demersal fish species elsewhere in the world.

Fitting to age-length keys and moving to length-based fishing selectivities: In earlier assessments, the models were fit to catch- and survey-proportion-at-age estimates where these were available, and to length distribution data where such age data were not, with selectivity taken to be age-specific. This led to some inconsistencies in results, with problems of lack of fit to proportions-at-age and -at-length data. In the OMP-2011 RS a consistent (by construction) approach is used of fitting to the length distribution data for all years plus the age length keys where available, with selectivity taken more realistically to be length-specific. Moving from age-specific to length specific selectivities successfully resolved the conflict in the fits to the proportions-at-age and -at-length data. Recent assessments achieve reasonable fits to all data.

Fitting directly to age-length keys takes care of the selectivity-related bias in the von Bertalanffy fits to the growth rates. The age-length key (ALK) likelihood term (equation App.8.II.40) is however difficult to interpret and overweighted compared to other terms in the likelihood, and the question of by how much to downweight it is difficult to answer. Other methods that use length samples as well as age subsamples to estimate proportions-at-age, such as those described in Morton and Bravington (2003), could turn out to be more efficient.

11.2.1.2 Stock statuses

M. paradoxus:

In the OMP-2007 Reference Set (RS) (Chapter 4), the B_{current}/K for *M. paradoxus* spawning biomass for 2006 was about 8% (median over the RS). The updated RS (Chapter 9) indicates an improved *M. paradoxus* stock at about 16% of pristine for 2009. This improved perspective is partly due to the recent survey and CPUE series showing upward trends and a change in the maturity definition, but is also due to the assumption about the pre-1978 species-split of the offshore trawl catches.

Previously (Chapter 4) the assessments favoured (in terms of the likelihood) earlier values in the range from 1940 to 1970 for the mid-year of the shift from a primarily *M. capensis* to a primarily *M. paradoxus* fishery, and this led to lower values for B_{current}/K for *M. paradoxus*. In the updated assessment (Chapter 8), the likelihood is neutral in this respect. Following analyses of historic information (Leslie and Glazer 2010 and SADSTIA and

OLRAC 2010) on the likely depths of fishing around that time, the range of the years specified for the *M. capensis* to *M. paradoxus* shift has been moved somewhat later (a central value of 1958 for the RC), leading to a more positive appraisal of *M. paradoxus* status. Importantly however, though K estimates vary depending on the choice for this central shift year for the species dominating the catch, estimates of B_{current} and B_{MSY} are broadly stable across the range considered, with $B_{\text{current}}/B_{MSY}$ quite consistently estimated in the range of higher 50%s to lower 60%s in the OMP-2011 RS.

M. capensis: The stock status of the shallow-water hake is not as clear as that of the deep-water hake since recent data show little contrast. In most OMs of the OMP-2011 RS, *M. capensis* is estimated to be well above its B_{MSY}. Slight changes in the basic assumptions (a combination of high natural mortality and low steepness, as in RS11 and RS12) however can lead to this stock being estimated to be at only about 40% of its MSY level in 2009. It has been shown (Chapter 7) that a switch to an estimated low steepness (and hence lower MSY and biomass at which MSY would be realised) could occur if a negative bias trend in GLM-CPUE series exists.

The estimates of depletion for both species are closely related to estimated fishing proportions, with the recent fishing proportion approximately ten fold larger for *M. paradoxus* than for *M. capensis*.

11.2.1.3 Unresolved issues

High natural mortality: Upper bounds on natural mortality for both species are imposed in the assessments since unrealistically high values would result if these parameters were freely estimated. Values in excess of 0.5 yr^{-1} for mature hake (age 4 and above), which are little affected by cannibalism or predation by other hake species, seem unrealistically large. Essentially, the high M estimates arise because ageing (both commercial and research survey samples) suggests the presence of only very few hake of ages 7 and above. This is despite the fact that a decrease in selectivity at older ages (either as a result of greater net avoidance or occurrence of these older hake in deeper waters than covered by fishing operations and surveys) is directly estimated in the model fitting procedure for the species and fleet combinations for which data are available. The inclusion of cannibalism and inter-specific predation or important changes in the ageing (which is currently under review) could resolve this issue.

Low extent of recruitment variability: The extent of residual variability indicated in the most recent assessment (Chapter 8) remains low compared to the norm for populations of similar demersal species (Ricard *et al*. 2011). The output σ_R values increase, but only slightly from 0.18 to 0.26 for *M. paradoxus* and from 0.14 to 0.29 for *M. capensis* in moving from the Reference Case for OMP-2007 to that for OMP-2011; this is despite the gender-split of the assessment that was motivated in part to hopefully resolve this issue.

It could be that recruitment fluctuations are moderated by the heavy degree of cannibalism and inter-species predation on younger hake, *M. paradoxus* in particular. Fish younger than 2 years of age are hardly captured either in surveys or commercially; the assessments' estimates of recruitment therefore really refer to the proportion of recruits that survive their first two years of life. Furthermore, as with natural mortality estimates, the possibility of systematic errors in ageing again arises, and these could confound the detection of stronger and weaker cohorts.

11.2.2 Management Procedure

At the time of the OMP-2007 revision, the hake fishery was in a poor condition with abundance having recently declined, in part as a result of poor incoming recruitment to the two species. Catch rates in the fishery had dropped to economically near non-viable levels. Furthermore, separating the species in the analyses revealed that although the abundance of the shallow-water species was still at a reasonable level, the deep-water species had dropped to well below B_{MSY}.

At the 2002 World Summit on Sustainable Development in Johannesburg, nations committed to restore their fish stocks to the levels that would provide MSY by 2014 if possible. However, calculations in 2006 showed that to attain this target for deep-water hake would have required an immediate 40% cut in the then hake TAC of 150 thousand tons, and keeping catches at this reduced level for the next decade. Such an approach would have led to enormous socio-economic dislocation. Instead therefore the OMP adopted for hake in 2006 involved a less stringent approach with deep-water hake anticipated to reach their MSY target level only after 20 years, while also seeking a 50% increase in catch rates within the following decade. Over the last four years (2007 to 2010) the TAC was reduced under OMP-2007 to a little less than 120 thousand tons. While this required cutbacks in vessels and employment, the benefits in terms of improved catch rates and more healthy resources were already being seen in 2010, and the outlook for the fishery was much improved.

OMP-2007 was, however, not as conservative as the international norm for seeking reasonably rapid recovery of depleted resources to MSYL in the case of *M. paradoxus* (estimated to be at 8% of *K* in 2006, with a 20 year period for recovery to MSYL). This international norm seems to be converging towards a default MSYL at 40% of *K* with a limit reference point of half this value, and a recovery period of at most 10 years to get to MSYL. This led to difficulties in securing the continued certification of the fishery by the MSC which surfaced late in 2009. For the fishery to be granted re-certification, OMP-2011 therefore had to build in further precautionary considerations and B^{sp}_{MSY} and B^{sp}_{2007} (a low point on the past abundance trajectory) were included in the operational objectives as Target and Limit Reference Points respectively.

OMP-2011 was also further simplified and refined. While OMPs applied pre-2006 were model-based, OMP-2007 was empirical and derivative-based and OMP-2011 empirical and primarily target-based (providing more stable TACs than derivative-based candidates*)*. In the spirit of a limit reference point approach where additional conservation measures are taken if resource abundance drops below a specified threshold, an extra penalty was added: if in future recent CPUE and surveys indices fall below their average value over 2006-2008, the constraint on the maximum inter-annual TAC change is loosened so that TACs can be reduced more rapidly. The rigour of these analyses have certainly facilitated the maintenance of the MSC certification.

The MP approach applied to South African hake is amongst the most mature of such approaches, this fishery being the one longest under MP management world-wide. This approach has played a major role in ensuring the sustainability and effective management of this resource, not least because of the excellent correlation between scientific advice and management action, and the promotion of stakeholder involvement which the approach facilitated, especially through the difficult period that the fishery encountered midway through the first decade of this century.

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