TROPHIC MODEL-GENERATED INDICATORS OF THE SOUTHERN BENGUELA ECOSYSTEM FOR COMMUNICATING WITH FISHERIES MANAGERS

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Thesis presented for the degree of

MASTER OF SCIENCE

In the Department of Zoology

Faculty of Science

UNIVERSITY OF CAPE TOWN

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October 2010

Trophic model-generated indicators of the southern Benguela ecosystem for communicating with fisheries managers

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Plagiarism Declaration

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Previously published models are included in this dissertation for comparative purposes (1980s and 1990s - Shannon *et al.* 2003, and 1900s and 1960s - Watermeyer *et al.* 2008a). Use of this published research is referenced as appropriate within the dissertation.

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Acknowledgements

This dissertation would not have been possible without the support of a number of people and organisations. I wish to express my most sincere gratitude and appreciation to them all. First to my supervisors, Dr Lynne Shannon and Associate Professor Astrid Jarre - thank you for the thought-provoking discussions, your motivation and encouragement. Your guidance allowed me to produce this dissertation to the best of my ability. Thank you.

My postgraduate studies were made possible with financial support from the Solm Yach Fellowship, the South African Research Chairs Initiative (SARChI) of the Department of Science and Technology and the National Research Foundation, the Harry Crossley Postgraduate Scholarship and the KW Johnstone Research Scholarship. I am most grateful for your support.

I was fortunate to receive data/advice/suggestions from various people who gave freely of their time and expertise: C. Attwood (UCT), M. Gibbons (UWC), K. Jolly (UCT) and K. Watermeyer (UCT). Data were also received from various people from the Department of Agriculture, Forestry and Fisheries (DAFF) formerly known as, and referred to in this document as, Marine and Coastal Management (MCM) – Rob Cooper, Rob Crawford, Tracey Fairweather, Steve Kirkman, Rob Leslie, Carl van der Lingen and Jan van der Westhuizen. Thank you for making the data available to me.

All those involved with the 2009/2010 Applied Marine Science MSc course at UCT: course convenors, lecturers, Pavitray Pillay, Gilly Smith, fellow students – thank you for making my time at UCT a stimulating and enjoyable one. A big thank you to Ed Hill (UCT) for his unfailing help with all things computer related.

Lastly, to my Mom, sisters, close friends and family: Shukran/Thank you for all your support during my MSc journey. The well wishes, lunches, telephone calls and listening ears kept me sane so that I could reach the finishing point.

Abstract

Trophic model-generated indicators of the southern Benguela ecosystem for communicating with fisheries managers

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October 2010

An Ecosystem Approach to Fisheries (EAF) is the new management paradigm considered for ecosystems worldwide. Its aim is to balance a multitude of objectives, including those of conservation and exploitation.

Ecosystem modelling is recognised as a tool that may be used towards achieving an EAF. Trophic models are explicitly based on the interactions between ecosystem components and therefore allow stakeholders to view how pressures (environmental or anthropogenic) impact upon the ecosystem, as well as its individual components. An updated trophic model representing the 2004-2008 period within the southern Benguela ecosystem was constructed. This current model complements historic 1900s, 1960s and 1980s trophic models previously published. Examinations of the model outputs signify a change in the food web structure of the southern Benguela ecosystem. Specifically, there has been an increase in biomass of small pelagic fish and cephalopods between the 1980s and 2004-2008 periods, which has been accompanied by decreases in biomasses of the higher trophic level groups (hake, chondrichthyans, mammals and seabirds). Modelled large pelagic fish biomass has remained constant since the 1980s, but this is due to the increase in biomass of the faster growing and more productive snoek. Model consumption patterns of predators have also changed in response to fishing sectors becoming significant consumers of potential food sources, as well as changes in environmental conditions which have changed geographical distributions of potential food sources, i.e. small pelagic fish.

Indicators were extracted from the range of the southern Benguela ecosystem trophic models available. The indicators emphasise that small, planktivorous fish have become more abundant, whereas large, predatory/piscivorous fish have decreased in abundance within the southern Benguela ecosystem. They indicate that the hake and linefish fishing sectors have not been operating at ecologically optimal levels after the 1960s and within the current period. Fishing sectors based upon the small pelagic/planktivorous fish are currently operating at ecologically optimal levels according to the indicators. Community- and ecosystem-based, model derived indicators can therefore provide fisheries managers with insights regarding the state of the southern Benguela ecosystem.

The indictors which were deemed most meaningful for management within the southern Benguela ecosystem were selected for use within an expert system. Expert systems are computerised decision trees providing users with a logical framework in which to access synthesised information. To assess the trend in ecosystem status in response to fishing, three decision trees were developed which examined the southern Benguela ecosystem on a community level (Pelagic-caught fish and Demersal-caught fish community decision trees) and on the system level (ecosystem decision tree). The decision trees classified one period of the southern Benguela ecosystem as 'Deteriorating' (the period when industrial fishing first began – 1960s vs. 1900s) and the remaining periods as 'Not Improving'. Results obtained were compared with data-based suites of indicators. The current management strategy has ensured that the offshore southern Benguela ecosystem has not deteriorated further at the scale of the fish community and ecosystem functioning. Although the decision trees are conservative with regard to trends, the logic they employ is sound and robust. The expert systems, which are based on the decision trees developed, therefore provide fisheries managers with a logical framework to access the synthesised information and the reasoning behind the conclusions reached. Future steps towards the inclusion of reference levels for the community and ecosystem-scale indicators within the decision trees and expert systems, are recommended.

Chapter 1
General Introduction

1.1. Introduction

To date, fisheries management is still based on single-species considerations, whereas an ecosystem perspective has been identified as important for a more holistic management approach. In response to various fish stock collapses in the 20th century, along with important fisheries these stocks were supporting, and most notably the collapse of the Canadian cod stock off Newfoundland in the early 1990s, the Food and Agricultural Organisation (FAO) developed a Code of Conduct for Responsible Fisheries (1995) which provided guidelines for responsible fishing practices with a view to "*ensuring the effective conservation, management and development of living aquatic resources, with due respect for the ecosystem and biodiversity*". The Code was unanimously adopted on 31 October 1995 at the FAO Conference. This Code encouraged the formulation of a management strategy which would explicitly incorporate ecosystem considerations. The change in management approach was formally realised with the issuing of the 2001 Reykjavík Declaration on Responsible Fisheries in the Marine Ecosystem, which recognised that "*sustainable fisheries management incorporating ecosystem considerations entails taking into account the impacts of fisheries on the marine ecosystem and the impacts of the marine ecosystem on fisheries*". This declaration was reinforced at the 2002 World Summit for Sustainable Development held in Johannesburg, South Africa, where it was agreed that management sectors from fishing nations would incorporate an Ecosystem Approach to Fisheries by the year 2010 (Cochrane *et al.* 2004). An Ecosystem Approach to Fisheries (EAF) is defined as "*the development and management of fisheries in a manner that addresses the multiple needs and desires of societies, without jeopardizing the options for future generations to benefit from the full range of goods and services provided by marine ecosystems*" (FAO 2003, 2005). As a signatory to this international convention, South Africa has committed to implement an ecosystem approach in its domestic fisheries.

South Africa borders the southern Benguela ecosystem, an eastern boundary upwelling ecosystem located along its west coast (Figure 1.1). The southern Benguela ecosystem extends from the South African Orange River border with Namibia (29°S) on the west coast, to East London on the south coast (28°E), covering an area of 220 000 km^2. The marine fauna in the ecosystem is particularly rich (Gibbons *et al.* 1999) and due to its productive, upwelling nature, the southern Benguela ecosystem is able to support a number of commercial fisheries including small pelagic fish, large pelagic fish and hake. Variability in the natural system is high on a variety of scales, ranging from monthly to decadal, and predictability of its dynamics is a matter of ongoing research (e.g. V. Shannon *et al.* 2006). In the second half of the 1990s, a shift in the distribution of small pelagic fish (anchovy and sardine) was detected (van der Lingen *et al.* 2002, Fairweather *et al.* 2006, van der Lingen *et al.* 2006), which lasted until the second half of the present decade and is hypothesised to have been a result of changing environmental conditions (Howard *et al.* 2007, Roy *et al.* 2007). The distribution of small pelagic fish, comparing the 1980s and the second half of this decade (2003-2008), is also mapped within Figure 1.1 (K. Watermeyer, UCT, pers. comm.). The reduced presence of small pelagic fish along the west coast and the increased presence of small pelagic fish along the south coast during the 2003-2008 period is very noticeable (Figure 1.1).

These changes rang warning bells with marine ecologists, because the south coast is generally regarded as less productive than the west coast (Demarq *et al*. 2008), but supporting a number of potential predators of small pelagic fish. Due to the lower productivity, small pelagic fish, and notably sardine, were expected to grow more slowly, recruit less well and be subjected to higher predation mortality. The possibility of an ecosystem regime shift was postulated. Regime shifts signify a complete change in ecosystem status and function, which is different to the phenomenon of species alternations (Collie *et al.* 2004, Cury and Shannon 2004). Species alternations are described as alternating dominance patterns displayed by two species in one ecosystem, without any discernable change in overall ecosystem functioning (Schwartzlose *et al.* 1999, Cury *et al.* 2000, Bakun 2006). Long-term, large-scale changes in the functioning of an ecosystem may require fisheries management to be carried out differently, as they increase the potential for collapses of target stocks due to changes in the functioning of the ecosystem (Rothschild and Shannon 2004, Shannon *et al.* 2009b).

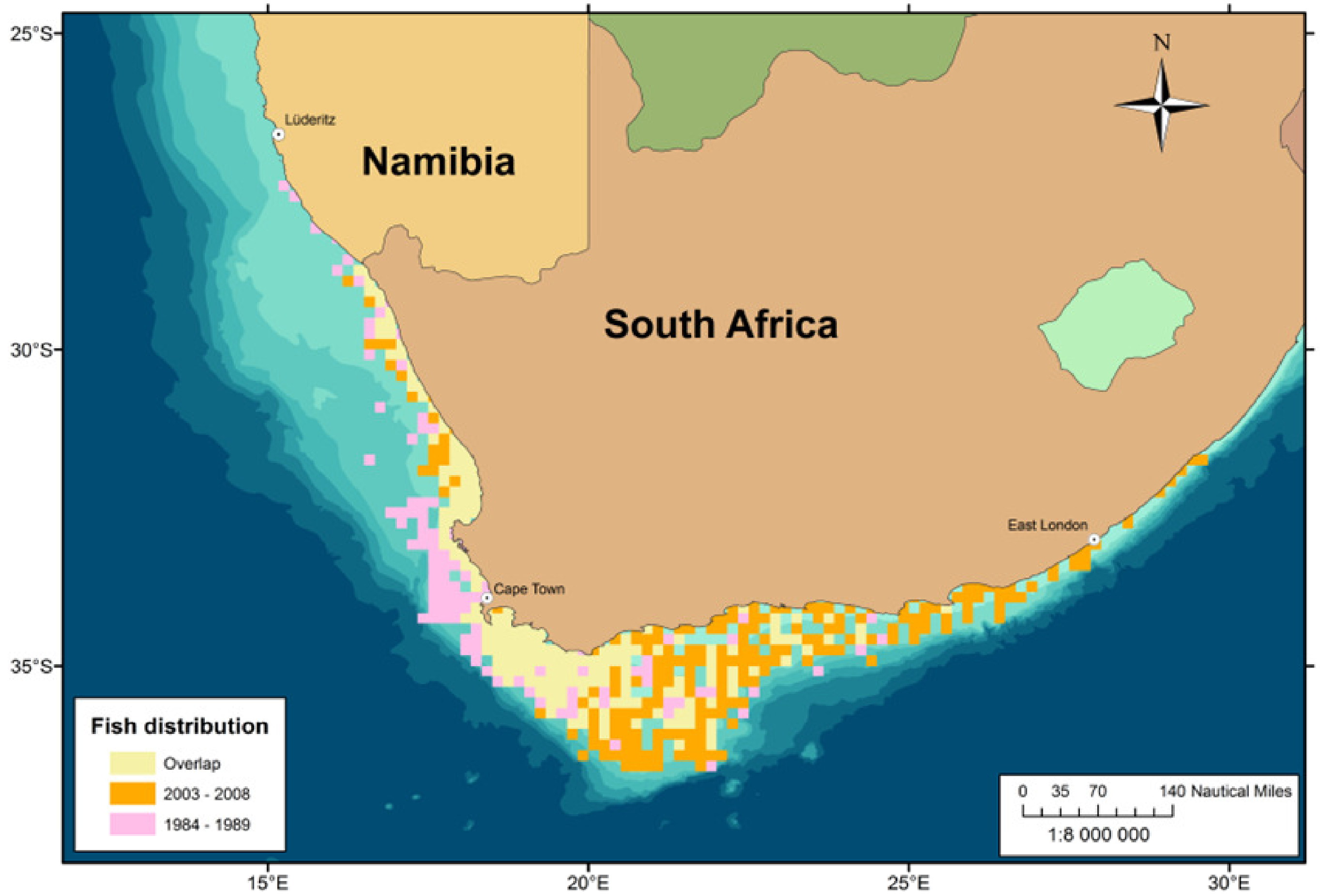


Figure 1.1: Map of the southern Benguela ecosystem (29°S to 28°E), and the distribution of small pelagic fish (anchovy and sardine) within the system during the 1980s and 2003-2008 periods. Distribution patterns provided by K. Watermeyer, UCT, based on Marine and Coastal Management (MCM) pelagic survey data. These distribution patterns represent 95% of small pelagic fish biomass surveyed (combined yearly summer and autumn surveys). The survey areas along the west coast between the two time periods do overlap. However, survey areas along the south coast were extended further eastwards along the coast from the 2000s, in response to reports of small pelagic fish catches from these previously un-surveyed areas (K. Watermeyer, UCT, pers. comm.)

Management and scientific research sectors within South Africa continue to need to prepare themselves to better face the challenges of dealing with unpredictable variability and change, and their interaction with fisheries management measures (Shannon *et al.* in press) within the southern Benguela ecosystem. Shannon *et al.* (2004) reported on the first workshop convened in 2002 which addressed potential ecosystem approaches within the South African domestic fisheries. The high priority objectives agreed upon at the workshop were:

(i) to rebuild depleted stocks

(ii) to take into account wider fisheries effects (e.g. bycatch issues)

(iii) to make better use of knowledge of the South African ecosystem, to reduce the risk of irrecoverable resource damage and economical/social crises

(Shannon *et al.* 2004)

Workshop participants acknowledged that ecosystem models would assist with the development of the overarching framework of a South African EAF (Shannon *et al.* 2004). There are a range of ecosystem modelling methods available for use within the southern Benguela ecosystem (Shannon *et al.* 2004). One of these is the Ecopath with Ecosim (EwE) modelling software (Pauly *et al.* 2000). EwE models represent the ecosystem and the flows (trophic interactions) between components, thus allowing scientists and managers to view potential ecosystem state scenarios in response to alternative fishing strategies (Pauly *et al.* 2000). This modelling method is especially useful because it provides management with a more holistic approach. It not only looks at future scenarios of the ecosystem, but can be used to reconstruct past ecosystem states. This is a useful exercise because it provides scientists, managers and other stakeholders with a standard view of the historic ecosystem, thus preventing the trap of shifting baselines (Pauly 1995). The historic northern Benguela ecosystem structure was similar to that of the current southern Benguela ecosystem (Watermeyer *et al.* 2008a, 2008b), i.e. a "wasp-waist" ecosystem structure in which mid-trophic level small pelagic fish exert top-down control of lower trophic level groups (plankton) and bottom-up control of higher trophic level groups (predatory fish, seabirds) (Cury *et al.* 2000, Bakun 2006). However, the northern Benguela ecosystem has undergone dramatic changes, starting with the collapse of the small pelagic fishery in the 1970s, and culminating in an ecosystem regime shift from a small pelagic fish dominated system, to that dominated by the less desirable pelagic goby and undesirable jellyfish (Lynam *et al.* 2006). Managers and researchers are therefore made aware that although the southern Benguela ecosystem is dynamic, it is still vulnerable to potential regime shifts, like that of the northern Benguela ecosystem.

Although the concepts of an EAF are now widely accepted, the sound implementation thereof remains a considerable challenge (Cochrane *et al.* 2004, Cochrane *et al.* 2009). Challenges include the reconciliation of objectives previously not addressed or considered in former management plans, including those of a socio-economic and an environmental nature (Cochrane *et al.* 2004, Shannon *et al.* 2006, FAO 2005). Indicators are system characteristics which provide feedback on progress towards management objectives (Slocombe 1998), and have been recognised as a necessary basis for the implementation of an EAF (Degnbol and Jarre 2004, Daan *et al.* 2005 and contributors therein, FAO 2005). Indicators are also a more cost-effective route for EAF implementation, which is crucial for a developing country like South Africa, which has limited resources for research (Degnbol and Jarre 2004). Data-based indicators for the assessment of ecosystem states and trends at the community and ecosystem scales were scrutinised in the IndiSeas project (Shin and Shannon 2010). Model-based indicators bear similar potential if based on good quality models (Fulton *et al.* 2005). For the southern Benguela ecosystem, the EwE suite of models is particularly well developed for analysis of long-term, large-scale changes in state (Shannon *et al.* 2003, Watermeyer *et al.* 2008a, 2008b, Shannon *et al.* 2009b).

Communication among stakeholders has been highlighted as one of the historic shortcomings in fisheries management. Degnbol and Jarre (2004) in particular emphasised that the selected indicators need to be accepted by and communicable among stakeholders. The information of a set of indicators of widely varying nature can be summarised into expert systems. Expert systems are computerised decision trees and as such, simple models for synthesis that guide users through the decision-making process in a transparent fashion, i.e. the user is able to review the process leading to the final decision, and explanations are provided at each step of the decision-making process. Typically, a user is asked to answer a list of questions, and with the application of simple IF-THEN rules, the user is guided along the decision tree towards a final decision (Starfield and Louw 1986). In contrast to a (computerised) expert system, the user cannot interact with a decision tree (on paper), where reasons for the routes taken along the decision tree, as well as for the final decision reached, are often embedded in long reports. Jarre *et al.* (2006) suggests that expert systems would be an appropriate tool for communication of long-term ecosystem-scale changes among stakeholders, since they contain "*a high degree of expertise in a form that makes it accessible to a novice*" (Starfield and Louw 1986). In this manner, knowledge can be accessed by all interested stakeholders.

This dissertation culminates in an expert system that uses trophic model-based indicators, which feed three decisions trees, to classify trends in the southern Benguela ecosystem, aiming to capture trends in response to fishing in particular. This is meant to serve as a step towards improving communication among scientists and fishery managers on indicators on a scale different to that of current practice, namely the scale of fish communities and the ecosystem that supports them.

1.2. Aims

This dissertation has three explicit aims. Each aim is tackled within a specific chapter of the dissertation as follows:

1. **2004-2008 Southern Benguela Ecosystem Trophic Model** (Chapter 2)
   Construction of an updated trophic model representing the current period (2004-2008) of the southern Benguela ecosystem. The trophic model for the current time period complements trophic models for past periods of the southern Benguela ecosystem published by Shannon *et al.* (2003) and Watermeyer *et al.* (2008a). The end result is a series of snapshots of the southern Benguela ecosystem from the largely unfished era to the current period.

2. **Trophic Model-Generated Indicators of the Southern Benguela Ecosystem** (Chapter 3)
   Extraction of indicators from current and past southern Benguela ecosystem trophic models and compilation of a list of trophic indicators that would be useful for management within the southern Benguela ecosystem.

3. **Developing a Decision Tree and Expert System for Fisheries Management within the Southern Benguela Ecosystem** (Chapter 4)
   Development of an expert system based on a decision tree for the southern Benguela ecosystem, using the trophic indicators generated from the models (Chapter 3). The

expert system aims to inform fisheries managers about trends of the southern Benguela ecosystem and its components.

A summary of the results and conclusions is presented in Chapter 5. Literature cited is given in Chapter 6, and details of the analyses are presented in an Appendix (Chapter 7).

Chapter 2

2004-2008 Southern Benguela Ecosystem Trophic Model

2.1. Model Construction

The southern Benguela ecosystem was modelled using the Ecopath with Ecosim (EwE) software version 5.1 (Pauly *et al.* 2000). The software is designed for the construction, parameterisation and analysis of mass-balanced trophic models of ecosystems (Pauly *et al.* 2000, Christensen *et al.* 2005).

The energy of a particular ecosystem component is balanced using the equation:

$$Consumption\ (Q) = Production\ (P) + Respiration\ (R) + Unassimilated\ food\ (\mathrm{U})$$

(Christensen *et al.* 2005)

The energy flows between ecosystem components are balanced using the equation:

$$\begin{aligned} &Production\ of\ (i) \\ &\quad = Mortality\ of\ (i)\ by\ predation \\ &\quad + Mortality\ of\ (i)\ by\ harvesting \\ &\quad + Other\ export\ of\ (i) from\ the\ system \\ &\quad + Other\ mortality\ of\ (i) \end{aligned}$$

(Christensen *et al.* 2005)

Typically, the data input required for each model component are Biomass (B), Production (P) / biomass (B) ratio, Consumption (Q) / biomass (B) ratio, Diet matrix, Catches and Other exports.

2.1.1 Input data

Thirty-two trophic groups, 31 living groups and a detritus group, were used in the trophic model representing the southern Benguela ecosystem for the period 2004-2008. Initial input parameters and data sources for the living groups are shown in Appendix Table 7.1.

2.1.1.1. Model groups and estimation of biomass

The biomass values (t) for each group and data sources are shown in Appendix Table 7.1. Biomass estimates for demersally surveyed groups excludes the year 2006 because different trawl gear was used from that in 2004-2005 and 2007-2008. The data collected by the two gear types are therefore not comparable.

Primary Producers (model groups 1 and 2)

The primary producers within the southern Benguela ecosystem include Phytoplankton and Benthic producers. Brown *et al.* (1991) estimated average primary production for the southern Benguela at 2.0 g C^{-1} d^{-1} in the 1980s. Recent estimates of primary production by Barlow *et al.* (2009) for the Benguela are within the range of Brown *et al.*'s (1991) observations, suggesting that productivity in the Benguela has been consistent for at least two decades (Barlow *et al.* 2009). An estimate of standing stock of phytoplankton specific to the southern Benguela ecosystem was derived from Barlow *et al.*'s (2009) measurements. The primary productivity measurements for the southern Benguela ecosystem for summer and winter were converted to wet weight for phytoplankton using a 14.25 conversion factor (Brown *et al.* 1991). Wet weight was converted to biomass using the production-biomass ratio, 154.4 yr^{-1}, following Shannon *et al.* (2003). The Phytoplankton biomass value entered into the model was the average biomass calculated for summer and winter in the southern Benguela ecosystem (Appendix Table 7.1). Biomass of Benthic producers was unknown and was thus estimated by the model.

Zooplankton (model groups 3-6)

Zooplankton is divided into four groups: Microzooplankton (2-200µm), Mesozooplankton (200-2000µm), Macrozooplankton (2-20mm) and Gelatinous zooplankton. Microzooplankton includes nanoflagellates, ciliates and zooplankton larvae. Mesozooplankton include copepod species, the majority of which are *Calanoides carinatus* and *Calanus agulhensis*. Macrozooplankton include euphausiids, amphipods and fish larvae. Long-term trends of zooplankton abundance from the southern Benguela ecosystem suggest a 100-fold increase from the 1950s until the mid-1990s (Verheye *et al.* 1998). However, recent data suggest that there has been a reversal in this trend (Marine and Coastal Management (MCM) unpublished data/report). Gelatinous zooplankton include cnidarians, ctenophores, tunicates and chaetognaths. Biomass of micro-, meso- and macrozooplankton was estimated by the model. The biomass of gelatinous zooplankton in the southern Benguela ecosystem is thought to be constant since the 1980s (M. Gibbons, UWC, pers. comm. at the time of these analyses), which is the complete opposite of the situation in the northern Benguela ecosystem, where jellyfish biomass is much greater than fish biomass in the system (Lynam *et al.* 2006).

Small pelagic fish (model groups 7-13)
In upwelling ecosystems across the world, including the southern Benguela, there is a mid-trophic level which is occupied by small pelagic fish. These small pelagic fish play an important role in the trophic dynamics within the ecosystem through top-down control of zooplankton and bottom-up control of the larger predators (Cury *et al.* 2000, Bakun 2006). These ecosystems have therefore been referred to as "wasp-waist" ecosystems (Cury *et al.* 2000, Bakun 2006). An additional complexity within the ecosystem is introduced when species alternations take place as a result of changing environmental conditions, i.e. one species flourishes while another declines, without any change to the functioning and structure of the ecosystem (Schwartzlose *et al.* 1999, Cury *et al.* 2000, Bakun 2006, Shannon *et al.* 2006). The extreme variability in abundance of small pelagic fish is one of the ecological issues which have been identified as a high risk threat to the sustainability of the small pelagic fishery within the southern Benguela ecosystem (Shannon *et al.* 2006, Nel 2007b).
Small pelagic fish in the model are separated into seven different groups: Anchovy (*Engraulis encrasicolus*), Sardine (*Sardinops sagax*), Redeye/Round herring (*Etrumeus whiteheadii*), Chub mackerel (*Scomber japonicus*), Adult and Juvenile horse mackerel (*Trachurus trachurus capensis*) and Other small pelagic fish, following Shannon *et al.* (2003). Horse mackerel are modelled as juveniles (<20cm) and adults (>20cm) because of differences in the diet and habitat between the two life stages. Adults are more piscivorous whereas juveniles are planktivorous (Crawford 1989). Adults and juveniles are also fished using different gear. Biomass estimates for the Anchovy, Sardine, Redeye, Chub mackerel, Adult and Juvenile horse mackerel model groups were obtained from unpublished MCM survey data and are shown in Appendix Table 7.1.
The Other small pelagic fish group comprises species which are less abundant within the southern Benguela ecosystem, such as flying fish (Exocoetidae), pelagic goby (*Sufflogobius bibarbatus*) and saury (*Scomberesox saurus*). The biomass for the Other small pelagic fish group was assumed to be the same as that used in the 1980s model, since the 2004-2008 catch reported for this group was the same as that reported for the 1980s and used in Shannon *et al.* (2003).

Mesopelagic fish (model group 14)
Mesopelagic fish are important in pelagic food webs and provide a link between the top predators and the plankton community (Prosch *et al.* 1989). Mesopelagic fish include the lanternfish (*Lampanyctodes hectoris*) and lightfish (*Maurolicus muelleri*). The biomass for this group is poorly known and was estimated by the model.

Large pelagic fish (model groups 15-16)
Large pelagic fish in the southern Benguela ecosystem were modelled as two separate groups: Snoek and Other large pelagic fish. Snoek (*Thyrsites atun*) is the most abundant and commercially important large pelagic fish in the southern Benguela ecosystem. No biomass estimate is available for this species and biomass was therefore estimated by the model and compared to that estimated for previous decades.

Species comprising the Other large pelagic fish group include kob (*Argyrosomus inodorus*), geelbek (*Atractoscion aequidens*), yellowtail (*Seriola lalandii*), tuna (*Thunnus* sp.), carpenter (*Argyrozona argyrozona*) and hottentot (*Pachymetopon blochii*). These species together represent an important portion of the commercial linefishery currently in operation. A review of the status of linefish stocks in the late 1990s by Griffiths (2000), revealed that nearly all linefish species were overexploited (*cpue* decline >75%). It is not believed that biomass levels have changed since this review.

Abundance indices for each species from research demersal surveys for the 1980s, 1990s, 2000-2003 and 2004-2008 periods, were obtained from unpublished MCM data. A combined abundance index (west and south coast) was calculated for each species, and then pooled for the Other large pelagic fish group for the various years. The percentage change in biomass for this group for successive time periods was calculated and used as a guide for adjusting the biomass estimate for the current period. Data from the demersal surveys indicate that biomass of the Other large pelagic fish group increased by 39% from the 1980s to 1990s, decreased by 46% from the 1990s to the early 2000s and decreased by a further 12% from the early 2000s to the current period. An overall decrease of 19% was therefore applied to the Other large pelagic fish biomass used in the 1980s model by Shannon *et al.* (2003) (Appendix Table 7.1).

Cephalopods (model group 17)
Various species of cephalopod occur in the southern Benguela ecosystem including *Loligo* sp. (squid/"chokka"), common and giant octopus (*Octopus* sp.), cuttlefish (*Sepia* spp.), greater flying squid (*Todarodes angolensis*) and lesser flying squid (*Todaropsis eblanae*). Cephalopods form an important dietary component of various groundfish species (Lipinski *et al.* 1992) and are known predators of mesopelagic and small pelagic fish within the southern Benguela ecosystem (Lipinski 1992).

Abundance indices for each species from demersal research surveys for the 1980s, 1990s, 2000-2003 and 2004-2008 periods, were obtained from unpublished MCM data. A combined abundance index (west and south coast) was calculated for each species, and then pooled for the Cephalopod group for the various years. The percentage change in biomass for this group for successive time periods was calculated and used as a guide for adjusting the biomass estimate for the current period. Data from the demersal surveys indicate that biomass of the Cephalopod group increased by 26% from the 1980s to 1990s, decreased by 5% from the 1990s to the early 2000s and increased by 8% from the early 2000s to the current period. An overall increase of 30% was therefore applied to the cephalopod biomass used in the 1980s model by Shannon *et al.* (2003) (Appendix Table 7.1).

Hake (model groups 18-21)

Two species of Cape hake occur within the southern Benguela ecosystem: the shallow-water hake *Merluccius capensis* and the deep-water hake *M. paradoxus*. Hake are modelled as four separate groups - Small and Large *M. capensis*, and Small and Large *M. paradoxus* - as a result of diet differences and cannibalism within and between the two species. Small hake are defined as 0-2 years old (smaller than 29cm), whereas large hake are defined as three years or older (bigger than 30cm), following Payne (1989). In order to calculate small vs. large ratios, hake length frequency data were provided by MCM on a cruise-by-cruise basis for each station sampled for the 2004-2008 period. The total estimated number of fish per 1cm length class per year was converted to biomass by applying the length-weight relationship of Fairweather (2008) to the data collected during the research surveys for each species. Annual small vs. large ratios could then be calculated for the west and south coasts separately, and were subsequently combined to obtain an overall small vs. large biomass ratio for each species.

For the period 2004-2008, the overall average ratio of large *M. paradoxus* was 90% and 50% for the south and west coasts respectively, i.e. 90% of the *M. paradoxus* surveyed on the west coast were large, whereas only 50% of those surveyed on the south coast were large. The annual portion of large *M. paradoxus* ranged between 84-95% on the south coast and 40-70% on the west coast. The annual large *M. capensis* ratio ranged between 86-94% and 31-80% for the south and west coasts respectively, for the period 2004-2008. The overall average portion of large *M. capensis* calculated for this period was 90% on the south coast and 53% on the west coast. Since the south coast research survey is conducted in autumn and the west coast survey in summer, it is not completely unreasonable to assume that combining the south and west coast surveys provides a rough estimate of the overall distribution of Cape hake in the southern Benguela ecosystem. The combined coast annual large hake ratio ranged between 46-72% for *M. paradoxus* and 59-86% for *M. capensis*. Thus, on average, of the *M. paradoxus* surveyed, 59% were large fish, and of the *M. capensis* surveyed, 75% were large fish. The overall average adult ratio for each species was applied to the demersal survey abundance estimates to obtain biomass estimates for large hake for both species (Appendix Table 7.1). Although small hake ratios were calculated for each species, these ratios were not used since the surveys are known to under-sample the proportion of small hake available (Shannon 2001). The biomass of small hake for both species was estimated by the model.

Demersal fish (model groups 22-23)

Demersal fish are classified as living near or on the seabed. To facilitate comparison with models of previous periods, the same model groupings were adopted, i.e. demersal fish in the southern Benguela ecosystem are divided into pelagic- and benthic-feeders. The species comprising each group are shown in Table 2.1. Since the biomass of all demersal fish species comprising each group are not adequately surveyed (surveys are designed specifically for the assessment of Cape hake), the biomass for each demersal group was estimated by the model and compared to estimates obtained for previous time periods.

Table 2.1: Demersal fish included in the 2004-2008 southern Benguela ecosystem trophic model.

Model Group	Common Name	Scientific Name
Pelagic-feeding demersal fish	Angelfish	*Brama brama*
	Southern rover	*Emmelichthys nitidus nitidus*
	Pencil cardinal	*Epigonus denticulatus*
	Buttersnoek (ribbonfish)	*Lepidopus caudatus*
	Jutjaw	*Parascorpis typus*
	Windtoy	*Spicara axillaris*
	Cutlass fish	*Trichuiurus lepturus*
	Cape John Dory	*Zeus capensis*
Benthic-feeding demersal fish	West Coast sole	*Austroglossus microlepis*
	Agulhas sole	*Austroglossus pectoralis*
	Hairy conger	*Bassango aalbescens*
	Sharp-nosed rattail	*Caelorinchus braueri*
	Large-scaled rattail	*Caelorinchus simorhynchus*
	Rattails	*Caelorinchus* sp.
	Cape gurnard	*Chelidonichthys capensis*
	Lesser gurnard	*Chelidonichthys queketti*
	Gurnards	*Chelidonichthys* sp.
	Bank steenbras	*Chirodactylus grandis*
	Large-scaled rattail	*Coelorinchus fasciatus*
	Spinenose horsefish	*Congiopodus spinifer*
	Smooth horsefish	*Congiopodus torvus*
	Redspotted tonguefish	*Cynoglossus zanzibarensis*
	Red rover	*Emmelichthys nitidus*
	Kingklip	*Genypterus capensis*
	Beaked sandfish	*Gonorhynchus gonorhynchus*
	Jacopever	*Helicolenus dactylopterus*
	Monkfish	*Lophius vomerinus*
	Smooth-scaled rattail/Purple grenadier	*Malacocephalus laevis*
	Dragonette	*Paracallionymus costatus*
	Panga	*Pterogymnus laniarius*
	African gurnard	*Trigloporus l. africanus*

Chondrichthyans (model groups 24-26)

There are 36 chondrichthyan species which inhabit the Benguela Current Large Marine Ecosystem (BCLME) region, i.e. waters alongside Angola, Namibia and South Africa (Basson *et al.* 2007). All of these species have a conservation status of “Threatened” (Basson *et al.* 2007).

Following the same species aggregation as adopted in previous models, chondrichthyans in the southern Benguela ecosystem are modelled as three separate groups based on feeding habits: Pelagic-feeding chondrichthyans, Benthic-feeding chondrichthyans and Apex chondrichthyans. The species comprising each group are shown in Table 2.2.

Abundance indices for each species from demersal research surveys for the years 2004-2005 and 2007-2008 were obtained from unpublished MCM data. A combined abundance index (west and south coast) was calculated for each species, and then pooled for the Pelagic- and Benthic-feeding chondrichthyan groups such that an average abundance could be calculated for each chondrichthyan group (Appendix Table 7.1). The demersal research surveys are not designed to sample apex chondrichthyans and as such, the only abundance index recorded for an apex chondrichthyan species occurred in 2006. Due to this lack of data, the apex chondrichthyan percentage estimation used in previous models was repeated for the current model (Shannon *et al.* 2003; 1980s model assumed apex chondrichthyans represented 3% of the total chondrichthyan biomass). The final biomass calculated is similar to that which was obtained in the 1980s model (Appendix Table 7.1).

The previous model estimated chondrichthyan group ratios based on shark biomass estimates of Wilkinson *et al.* (1994). Although the biomass indices calculated for the current model are only minimum estimates based on a sub-set of chondrichthyan species, they are based on actual data collected for the recent period. These estimates are therefore considered to be a more accurate representation of chondrichthyan biomass occurring in the southern Benguela ecosystem, than an estimated ratio adopted in models of previous periods.

Table 2.2: Chondrichthyans included in the 2004-2008 southern Benguela ecosystem trophic model.

Model Group	Common name	Scientific name
Pelagic-feeding chondrichthyans	Copper shark	*Carcharhinus brachyurus*
	Short-finned mako shark	*Isurus oxyrhincus*
	Blue shark	*Prionace glauca*
	Skates and Rays	*Raja* spp.
	Leopard skate	*Raja leopardus*
	Twineye skate	*Raja miraletus*
	Biscuit skate	*Raja straeleni*
	Smooth hammerhead	*Sphyrna zygaena*
	Dog shark	*Squalus acanthias*
	Dog shark	*Squalus mitsukurii*
	Atlantic electric ray	*Torpedo nobiliana*
Benthic-feeding chondrichthyans	St Joseph's shark	*Calliorhincus capensis*
	Ragged-tooth shark	*Carcharius taurus*
	Blue stingray	*Dasyatis chrysonota*
	Stingrays	*Dasyatis* spp.
	Thorntail stingray	*Dasyatis thetidis*
	Soupfin shark	*Galeorhinus galeus*
	Puffadder shyshark	*Haploblepharus edwardsii*
	Smooth houndshark	*Mustelus mustelus*
	White-spotted hound shark	*Mustelus palumbes*
	Houndsharks	*Mustelus* spp.
	Sawshark	*Pliotrema warreni*
	Spotted catshark	*Porodera africanum*
	Striped catshark	*Porodera pantherium*
	Barbled catsharks	*Poroderma* spp.
	Spearnosed skate	*Raja alba*
	Slimeskate	*Raja pullopunctata*
	Blancmange skate	*Raja wallacei*
	Yellowspotted catshark	*Scyliorhinus capensis*
	Dogfish	*Squalops megalops*
	Spiny dogsharks	*Squalus* spp.
	Two fin electric rays	*Torpedo* spp.
	Electric ray	*Torpedo fuscomaculata*
	Spotted gully shark	*Triakis megalopterus*
Apex chondrichthyans	Great white shark	*Carcharodon carcharias*
	Six-gilled shark	*Hexanchus griseus*
	Seven-gilled shark	*Notorhinchus cepedianus*

Marine mammals (model groups 27-28)

Marine mammals in the southern Benguela ecosystem are modelled as two groups: Seals and Cetaceans. The Cape fur seal (*Arctocephalus pusillus pusillus*) currently breeds at 11 localities around South Africa (Kirkman *et al.* 2007). Overall seal population estimates for South Africa and Namibia have increased from 100 000 individuals during the peak harvesting period (Shaughnessy and Butterworth 1981 as cited by Kirkman *et al.* 2007) to approximately 2 million individuals in 1993 (Butterworth *et al.* 1995). Recent population censuses suggest that there has been very little change in the population size since 1993 (Kirkman *et al.* 2007; S. Kirkman, MCM, pers. comm. at the time of these analyses). Biomass for this group was therefore kept at the constant value used in the previous 80s, 90s and early 2000s trophic models (Shannon *et al.* 2003, Watermeyer *et al.* 2008a) (Appendix Table 7.1). The Cetaceans group only includes species considered to be regular feeders within the southern Benguela ecosystem (Table 2.3).

Table 2.3: Cetaceans included in the 2004-2008 southern Benguela ecosystem trophic model.

Common name	**Scientific name**
Heavyside's dolphin	*Cephalorhynchus heavisidii*
Common dolphin	*Delphinus delphis*
Dusky dolphin	*Lagenorhyncus obscurus*
Bottlenose dolphin	*Tursiops truncatus*
Bryde's whale	*Balaenoptera edeni*
Sperm whale	Physeteridae

Seabirds (model group 29)

There are 15 resident seabird species in the southern Benguela ecosystem (Table 2.4). The Leach's storm petrel was only confirmed as a resident breeding seabird in 1997 (Whittington *et al.* 1999, Kemper *et al.* 2007). The conservation status for these seabirds have been reviewed and only six of the species are classified as of "Least concern" (Kemper *et al.* 2007). The other nine species fall within the "Vulnerable to Critically Endangered" conservation status (Kemper *et al.* 2007).

Biomass for each seabird species for the 1980s (excluding Leach's storm petrel) was originally calculated by Crawford *et al.* (1991). Updated breeding population numbers for each seabird species are available in Underhill *et al.* (2002), Crawford *et al.* (2006), Crawford *et al.* (2007a), Crawford *et al.* (2007c) and Kemper *et al.* (2007). The breeding population of White-breasted cormorants in South Africa was calculated as a ratio of the entire Namibian-South African breeding population estimate available (Kemper *et al.* 2007). Non-breeding population numbers for each species were obtained after applying a conversion factor (Crawford *et al.* 1991) to the updated breeding population numbers. No conversion factor was applied to Leach's storm petrel since the breeding population represents less than 0.1% of total seabird breeding numbers available in the southern Benguela ecosystem. Biomass per species was calculated by multiplying the entire population size (breeding plus non-breeding numbers) by the mass for each bird species (Crawford *et al.* 1991). Mass for the Leach's storm petrel was obtained from Underhill *et al.* (2002). The overall biomasses calculated for the seabird group, as well as individual biomasses calculated for each species, are shown in Appendix Tables 7.1 and 7.2 respectively.

Table 2.4: The 15 resident seabird species included in the 2004-2008 southern Benguela ecosystem trophic model.

Common Name	Scientific name
African penguin	*Spheniscus demersus*
Bank cormorant	*Phalacrocorax neglectus*
Cape cormorant	*Phalacrocorax capensis*
Crowned cormorant	*Phalacrocorax coronatus*
White-breasted cormorant	*Phalacrocorax lucidus*
Cape gannet	*Morus capensis*
Greyheaded gull	*Larus cirrocephalus poicephalus*
Hartlaub's gull	*Larus hartlaubii*
Kelp gull	*Larus dominicanus vetula*
Great white pelican	*Pelecanus onocrotalus*
Leach's storm petrel	*Oceanodroma leucorhoa*
Caspian tern	*Sterna caspia*
Damara tern	*Sterna balaenarum*
Roseate tern	*Sterna dougallii*
Swift tern	*Sterna bergii bergii*

2.1.1.2. Catches

The total catches ($t.yr^{-1}$) calculated for each model group, with the source document, are shown in Appendix Table 7.1. The catches calculated per fishing gear per model group can be viewed in Appendix Table 7.3.

Small pelagic fish (model groups 7-13)

The small pelagic fishery in South Africa developed in the 1940s. The target species are anchovy and sardine, with the associated bycatch species being redeye/round herring and horse mackerel. Catches within this fishery have fluctuated dramatically over the years, but have remained at an average 250 000 tons for both anchovy and sardine for the years 2000-2005 (Nel 2007b). The industry employs 7 800 people and the approximate market value of the landed catch in 2005 was R800 million per annum (Nel 2007b). 2004-2008 Catches for the small pelagic fish groups were obtained from unpublished MCM data (Appendix Table 7.1).

Mesopelagic fish (model group 14)
Mesopelagic fish are caught alongside conventionally harvested species within the pelagic (purse-seine) fishery, with the lanternfish being caught since the late 1960s (Prosch *et al.* 1989). 2004-2008 Catches were obtained from unpublished MCM data (Appendix Table 7.1).

Large pelagic fish (model groups 15-16)
Large pelagic fish are caught within the pelagic longline fishery and the commercial linefishery. 2004-2008 Catches were obtained from unpublished MCM data (Appendix Table 7.1).

Cephalopods (model group 17)
Cephalopods have been exploited since the 1960s. The fishery currently employs 3 000 people and the landed catch is worth more than R180 million per year (Petersen and Nel 2007). 2004-2008 Catches were obtained from unpublished MCM data (Appendix Table 7.1).

Hake (model groups 18-21)
The South African hake fisheries consist of the offshore and the inshore trawl fisheries, the handline fishery and the longline fishery. The inshore trawl fishery commenced in the 19th Century and the offshore trawl fishery in the 20th Century. The handline and longline fisheries developed fairly recently, in 1990 and 1998 respectively. The hake fishery is one of the most important in South Africa, employing more than 14 000 people. This fishery is also the most valuable, with the combined annual market value of landed hake in all fishery sectors in excess of approximately R1.6 billion (Nel 2007a).
Hake catches were obtained from unpublished MCM data (Rademeyer and Butterworth 2009) and split according to fishing gear: offshore trawl, inshore trawl, longline and handline. Following Rademeyer and Butterworth (2009), hake caught by handline were assumed to be exclusively *M. capensis* from the south coast. Handlines also target the larger sized hake and handline catches were therefore assumed to be of large *M. capensis*, in line with Rademeyer and Butterworth (2009).
Length frequency data were available for the hake caught by longline (both species aggregated) for the years 1994-1997 (Rademeyer and Butterworth 2009). None of the hake caught in that period were smaller than 31cm. It was therefore assumed that 2004-2007 longline hake catches, which were split by species *M. capensis* and *M. paradoxus*, would also exclusively be large hake (>30cm) since this is the size this fishery is targeting.

Inshore trawls take place on the south coast. In line with Rademeyer and Butterworth (2009), it is assumed that these vessels only catch *M. capensis* since they are fishing in shallow water where the deep-water hake, *M. paradoxus*, would not be found (Payne 1989). Length frequency catch data for the year 2000 was made available from unpublished MCM data (Rademeyer and Butterworth 2009). These data were converted to biomass by applying the *M. capensis* length-weight relationship (Fairweather 2008) and were used to calculate the ratio of small vs. large *M. capensis* caught. The ratio calculated was 99.7% large and 0.3% small *M. capensis* and was applied to the 2004-2007 inshore hake catches (Appendix Table 7.3).

Offshore trawling occurs along both the west and south coasts, and the fleet targets both hake species. Following Shannon *et al.* (2003), the assumption was made that the only small hake caught in these trawls would be *M. paradoxus*, since the vessels are fishing in deeper water, where small *M. capensis* would not be found (Payne 1989). The *M. capensis* caught in these trawls were therefore classified as large *M. capensis*. Catch data were obtained from unpublished MCM data (2004-2007 – species disaggregated) (Rademeyer and Butterworth 2009) and length frequency data were available for the years 2005-2007 (species aggregated) (Rademeyer and Butterworth 2009). The combined-species length frequency data were converted to biomass by applying a combined length-weight relationship (Fairweather 2008), and were used to calculate the ratio of small vs. large *M. paradoxus* caught. The 2005-2007 ratio calculated was 91.2% large and 8.8% small *M. paradoxus* and was applied to the 2004-2007 *M. paradoxus* catches (Appendix Table 7.1). It is recognised that under the assumption that no small *M. capensis* are caught in offshore trawls, this method may be biased towards large fish, but since species-disaggregated length frequency data were not readily available, this was the best approach available at the time.

Previous southern Benguela ecosystem trophic models only used one trawl gear for hake catches – demersal trawl. The catches reported by MCM were also made by the fishing gear, namely demersal trawl, as opposed to being reported on the basis of fleet. Therefore, for consistency, the inshore and offshore hake trawl catch was subsequently summed and entered into the model as demersal trawl catches.

Demersal fish (model groups 22-23)

The most valuable demersal fish species exploited are the two soles, kingklip and monkfish (Payne and Badenhorst 1989). These species, along with other demersal fish species, are caught either in directed fisheries or as commercially valuable bycatch in overlapping fisheries. 2004-2008 Catches were obtained from unpublished MCM data (Appendix Table 7.1).

Chondrichthyans (model groups 24-26)

Chondrichthyans are caught as bycatch by several fishing sectors within the southern Benguela ecosystem, including pelagic longline, demersal trawl and commercial line fish. A dedicated shark longline fishery developed in 1992, but was closed following concern of the conservation status of several shark species (Petersen 2007, Petersen *et al.* 2009). 2004-2008 Catches were obtained from unpublished MCM data (Appendix Table 7.1).

Seals (model group 27)

Incidental mortalities of seals as a result of fishing practices do take place. The value used in the current model was the same as that used in the previous models (Shannon *et al.* 2003, Watermeyer *et al.* 2008a) (Appendix Table 7.1).

Discards

Discarding, i.e. dumping of (mostly dead) fish at sea, does take place within the various fisheries. However, there is difficulty with the quantification of these discards since only the landed catch, i.e. the retained catch is reported. Walmsley *et al.* (2007a) quantified discards within the South African demersal trawl fishery. However, the hake discards in that study were grouped as *Merluccius* spp. In order to separate the species, the assumption was made that the west coast 0-300m hake directed fishery, and the inshore hake-directed and sole-directed fisheries on the south coast would only be catching and therefore discarding *M. capensis*, since these fisheries are operating in shallow water. The offshore hake-directed fisheries on the south coast (east and west) and the west coast hake-directed fisheries (301-400m, 401-500m, >500m) and monk-directed fishery were grouped and assumed to be only catching and discarding *M. paradoxus*. Discards for both hake species were classified as "small" following Walmsley *et al.*'s (2007b) definition of discarded bycatch (undersized target and non-target fish). Using data extracted from Walmsley *et al.* (2007a), the proportion of landed vs. discarded catch was calculated for the species listed in Walmsley *et al.* (2007a) (Appendix Table 7.4). These proportions were applied to the mean 2004-2008 landed catches of corresponding species (MCM unpublished data) and only these amounts were included as discards in the 2004-2008 trophic model (Appendix Table 7.4).

Pelagic sharks are caught as bycatch in the South African pelagic longline fishery. Using the catch rates (number of sharks caught per 1000 hooks) reported by Petersen *et al.* (2009) for South African and Asian vessels operating in the fishery, an estimate of the number of sharks caught annually as bycatch was calculated. The two most commonly caught species were the blue shark and short-finned mako shark (Petersen *et al.* 2009). Pre-caudal lengths were recorded for each of the sharks caught and therefore, using average length calculated for each species (Petersen *et al.* 2009), the numbers caught were converted to weight using length-weight relationships (short-finned mako: Cliff *et al.* (1990); blue shark: K. Jolly, UCT, Blue Shark Research, unpublished data, pers. comm. at the time of these analyses). Discard proportions were also recorded for the two pelagic shark species (Petersen *et al.* 2009) and were applied to the estimated annual bycatch of the two species within the pelagic longline fishery. Discard proportions for anchovy and sardine were estimated from an unpublished MCM report (Somhlaba *et al.* 2006).

Since discards could not be quantified for all potential model groups, the implication is that fishing effects are very conservatively quantified in the model results and should thus be regarded as conservative estimates. Similarly, Walmsley *et al.*'s (2007a) estimates have since been revised (C. Attwood, UCT, pers. comm. at the time of these analyses), with a particular problem arising when the inshore fishery is targeting species other than hake, in which case large hake could be discarded as well. An additional potential problem arises from the loss of (large) hake from longlines. However, these problems are not expected to compromise the overall picture derived from our estimates of discards in the aggregate hake fisheries. Making best use of the published information and following the procedure outlined above, discard proportions and values calculated for the various species within the model groups are shown in Appendix Table 7.4.

2.1.1.3. Diet Data

The original and unbalanced diet data used in the 1980s model (Shannon *et al.* 2003) were applied to the current model. This period was selected as the "base case" because it was the period for which a concerted effort was made to collect diet data in the region. The diet data for all model groups which feed on small pelagic fish, specifically anchovy, sardine and redeye, were updated according to the ratio of anchovy, sardine and redeye estimated to have been available in the system for the 2004-2008 period (Appendix Table 7.5). Since more small pelagic fish were available in the current period than the 1980s, the adjustment of small pelagic fish diet of top predators may suggest increased pressure on small pelagic fish. However, the decline in biomass of top predatory fish, such as the large pelagic fish, would not necessarily mean an unreasonably high consumption of small pelagic fish within the system.

2.1.2. Balancing the Model

The biomass of chub mackerel as estimated by Twatwa *et al.* (2009) (13 860 t) was too small to support the level of predation of large *M. capensis* on chub mackerel. Using an ecotrophic efficiency (EE) of 0.9, the model was allowed to estimate the biomass of chub mackerel needed for the system (30 360 t). This model estimated biomass was deemed reasonable since the value was within the range of the early 2000s model biomass (100 100 t; Watermeyer *et al.* 2008) and the estimate of Twatwa *et al.* (2009). Twatwa *et al.*'s (2009) estimate is likely to be an underestimate of the available chub mackerel biomass in the system, as it only includes the portion of the chub mackerel stock available to acoustic sampling over the geographic range occupied by small pelagic fish.

Initially the phytoplankton biomass used (Appendix Table 7.1), as estimated from Barlow *et al.* (2009), was not large enough to support the system (ecotrophic efficiency (EE) >1). The value used was the average (summer and winter) southern Benguela ecosystem biomass estimate (57.797 $t.km^{-2}$). The model was allowed to estimate the biomass of phytoplankton needed to sustain the system using an EE of 0.6. The model estimated a biomass for the phytoplankton trophic group at 91.333 $t.km^{-2}$. This model estimated value was deemed reasonable since the value was within range of the value used in the 1980s model (76.938 $t.km^{-2}$; Brown *et al.* 1991, Shannon *et al.* 2003) and the recent maximum summer estimate of Barlow *et al.* (2009) (134.747 $t.km^{-2}$).

Although the model balanced, the EE's of the Anchovy (0.54), Sardine (0.59) and Redeye (0.44) model groups were lower than expected. Refinements to the balanced model were done to improve the model's representation of the southern Benguela ecosystem. This was achieved through conducting hypothetical diet tests on specifically the Cephalopod and Snoek model groups. Consumption of Macrobenthos by Cephalopods was decreased and replaced with small pelagic fish (Anchovy, Sardine and Redeye). We hypothesised that this would be a realistic diet shift since small pelagic fish have been occurring more frequently on the south coast (Chapter 1 Figure 1.1) where cephalopods occur, and are thus more available to be eaten by cephalopods. Snoek consumption on small hake and Pelagic-feeding demersal fish was decreased and also replaced with Anchovy, Sardine and Redeye. These two diet tests resulted in the EE's of the model groups Anchovy, Sardine and Redeye increasing to 0.66, 0.74 and 0.56 respectively.

2.2. Model Results

The balanced trophic model for the southern Benguela ecosystem representing the period 2004-2008 is shown in Table 2.5. The 2004-2008 model representing the current state of the ecosystem was also compared to models of previous time periods, i.e. past ecosystem states. The three historic time periods included were the 1900s "Pristine", 1960s "Industrial" and 1980s "Anchovy Period". The 1900s and 1960s models were compiled by Watermeyer *et al.* (2008a) and the 1980s model was constructed by Shannon *et al.* (2003).

2.2.1. Biomass

Model groups were aggregated to allow for comparisons between the current and previous trophic models of the southern Benguela ecosystem. The model groups comprising each aggregated group are shown in Table 2.6. Estimated biomass for the aggregated model groups, Producers, Zooplankton and Benthos, were higher during 2004-2008 than in previous periods (Figure 2.1). These were model-estimated values required to sustain the components within the system, indicating that biomasses of other model groups have increased during the current period. In fact, comparisons across the four time periods reveal that biomasses are at a maximum during the current period for the aggregated model groups, All Small Pelagic Fish, Cephalopods and All Demersal Fish (Figure 2.1). These three groups experienced biomass increases from the 1980s to the current period of 30%, 13% and 8% respectively.

The dominant small pelagic fish in the system for the current period is anchovy. The input biomass of Anchovy in the current period (11.445 t.km^{-2}) is approximately double that of Sardine and Redeye (5.381 t.km^{-2} and 6.638 t.km^{-2} respectively) (Table 2.5). The remaining small pelagic fish groups in the system, Other small pelagic fish, Chub mackerel, Juvenile horse mackerel and Adult horse mackerel, all have biomasses of less than 1 t.km^{-2}. It should be noted that Chub mackerel biomass was the only model-estimated value among the small pelagic fish groups (Table 2.5). All other biomass values were inputs obtained from survey data.

Table 2.5: Balanced trophic model of the southern Benguela ecosystem for the period 2004-2008. Input parameters are in bold and all other values were estimated by the model. TL = trophic level; B = biomass ($t.km^{-2}$); Y = catch ($t.km^{-2}.yr^{-1}$); EE = ecotrophic efficiency.

Model Group	**TL**	**B ($t.km^{-2}$)**	**Y ($t.km^{-2}.yr^{-1}$)**	**EE**
Phytoplankton	1	91.333	**0**	**0.676**
Benthic producers	1	7.232	**0**	**0.500**
Microzooplankton	2.25	10.492	**0**	**0.950**
Mesozooplankton	2.63	10.974	**0**	**0.950**
Macrozooplankton	2.65	16.565	**0**	**0.950**
Gelatinous zooplankton	3.33	**5.000**	**0**	0.152
Anchovy	3.54	**11.445**	**1.126**	0.662
Sardine	2.99	**5.381**	**1.165**	0.743
Redeye	3.64	**6.638**	**0.209**	0.565
Other small pelagic fish	3.65	**0.364**	**0.001**	0.708
Chub mackerel	3.82	0.138	**0.002**	**0.900**
Juvenile horse mackerel	3.63	**0.298**	**0.015**	0.552
Adult horse mackerel	3.71	**0.967**	**0.148**	0.930
Mesopelagic fish	3.64	9.247	**0.003**	**0.950**
Snoek	4.37	0.272	**0.042**	**0.950**
Other large pelagic fish	4.54	**0.106**	**0.032**	0.882
Cephalopods	4.08	**1.773**	**0.041**	0.712
Small *M. capensis*	3.95	0.533	**0**	**0.950**
Large *M. capensis*	4.64	**0.653**	**0.130**	0.869
Small *M. paradoxus*	3.87	1.907	**0.045**	**0.950**
Large *M. paradoxus*	4.52	**0.959**	**0.474**	0.859
Pelagic-feeding demersal fish	3.98	3.877	**0.037**	**0.950**
Benthic-feeding demersal fish	3.43	4.290	**0.056**	**0.950**
Pelagic-feeding chondrichthyans	4.94	**0.176**	**0.007**	0.984
Benthic-feeding chondrichthyans	3.7	**1.210**	**0.002**	0.754
Apex chondrichthyans	5.08	**0.042**	**0**	0.001
Seals	4.67	**0.133**	**0.003**	0.399
Cetaceans	4.59	**0.082**	**0**	0.640
Seabirds	4.49	**0.011**	**0**	0
Meiobenthos	2	13.421	**0**	**0.950**
Macrobenthos	2.16	63.748	**0**	**0.950**
Detritus	1	-	**0**	0.914

Table 2.6: Aggregated model groups used for comparisons between trophic models of the southern Benguela ecosystem for the four time periods, 1900, 1960, 1980 and 2004-2008.

Aggregated Model Group	Individual Model Groups
Producers	Phytoplankton & Benthic producers
Zooplankton	Micro-, Meso-, Macro- & Gelatinous zooplankton
All Small Pelagic Fish	Anchovy, Sardine, Redeye, Other small pelagic fish, Chub mackerel, Juvenile & Adult horse mackerel
All Large Pelagic Fish	Snoek & Other large pelagic fish
All Hake	Small & Large *M. capensis* and Small & Large *M. paradoxus*
All Demersal Fish	Pelagic- & Benthic-feeding demersal fish
All Chondrichthyans	Apex, Pelagic- & Benthic-feeding chondrichthyans
All Mammals	Seals & Cetaceans
Benthos	Meio- & Macrobenthos

2004-2008 Cephalopod biomass, from surveys conducted during this time period, is estimated at 1.773 t.km^{-2}, which is higher than in previous periods (Figure 2.1; 1900 = 1.406 t.km^{-2}, 1960 = 1.474 t.km^{-2}, 1980 = 1.364 t.km^{-2}). Model-estimated biomasses of All Demersal Fish, both pelagic- and benthic-feeders, have increased over the last three time periods examined (Figure 2.1). Maximum model-estimated biomass values for both feeding types occur within the current period (Table 2.5; Figure 2.1).

Model groups which did not demonstrate a significant change in estimated biomass (<4% decrease or increase) from the 1980s to the current period were Mesopelagic fish, and the aggregated groups, All Large Pelagic Fish and All Chondrichthyans (Figure 2.1). Model-estimated biomass for Mesopelagic fish was highest during the 1900s pristine period (10.812 t.km^{-2}) followed by the 2004-2008 period (9.247 t.km^{-2}) (Figure 2.1; Table 2.5). Aggregated biomass of All Large Pelagic Fish within the system has remained constant (Figure 2.1; 1980 = 0.371 t.km^{-2}, 2004-2008 = 0.378 t.km^{-2}). However, closer inspection of the biomass breakdown between the two periods reveals that the biomass of the model group, Other large pelagic fish, has decreased by 10%, which has been accompanied by a 6% increase in Snoek model-estimated biomass (Figure 2.1).

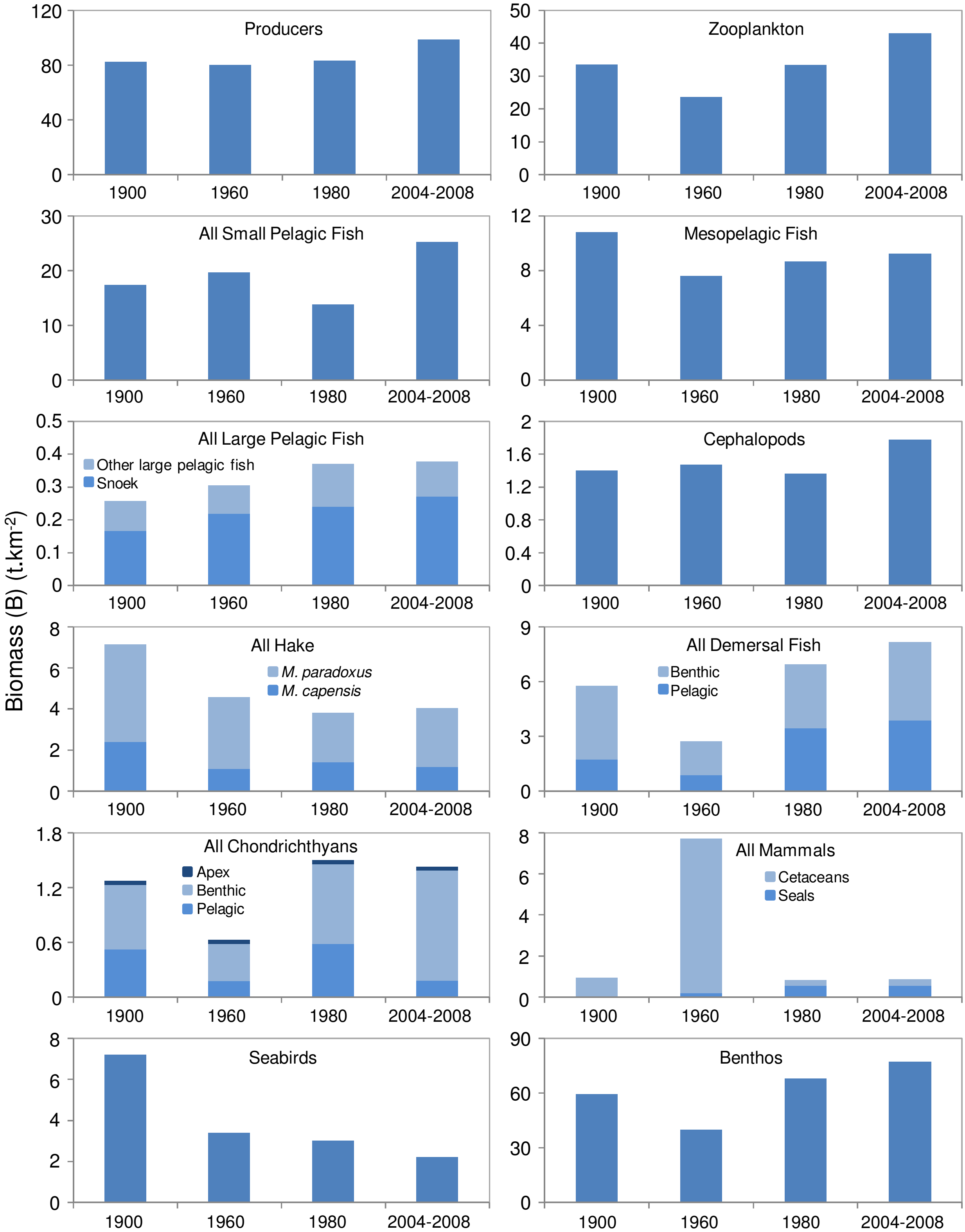


Figure 2.1: Biomasses (B; t.km^{-2}) of aggregated model groups in the southern Benguela ecosystem over the time periods 1900, 1960, 1980 and 2004-2008. Data for 1980 were sourced from Shannon *et al.* (2003) and for 1900 & 1960 from Watermeyer *et al.* (2008a). Producers = phytoplankton & benthic producers; Zooplankton = micro-, meso-, macro- & gelatinous zooplankton; All Small Pelagic Fish = anchovy, sardine, redeye, other small pelagic fish, chub mackerel, juvenile & adult horse mackerel; All Large Pelagic Fish = snoek & other large pelagic fish; All Hake = small & large *M. capensis* and small & large *M. paradoxus*; All Demersal Fish = pelagic- & benthic-feeding demersal fish; All Chondrichthyans = apex, pelagic- & benthic-feeding chondrichthyans; All Mammals = seals & cetaceans; Benthos = meio- & macrobenthos.

Aggregated Chondrichthyan biomass was at a maximum in the 1980s and has remained at a similar level for the current period (Figure 2.1; 1980 = 1.5 $t.km^{-2}$, 2004-2008 = 1.428 $t.km^{-2}$). However, between the last two time periods compared, Pelagic-feeding chondrichthyan biomass decreased (54%), Benthic-feeding chondrichthyan biomass increased (16%) and Apex chondrichthyan biomass decreased (3%) (Figure 2.1; Table 2.5). It must be noted that these were estimated biomasses obtained from survey data, and were thus entered as model inputs.

Three model groups experienced significant decreases in biomass levels (>25% decline) from the 1900s and 1960s to the current period. These groups are All Hake (aggregated group), All Mammals (aggregated group) and Seabirds (Figure 2.1). Combined hake, i.e. both hake species biomass in the 1900s was as large as 7.15 $t.km^{-2}$, whereas now in the current period, the biomass is considered to be 4.052 $t.km^{-2}$ (Figure 2.1). The 2004-2008 model-estimated biomass for small *M. capensis* is less than half of the estimated value for small *M. paradoxus* (0.533 $t.km^{-2}$ and 1.907 $t.km^{-2}$ respectively) (Table 2.5). Survey-estimated biomass for large *M. paradoxus* is higher than for *M. capensis* (0.959 $t.km^{-2}$ and 0.653 $t.km^{-2}$ respectively, Table 2.5).

Combined Mammal biomass was at a maximum in the 1960s (1.927 $t.km^{-2}$), but then dropped to less than a tenth of that value during the 1980s (0.207 $t.km^{-2}$) (Figure 2.1). The biomass for Seals and Cetaceans remained similar until the current period (Table 2.5). Current Seabird biomass is estimated at 0.011 $t.km^{-2}$, a 75% reduction in the biomass estimated to have been present in the 1900s (0.036 $t.km^{-2}$) (Table 2.5; Figure 2.1).

2.2.2. Consumption

The proportion of aggregated model groups' production consumed by aggregated model predators, including fishery sectors, for the period 2004-2008 is shown in Figure 2.2. Consumption of the two lowest groups in the food model, Producers and Zooplankton, was dominated by Zooplankton (Figure 2.2). The aggregated group All Small Pelagic Fish consumed <1% of the Producers. Approximately 92% of the aggregated group Zooplankton was consumed by the various zooplankton groups (Figure 2.2). The remaining 8% were consumed by All Small Pelagic Fish (5%), Mesopelagic Fish (2%), All Large Pelagic Fish (<1%), Cephalopods (<1%), All Hake (<1%), All Demersal Fish (<1%) and All Mammals and Seabirds (<1%) (Figure 2.2).

The greatest consumers of production from the aggregated group All Small Pelagic Fish in the southern Benguela ecosystem were Cephalopods (26%), All Hake (21%) and All

Demersal Fish (16%) (Figure 2.2). The fishing sectors focussed on small pelagic fish collectively removed 12% of All Small Pelagic Fish production in the system. The remaining predators of small pelagic fish were All Mammals and Seabirds (11%), All Large Pelagic Fish (7%), All Small Pelagic Fish themselves (5%) and Chondrichthyans (2%) (Figure 2.2). Mesopelagic fish were consumed in nearly equal proportions by the aggregated model groups All Hake and All Demersal Fish (39% and 38% respectively). The natural aggregated predators of Mesopelagic fish, All Hake, All Demersal Fish, All Small pelagic Fish (1%), All Large Pelagic Fish (1%), Cephalopods (17%), All Chondrichthyans (3%) and All Mammals and Seabirds (2%) far outweigh the proportion removed by the fishery (<0.1%) (Figure 2.2). This was not the case for the model group All Large Pelagic Fish. The various fishery sectors collectively removed 42% of All Large Pelagic Fish production; 16% more than that of the highest natural consumer/predator, *M. paradoxus* (26%). The remaining 32% were consumed by the aggregated model groups All Chondrichthyans (15%), All *M. capensis* (9%), All Large Pelagic Fish (5%) and All Mammals and Seabirds (5%) (Figure 2.2).

The greatest proportion of Cephalopods were consumed by the aggregated model predator All Hake (27%), and then in relatively equal proportions by Cephalopods themselves (20%), All Demersal fish (18%) and All Mammals and Seabirds (18%) (Figure 2.2). The aggregated groups All Large Pelagic Fish and the Fishery consumed 3% and 1% of the cephalopod production respectively.

As All Hake were the greatest consumer of Cephalopods, Cephalopods were the greatest consumers of All Hake (31%). The hake fishery removed 11% of All Hake production, the fifth largest consumer behind Cephalopods, All *M. capensis* (18%), All Mammals and Seabirds (15%) and All *M. paradoxus* (13%) (Figure 2.2). All Demersal Fish, All Chondrichthyans and All Large Pelagic Fish consumed the remaining 12% (7%, 3% and 2% respectively).

The smallest consumer of All Demersal Fish was the fishery (1%), whereas the greatest consumer was the aggregated model group All Chondrichthyans (40%). Other consumers of demersal fish include All *M. paradoxus* (27%), All Demersal Fish (20%), All *M. capensis* (6%), All Mammals and Seabirds (4%) and All Large Pelagic Fish (2%) (Figure 2.2). Chondrichthyans in the southern Benguela ecosystem were consumed by the various chondrichthyan groups (78%), followed by All Demersal Fish (21%) and then the fishery sector (1%) (Figure 2.2). Predation upon All Mammals and Seabirds was dominated by All Chondrichthyans (90%) followed by All Mammals and Seabirds (6%) and finally the Fishery sector (4%) (Figure 2.2).

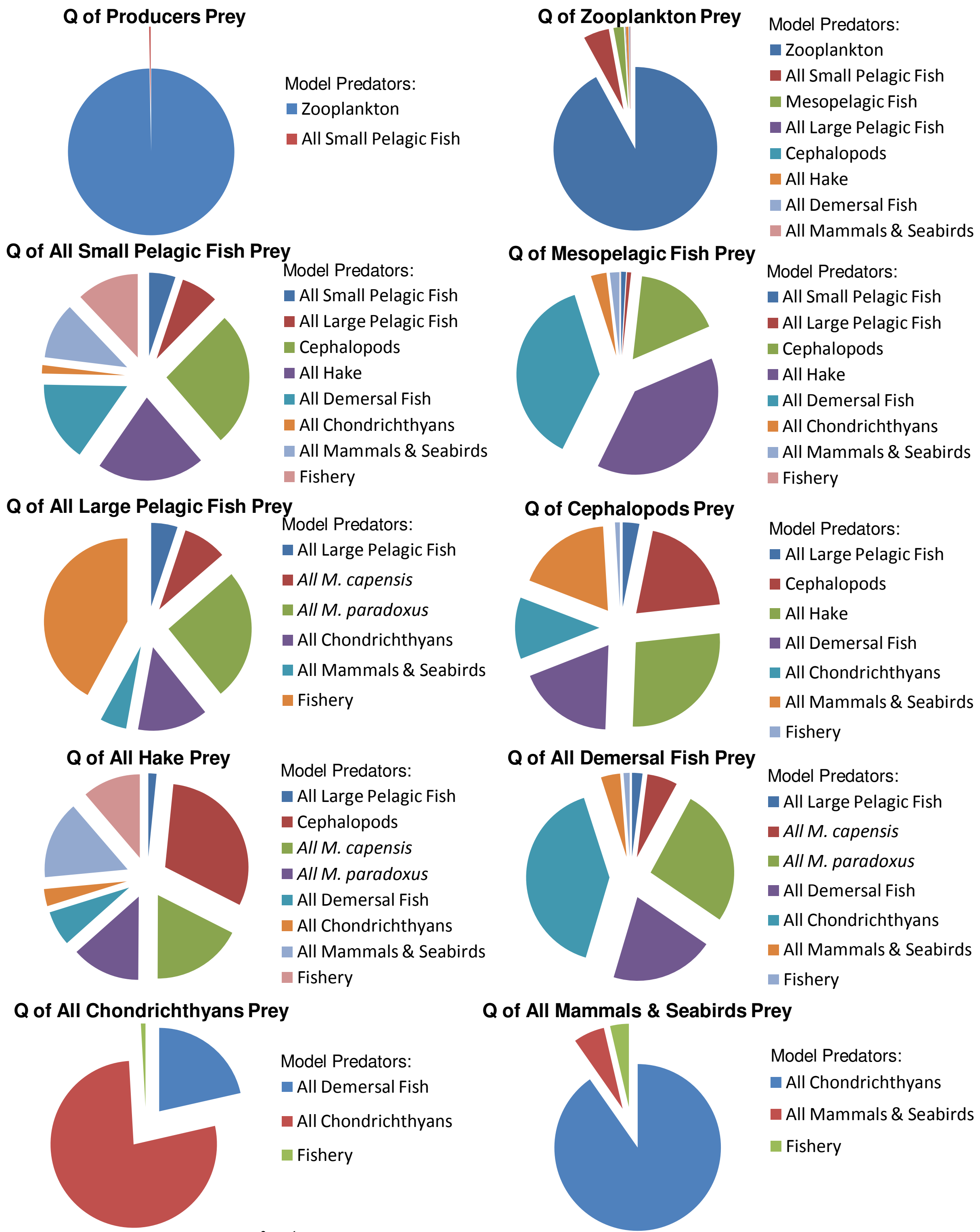


Figure 2.2: Consumption (Q; $t.km^{-2}.yr^{-1}$) breakdown of aggregated model prey groups by aggregated model predators and fishery sectors in the southern Benguela ecosystem during the period 2004-2008. Producers = phytoplankton & benthic producers; Zooplankton = micro-, meso-, macro- & gelatinous zooplankton; All Small Pelagic Fish = anchovy, sardine, redeye, other small pelagic fish, chub mackerel, juvenile & adult horse mackerel; All Large Pelagic Fish = snoek & other large pelagic fish; All Hake = small & large *M. capensis* and small & large *M. paradoxus*; All Demersal Fish = pelagic- & benthic-feeding demersal fish; All Chondrichthyans = apex, pelagic- & benthic-feeding chondrichthyans; All Mammals & Seabirds = seals, cetaceans & seabirds.

The 2004-2008 consumption breakdowns of significant trophic model groups in the southern Benguela ecosystem, All Small Pelagic Fish, All Large Pelagic Fish, Cephalopods and All Hake, were compared to the three historic time periods, 1900, 1960 and 1980. The results of these comparisons are illustrated in Figure 2.3. Consumption of All Small Pelagic Fish by themselves has remained relatively stable and ranged from the maximum 10% in the 1980s, to the 5% experienced in the current period (Figure 2.3). Production removed by All Chondrichthyans has also remained constant across the four time periods (<4%) (Figure 2.3). Model groups which have shown a vast reduction in consumption of All Small Pelagic Fish across the four periods, with minimum consumption values occurring in the current period, are All Hake (All *M. capensis* and All *M. paradoxus* combined - 21%) and All Mammals and Seabirds(11%). All Hake (All *M. capensis* and All *M. paradoxus* combined) were the greatest consumers of All Small Pelagic Fish during the 1900s (56%). This consumption figure decreased to 25% in the 1960s and increased to 29% in the 1980s (Figure 2.3). All Mammals and Seabirds were the greatest consumer of All Small Pelagic Fish in the 1960s (46%), but dropped to the third highest consumer in the 1980s (15%) (Figure 2.3). Natural model predators which have shown an increase in their consumption of All Small Pelagic Fish are All Large Pelagic Fish, Cephalopods and All Demersal Fish. The proportion removed by All Large Pelagic Fish has doubled from 3% in the 1900s and 1960s, to 7% in the 1980s and 2004-2008 (Figure 2.3). Cephalopods consumed 6%, 4% and 9% of All Small Pelagic Fish production in 1900, 1960 and 1980 respectively, but have become the highest consumer for the current period (26%) (Figure 2.3). Demersal Fish consumption of All Small Pelagic Fish was minimal in 1900 and 1960, 5% and 2% respectively, but increased to 16% in the 1980s (Figure 2.3). The Small Pelagic Fishery only started in the 1960s, when it removed 7% of All Small Pelagic Fish production (Figure 2.3). The Fishery has become one of the top four consumers of All Small Pelagic Fish during the 1980s and current period (14% and 13% respectively) (Figure 2.3).

The most noteworthy consumer of All Large Pelagic Fish is the Fishery. The Fishery removed 15% of All Large Pelagic fish production in the 1900s (Figure 2.3). It has become the greatest consumer of All Large Pelagic Fish production with 50%, 44% and 42% removal of the production in 1960, 1980 and 2004-2008 respectively (Figure 2.3). Consumption of All Large Pelagic Fish by themselves has remained small across the four time periods (<5%) (Figure 2.3). The remaining natural predators, All *M. capensis*, All *M. paradoxus*, All Chondrichthyans and All Mammals and Seabirds, show alternating periods of increases and decreases in consumption across the four time periods (Figure 2.3).

Predation of Cephalopods by All Large Pelagic Fish has remained small (<3%) for all four time periods (Figure 2.3). Consumption of Cephalopods by Cephalopods was similar in 1900, 1960 and 1980 (15%, 14% and 16% respectively) (Figure 2.3). All Hake was the greatest consumer of Cephalopods during the 1900s (50%), and although this proportion has decreased over time (1960 = 32%, 1980 = 26%, 2004-2008 = 27%), All Hake was still the greatest consumer during the current time period (Figure 2.3). Consumption by All Demersal Fish has increased over time (1900 = 9%, 1960 = 4%, 1980 = 16%) (Figure 2.3). The Squid Fishery, which only started in 1980, has removed <1% of Cephalopod production for the last two time periods (Figure 2.3). All Large Pelagic Fish and All Chondrichthyans have consumed 1-3% and 3-6% respectively of All Hake production over the four time periods, making them the smallest consumers of All Hake (Figure 2.3). Consumption of All Hake by All Demersal Fish is <10% for each of the four time periods (1900 = 4%, 1960 = 4%, 1980 = 10%, 2004-2008 = 7%; Figure 2.3). Consumption of All Hake by All Mammals and Seabirds was highest in the 1960s (27%), but was relatively similar during the other time periods (1900 = 11%, 1980 = 16%, 2004-2008 = 15%; Figure 2.3). The proportion of All Hake production removed by the hake Fishery has remained consistent (1960 = 9%, 1980 and 2004-2008 = 11%; Figure 2.3). The proportion of All Hake production removed through predation/cannibalism by *M. paradoxus* and *M. capensis* has decreased from the “pristine” era (*M. paradoxus*: 1900 = 29%, 1960 = 22%, 1980 = 9%, 2004-2008 = 13%; *M. capensis*: 1900 = 31%, 1960 = 13%, 1980 = 22%, 2004-2008 = 18%; Figure 2.3). However, consumption of All Hake by *M. paradoxus* has undergone a much faster overall decline than that experienced by *M. capensis* (37% vs. 27% respectively).

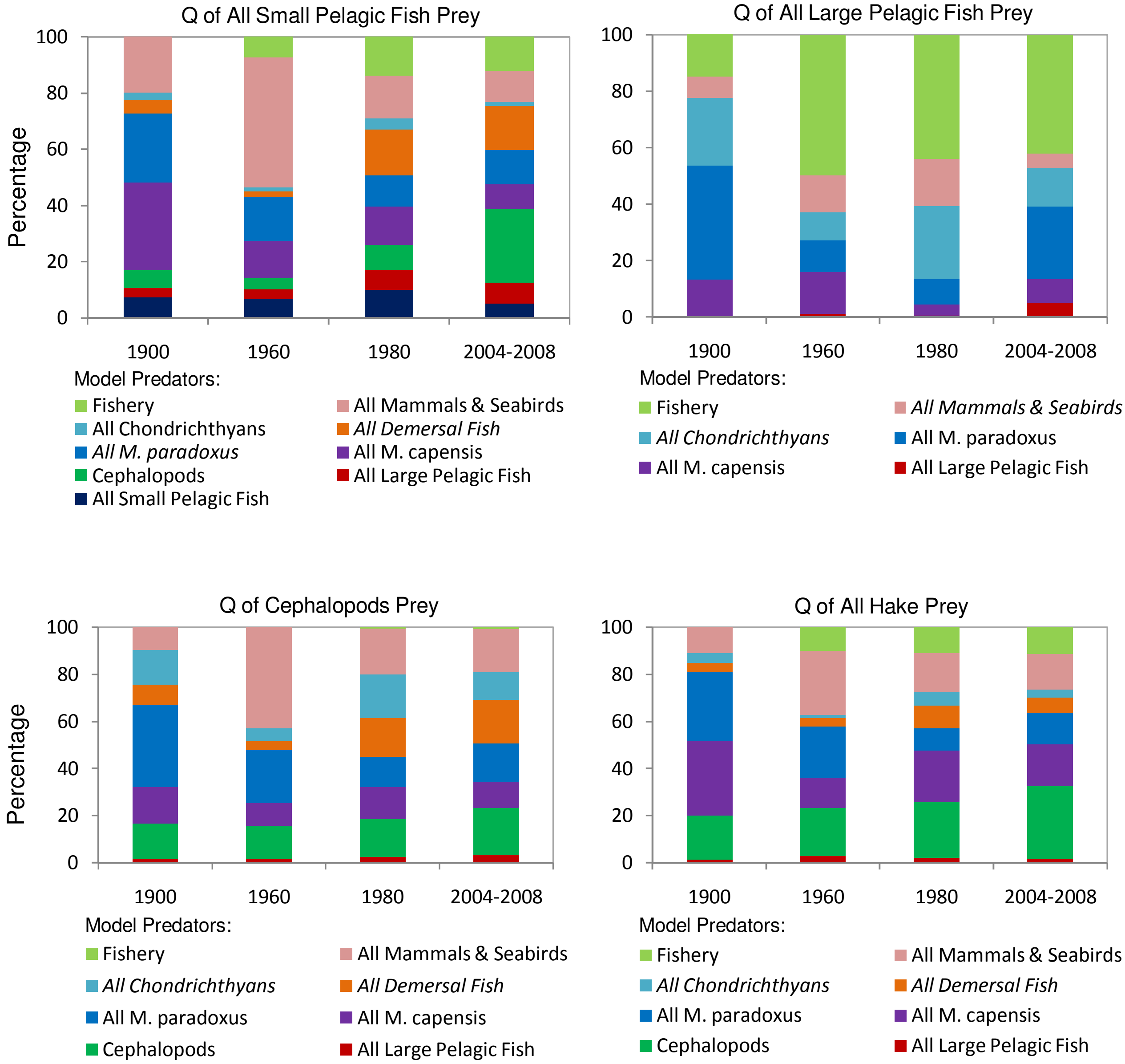


Figure 2.3: Consumption (Q; t.km^{-2}.yr^{-1}) breakdown of aggregated model prey groups All Small Pelagic Fish, All Large Pelagic Fish, Cephalopods and All Hake by aggregated model predators and fishery sectors in the southern Benguela ecosystem for the periods 1900, 1960, 1980 and 2004-2008. Data for 1980 were sourced from Shannon *et al.* (2003) and for 1900 & 1960 from Watermeyer *et al.* (2008a). All Small Pelagic Fish = anchovy, sardine, redeye, other small pelagic fish, chub mackerel, juvenile & adult horse mackerel; All Large Pelagic Fish = snoek & other large pelagic fish; All Hake = small & large *M. capensis* and small & large *M. paradoxus*; All Demersal Fish = pelagic- & benthic-feeding demersal fish; All Chondrichthyans = apex, pelagic- & benthic-feeding chondrichthyans; All Mammals = seals & cetaceans

2.2.3. Fishing

Fishery landings for aggregated model groups across the four time periods are shown in Figure 2.4. The summed catches of the target species of the small pelagic fishery, Anchovy, Sardine and Redeye, have increased since the 1960s and has peaked during the 2004-2008 period (Figure 2.4). The small pelagic fish constituting the highest proportion of the catch is Sardine (47%) followed by Anchovy (45%) and then Redeye (8%) (Table 2.5). However, landings of mackerel fish (both Chub and Horse mackerel) have decreased over time. 2004-2008 Chub mackerel catches were 88% lower than those recorded in the 1980s, when the catches were at a maximum (Table 2.5; Figure 2.4). Summed catches of Juvenile and Adult horse mackerel were largest in 1960 (0.288 t.km^{-2}.yr^{-1}). The catch dropped by 50% in the 1980s and remained stable in 2004-2008 (Figure 2.4; Table 2.5). The 2004-2008 catch of Other small pelagic fish was the same as in 1980 (Figure 2.4; Table 2.5). In 1980, the average catch of Mesopelagic fish was 0.031 t.km^{-2}.yr^{-1}, but this figure dropped to 0.003 t.km^{-2}.yr^{-1} in 2004-2008. Summed catches of All Large Pelagic Fish (Snoek and Other large pelagic fish) increased by 60% between 1900 and 1960 (0.075 t.km^{-2}.yr^{-1}). Since 1960, the overall catches have remained constant (Figure 2.4; 1980 = 0.078 t.km^{-2}.yr^{-1}, 2004-2008 = 0.074 t.km^{-2}.yr^{-1}). The Cephalopod catch in 2004-2008 was 0.041 t.km^{-2}.yr^{-1}, an increase of 20% from 1980 (Table 2.5; Figure 2.4). Catches for the two hake species have undergone opposite trends between 1980 and 2004-2008 (Figure 2.4). The average 1980 *M. capensis* catch was 0.254 t.km^{-2}.yr^{-1}, whereas 2004-2008 average catches have decreased by 32% to 0.13 t.km^{-2}.yr^{-1}. On the other hand, *M. paradoxus* catches have increased by 15% between 1980 and 2004-2008, increasing from 0381 t.km^{-2}.yr^{-1} to 0.519 t.km^{-2}.yr^{-1}. The catches for the aggregated model groups, All Demersal Fish and All Mammals, have decreased across the last three time periods compared. The summed catches of All Demersal Fish has been decreasing since 1960 (Figure 2.4) and the 2004-2008 summed catch is the lowest of the time periods, 0.093 t.km^{-2}.yr^{-1} (Table 2.5; Figure 2.4). Catches of All Chondrichthyans saw an increase of 86% between 1960 and 1980. Since then, All Chondrichthyan catches have dropped by 18% to 0.009 t.km^{-2}.yr^{-1} in 2004-2008 (Figure 2.4; Table 2.5). Seals are reported to have been harvested as early as the 1900s (Watermeyer *et al.* 2008). The largest recorded catch of All Mammals took place in 1960 (0.271 t.km^{-2}.yr^{-1}; Figure 2.4), although Seals constituted <1% of the catch. Since that period, targeted harvesting of both Seals and Cetaceans have ceased in the southern Benguela ecosystem. Mammal catches reported in 2004-2008 are a result of incidental mortalities of Seals caught in fishing gear (Table 2.5).

2.2.4. Trophic Levels

The trophic levels calculated for model groups for the 2004-2008 period in the southern Benguela ecosystem are shown in Table 2.5. A comparison of the trophic levels for the model groups over the four time periods (1900, 1960, 1980 and 2004-2008) are illustrated in Figure 2.5. The trophic levels of model groups were similar in 1980 and 2004-2008 for all groups except Snoek, Other large pelagic fish, Cephalopods and Apex chondrichthyans (Figure 2.5). The trophic levels of the Snoek and Apex chondrichthyans model groups decreased by 0.09 and 0.12 respectively, whereas the trophic levels of Other large pelagic fish and Cephalopods increased by 0.05 and 0.24 respectively (Figure 2.5).

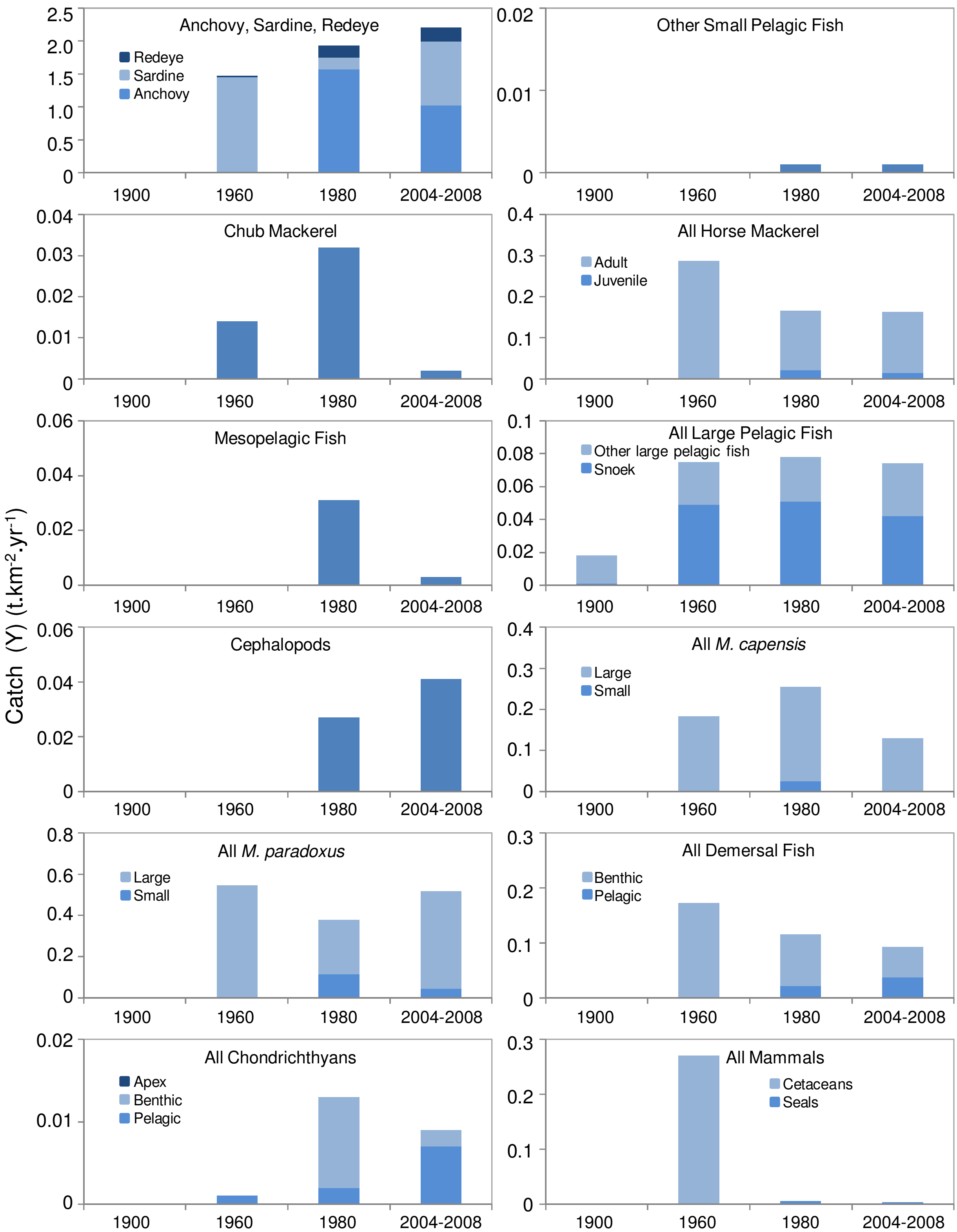


Figure 2.4: Fishery landings of aggregated model groups in the southern Benguela ecosystem over the time periods 1900, 1960, 1980 and 2004-2008. Catch (Y) is in t.km^{-2}.yr^{-1}. Data for 1980 were sourced from Shannon *et al.* (2003) and for 1900 & 1960 from Watermeyer *et al.* (2008a). All Horse Mackerel = juvenile & adult horse mackerel; All Large Pelagic Fish = snoek & other large pelagic fish; All *M. capensis* = small & large *M. capensis*; All *M. paradoxus* = small & large *M. paradoxus*; All Demersal Fish = pelagic- & benthic-feeding demersal fish; All Chondrichthyans = apex, pelagic- & benthic-feeding chondrichthyans; All Mammals = seals & cetaceans.

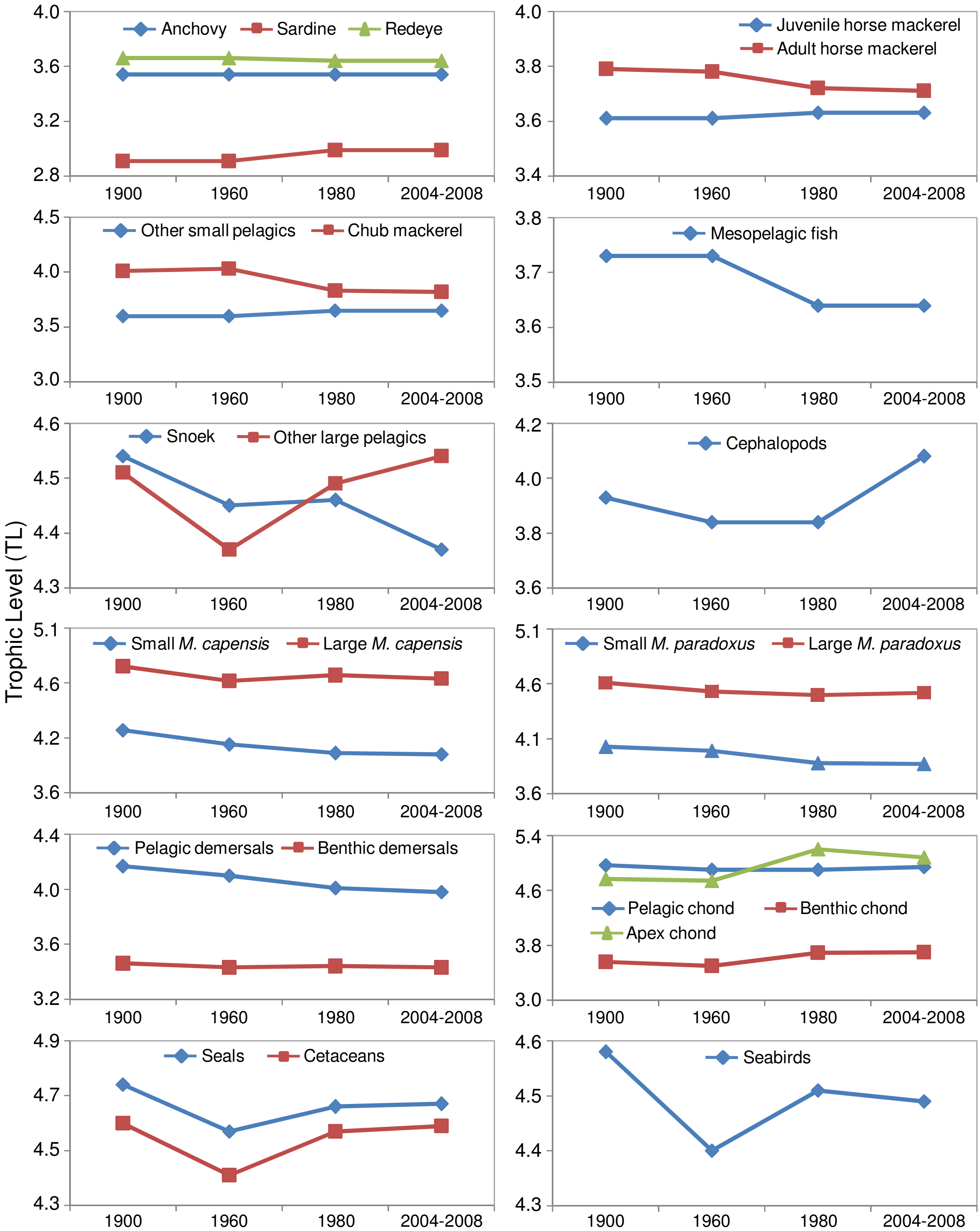


Figure 2.5: Trophic levels (TL) of model groups in the southern Benguela ecosystem over the time periods 1900, 1960, 1980 and 2004-2008. Data for 1980 were sourced from Shannon *et al.* (2003) and for 1900 & 1960 from Watermeyer *et al.* (2008a). Other small pelagics = Other small pelagic fish; Other large pelagics = Other large pelagic fish; Pelagic demersals = Pelagic-feeding demersal fish; Benthic demersals = Benthic-feeding demersal fish; Pelagic chond = Pelagic-feeding chondrichthyans; Benthic chond = Benthic-feeding chondrichthyans; Apex chond = Apex chondrichthyans

2.3. Model Discussion

2.3.1. Biomass

The small pelagic fish, anchovy and sardine, have undergone alternating periods of dominance within the southern Benguela ecosystem. As is the case for the current period, anchovy was also the dominant small pelagic fish in the 1980s (Shannon *et al.* 2003) and 1900s (Watermeyer *et al.* 2008a) southern Benguela ecosystem trophic models. Sardine was the dominant small pelagic fish in the 1960s trophic model (Watermeyer *et al.* 2008). This pattern of fluctuating abundance has been documented in a number of ecosystems around the world, including the North-Western Pacific (Japan), North-Eastern Pacific (west coast of North America) and the South-Eastern Pacific (Peru and Chile) (Schwartzlose *et al.*1999). Redeye biomass has consistently represented 30-40% of All Small Pelagic Fish Biomass in the southern Benguela ecosystem, and has not undergone the great biomass fluctuations displayed by anchovy and sardine (Shannon *et al.* 2003, Watermeyer *et al.* 2008a). The remaining small pelagic fish groups, Other small pelagic fish, Juvenile and Adult horse mackerel and Chub mackerel collectively never dominated the biomass in any of the historic time periods (Shannon *et al.* 2003, Watermeyer *et al.* 2008) nor for the current period.

Hake survey biomass indices for small *M. capensis* and small *M. paradoxus* obtained from Rademeyer and Butterworth (2009) were lower than the small hake biomass estimated by the trophic model. This was expected since surveys are known to underestimate the proportion of small hake available (Shannon 2001). The higher survey-estimated *M. paradoxus* biomass than *M. capensis* observed during the current period was also observed during the 1900s and 1960s (Figure 2.1; Watermeyer *et al.* 2008a).

It was unexpected that the biomass of All Large Pelagic Fish would remain constant within the system over the last two time periods examined. However, biomass of this aggregated group has increasingly become dominated by Snoek (1980: 65% Snoek vs. 35% Other large pelagic fish; 2004-2008: 72% Snoek vs. 28% Other large pelagic fish), suggesting a change in the large pelagic fish community structure as was documented by Yemane *et al.* (2004). Yemane *et al.* (2004) found a decrease in size structure and abundance of large pelagic fish within the Cape region. Analyses conducted by Yemane *et al.* (2004) reveal that the mean length of certain large pelagic fish species within the southern Benguela ecosystem has decreased, and this change could be attributed to overfishing (Griffiths 2000, Yemane *et al.* 2004). Yemane *et al.* (2004) also documented a change in the catch composition of large pelagic fish, with Snoek (*Thrysites atun*) being the dominant species caught. This supports

the findings of Griffiths (2000), i.e. snoek does not fall within the overexploited classification as with some other large pelagic fish species (e.g. carpenter, geelbek, hottentot). Griffiths (2000) identified the migratory lifestyle and fast growth-rates of snoek as the overriding factors preventing an exponential decline in the snoek stock. Large pelagic fish like carpenter, geelbek and hottentot, have predictable locations in time and space as well as slow growth rates, making them more susceptible to experience stock declines/crashes because they are easier to target and catch, as well as their production not being high enough to support the commercial fishery (Griffiths 2000). This is evident in the reduced survey-estimated biomass observed for the model group, Other large pelagic fish, since the 1980s.
The increased cephalopod biomass between the 1980s and current period in the southern Benguela ecosystem observed in this study, has also been observed in other ecosystems around the world (Caddy and Rodhouse 1998). This increase in biomass is thought to be in response to the declining biomass of groundfish species as a result of overfishing (Caddy and Rodhouse 1998), thus releasing cephalopods from the potentially limiting predator-prey interactions with groundfish species.
The life-history characteristics of chondrichthyans (e.g. slow growth and late maturity; Hoenig and Gruber 1990 as cited by Petersen *et al.* 2009) has made them vulnerable to fishing. Chondrichthyans in the southern Benguela ecosystem have been caught as bycatch within a number of fishery sectors and have been targeted within the shark longline fishery since 1992 (Petersen *et al.* 2009). Records of chondrichthyans caught as bycatch were not always kept since they were not considered to be important by the fishery sector. However, chondrichthyans have been recognised as an essential component within the ecosystem because they are top predators and therefore play a role in maintaining the natural structure and functioning of the ecosystem. As a result, a conscientious effort has been made to record both the numbers and species of chondrichthyans caught within surveys and fishery sectors over the last 20 years. Based on these records, it seems that pelagic-feeding chondrichthyans are especially affected by fishing. During the current period, >70% of all chondrichthyans caught in the fishery were pelagic-feeders (Table 2.5), which can be attributed to the fact that because they are pelagic-feeders, they are more available to be caught by the various fishing sectors. The survey-estimated decline in pelagic-feeding chondrichthyan biomass could be a result of these fishing practices. The observed increase in survey-estimated biomass of benthic-feeding chondrichthyans between the last two time periods may be a consequence of the deliberate effort made to collect information on the potential biomass of benthic-feeding chondrichthyans in the southern Benguela ecosystem, since no baseline of data exists.

Mammal estimated biomass in the southern Benguela ecosystem seems to have undergone a significant reduction since the 1960s. Although All Mammal biomass appears to have stabilised over the last two time periods, especially with regards to seals in the southern Benguela ecosystem (Kirkman *et al.* 2007), it is assumed that these biomasses are not close to pristine levels. In fact, it is unreasonable to envisage All Mammals biomass at pristine levels again, since various fishery sectors have become significant consumers of the abundant prey originally consumed by mammals (Pitcher 2005). This is also in conjunction with a number of other pressures which have been identified as threats to mammals; more specifically seals (Kemper *et al.* 2007). Interactions between seals and fishery operations have increased. This has resulted in seal death and injuries either through net-entanglement or drowning in nets, as well as the deliberate killing of seals by fishermen (Wickens *et al.* 1992). A threat which has become significant in recent years is the documented change in distribution of small pelagic fish within the southern Benguela ecosystem (van der Lingen *et al.* 2006b). The location of the bulk of commercial sardine catches (Fairweather *et al.* 2006) and of anchovy spawners (van der Lingen *et al.* 2002) have shifted eastwards since the late 1990s. This change in prey distribution means that the prey is no longer available to seals and seabirds (van der Lingen *et al.* 2006b). In the case of seabirds, breeding success was reduced at existing African penguin and Cape gannet colonies in the west, a new penguin colony was established in the east and breeding success increased at Cape cormorant, tern and Cape gannet colonies in the south and east (Crawford *et al.* 2007b). It can be seen that a significant change in an essential ecosystem component, in this case small pelagic fish, will have significant effects that will trickle through the entire ecosystem because all ecosystem components are connected.

2.3.2. Consumption

The consumption pattern displayed by zooplankton groups in this model is simplified hypothetical replications by real time communities. Zooplankton feeding dynamics are much more complex than is represented and can have far reaching implications for the ecosystem as a whole (Moloney *et al.* 2010). For example, in the southern Benguela ecosystem, it is hypothesised that the alternating fluctuations of anchovy and sardine may be a result of changes within the zooplankton community, i.e. smaller-sized zooplankton favour sardine whereas larger-sized zooplankton favour anchovy (van der Lingen *et al.* 2006a). The current trophic model of the southern Benguela ecosystem was developed from a fishery perspective. It fulfils its purpose of focusing on the mid-trophic level groups in detail, but in so doing, does not adequately represent the lower trophic level groups. For a more complete representation of zooplankton communities' feeding dynamics, a purpose built model would be needed (Moloney *et al.* 2010), but was not the objective of this study.

Small pelagic fish, mainly anchovy and sardine, have recently undergone an eastward distribution shift within the southern Benguela ecosystem (van der Lingen *et al.* 2002, Fairweather *et al.* 2006, van der Lingen *et al.* 2006b). More anchovy and sardine are now located on the south coast of South Africa (Chapter 1 Figure 1.1). Following this shift in distribution, changes within the ecosystem food web can be expected and are in fact evident in the consumption pattern displayed by cephalopods. Adult cephalopods occur in the inshore waters off the south-east coast of South Africa, the location of the main cephalopod spawning grounds (Augustyn and Smale 1989). For the three historic time periods, the model-estimated cephalopod consumption of small pelagic fish never exceeded 10%, and field studies of estimated cephalopod diet report the frequency of occurrence of small pelagic fish within the diet from low to variable (Lipinski 1992). However, for the current period, the model-estimated cephalopod consumption of small pelagic fish has doubled, which means that cephalopods and small pelagic fish within the southern Benguela ecosystem have been encountering one another much more frequently.

It was very interesting to note the hake-cephalopod "flip-flop", i.e. All Hake and Cephalopods were the greatest consumers of each other. Cephalopods are known opportunistic predators that feed on a wide variety of prey items including macrozooplankton, anchovy, lightfish, lanternfish and hake (Lipinski 1992). Cephalopods are also important prey items of various fish species in the southern Benguela ecosystem, especially the two hake species (Lipinski *et al.* 1992). Lipinski *et al.* (1992) documented geographic, seasonal and species variability with regards to the cephalopods consumed by *M. capensis* and *M. paradoxus*. This evidence confirms that cephalopods are an important trophic link within the ecosystem. This is especially true since their biomass has increased between the last two time periods, perhaps as a result of increased prey availability, and can therefore act as a secondary prey source for the various opportunistic predators in the system, especially hake.

Hake has been described as an opportunistic predator within the southern Benguela ecosystem, feeding on a variety of prey items such as crustaceans, cephalopods and fish (Payne *et al.* 1987, Payne 1989). Concern has been raised regarding fisheries operating on prey species of hake (Payne *et al.* 1987, Payne 1989). Payne *et al.* (1987) observed mesopelagic fish (lightfish and lanternfish) in the stomachs of hake. This observation is especially important in the wake of the recent estimated increase in mesopelagic fish biomass which has prompted suggestions of declaring an official mesopelagic fish fishery. However, this option requires careful consideration because mesopelagic fish have been observed on the shelf edge where hake are found, and therefore represent a realistic food source for hake (A. Jarre, UCT, pers. comm. at the time of these analyses).

Chondrichthyans and Demersal Fish feeding patterns are also not adequately represented within the model. This is a consequence of the model design, which focuses on the pelagic, mid-trophic level components of the ecosystem. As is the case with zooplankton, a dedicated benthic/demersal model needs to be constructed if a more accurate depiction of the feeding patterns of chondrichthyans and demersal fish is required, but was not the focus of this study.

Comparisons of key trophic groups within the southern Benguela ecosystem reveal patterns of changing consumption over time. It highlights how the fishery has become a significant consumer of the various model groups and as a result, the natural predators have changed their consumption patterns. The various trophic groups may tap into alternate food sources available to compensate for the loss of an original food source. This is a property of the highly dynamic and productive southern Benguela ecosystem. The fishery, however, does not flip between prey items as natural consumers do. This exhibits a warning that continuous degradation of the ecosystem through unsustainable fishing, i.e. overfishing of prey items, will ultimately result in the collapse of the ecosystem, because original and alternative food sources will have been removed.

2.3.3. Fishing

The catch values used for the Anchovy and Sardine model groups within the 2004-2008 trophic model include discards. A greater discard amount was calculated for Sardine than for Anchovy, and has resulted in Sardine constituting the greatest proportion of the overall catch of small pelagic fish, even though Anchovy is the dominant small pelagic fish within the ecosystem for the current period according to biomass survey estimates. If discards were excluded, Anchovy would constitute the highest proportion of the recorded catch; i.e. 47% anchovy vs. 45% sardine, with redeye contributing the remaining 8%.

The fishery catches recorded for the current period for all model groups except Snoek, were inconspicuous, i.e. they have increased in response to increased biomass levels. Snoek biomass is estimated to have increased between the 1980s and current period, whereas the recorded fishery catches have decreased. The availability of Snoek to the fishery is hypothesised to be the cause of this discrepancy. Griffiths (2002) constructed a life history model for snoek in the Benguela ecosystem and found that adult snoek migrate offshore to spawn and the juveniles migrate in response to prey availability, i.e. inshore-offshore following clupeoid recruits. These migratory patterns cause snoek to be out of range of the line fishery for certain periods of time.

2.3.4. Trophic Level

During the current period, Other large pelagic fish were consuming less Anchovy, Sardine and Redeye, and more Other large pelagic fish. The effect of this diet adjustment resulted in the significant increase in trophic level of the model group, Other large pelagic fish. In the model, the diet of Snoek was adjusted such that it consumed more Anchovy, Sardine and Redeye, to better represent the southern Benguela ecosystem. This increase in small pelagic fish consumption by Snoek was compensated by a decrease in consumption of the higher trophic level groups, small hake (both *M. capensis* and *M. paradoxus*) and Pelagic-feeding demersal fish, with the result that the trophic level of Snoek decreased. Cephalopods were the greatest consumers of hake for the period 2004-2008. This has resulted in an increase of trophic level for Cephalopods. The biomass of the higher trophic level Pelagic-feeding chondrichthyans has decreased whereas the biomass of the lower trophic level benthic-feeders has increased. It was therefore assumed that in the new model, Apex chondrichthyans have been consuming more Benthic-feeding chondrichthyans because there are more available and has resulted in the trophic level decrease for Apex chondrichthyans. The lack of a significant trophic level decrease within all of the model groups suggests that no "fishing down the food web" (Pauly *et al.* 1998) has taken place within the southern Benguela ecosystem.

The 2004-2008 southern Benguela ecosystem food web components are depicted in Figure 2.6. The diagram displays the model groups with respect to the trophic level position they occupy within the current trophic model. Consumption matrices of the mid-trophic level predators (Anchovy, Sardine, Redeye, Other small pelagic fish, Chub mackerel, Juvenile horse mackerel, Adult horse mackerel, Mesopelagic fish, Snoek, Other large pelagic fish, Cephalopods, Small *M. capensis*, Large *M. capensis*, Small *M. paradoxus* and Large *M. paradoxus*) are presented in Tables 2.7a (planktivorous predators) and 2.7b (piscivorous predators). The predators mentioned previously were selected because they were the focus of the 2004-2008 southern Benguela ecosystem trophic model and their diets are better represented within the model, since their dietary habits have been more thoroughly researched within the southern Benguela ecosystem.

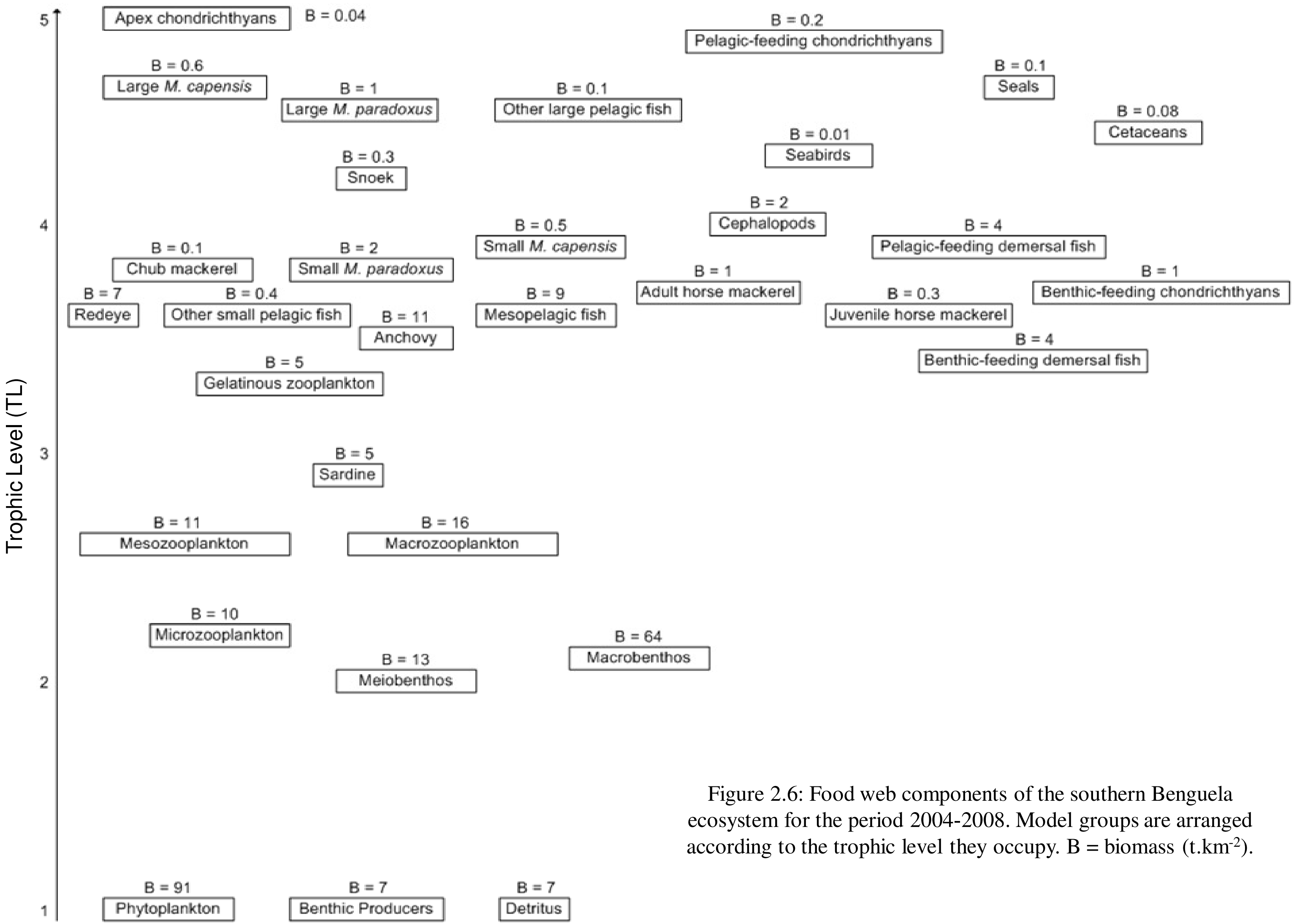


Figure 2.6: Food web components of the southern Benguela ecosystem for the period 2004-2008. Model groups are arranged according to the trophic level they occupy. B = biomass (t.km^{-2}).

Table 2.7a: Qualitative consumption matrix representing the mid-trophic level planktivorous predators and their main prey items from the 2004-2008 southern Benguela ecosystem trophic model. Prey item contributions (marked with an x) to overall predator diet have been divided into three categories: 10-24% (cells shaded light grey), 25-49% (cells shaded dark grey) and ≥50% (cells shaded black). Cells not shaded indicate that the prey contributes <10% or does not contribute to the predator diet.

Predator \ Prey	Phytoplankton	Microzooplankton	Mesozooplankton	Macrozooplankton
Anchovy				x
Sardine	x	x	x	
Redeye				x
Other small pelagic fish				x
Chub mackerel				
Juvenile horse mackerel				x
Adult horse mackerel			x	
Mesopelagic fish			x	

Table 2.7b: Qualitative consumption matrix representing the mid-trophic level piscivorous predators and their main prey items from the 2004-2008 southern Benguela ecosystem trophic model. Prey item contributions (marked with an x) to overall predator diet have been divided into three categories: 10-24% (cells shaded light grey), 25-49% (cells shaded dark grey) and ≥50% (cells shaded black). Cells not shaded indicate that the prey contributes <10% or does not contribute to the predator diet.

Predator \ Prey	Macrozooplankton	Anchovy	Sardine	Redeye	Adult horse mackerel	Mesopelagic fish	Cephalopods	Small *M. capensis*	Small *M. paradoxus*	Macrobenthos
Snoek	x	x	x	x						
Other large pelagic fish		x	x	x			x			
Cephalopods	x	x				x				x
Small *M. capensis*										
Large *M. capensis*	x	x			x	x		x	x	
Small *M. paradoxus*										
Large *M. paradoxus*	x					x	x		x	

Chapter 3

Trophic Model-Generated Indicators of the Southern Benguela Ecosystem

3.1. Introduction

Management of fishery sectors is moving towards an ecosystem approach, i.e. fisheries management within an ecosystem context (Link 2002). It has been recognised that fisheries cannot be managed independently to that of the ecosystem since the two are inter-connected and are essentially part of the same social-ecological system. One of the challenges towards achieving an Ecosystem Approach to Fisheries (EAF) is the actual implementation of an EAF management plan. The first step in this process is the identification of agreed upon goals and objectives (Slocombe 1998). Goals are classified as the overarching ambition towards which management is working (Slocombe 1998), for example, rebuilding stocks to healthy levels. These can only be observed over long time periods and are not appropriate for the dynamic nature of a fishery sector. Objectives are more measurable and ultimately achievable in the short-term (Slocombe 1998).

Slocombe (1998) defines an indicator as a system characteristic that provides feedback on progress towards management objectives. Indicators have been recognised as an aid for the implementation of an EAF framework in the fishing industry because (1) they can be related to fisheries management objectives, (2) they should be observable and (3) they should be understood by stakeholders (Degnbol and Jarre 2004, Rice and Rochet 2005). Various indicators have been identified and those describing the biological system, i.e. ecosystem functioning, fall into three categories: Single-species Indicators, Trophic Indicators and Size-based Indicators (Degnbol and Jarre 2004). Trophic Indicators measure the strength of interactions between ecosystem components and of structural ecosystem changes resulting from exploitation (Cury *et al.* 2005). This information would aid fisheries management because a better understanding of the structure and function of the ecosystem can be gained. However, the plethora of indicators being made available poses a threat by rendering management ineffective. Shin *et al.* (2010) have made progress in this regard through the identification of a small group of data-based ecological indicators that would monitor progress towards strategic management objectives, such as maintaining ecosystem structure and functioning, conservation of biodiversity and maintaining resource potential. Shin *et al.* (2010) emphasise that their selection of generic data-based indicators were intended as a starting point in the classification of exploited marine ecosystems around the world, in a comparative fashion. By comparison, this study considers trophic models as an additional source of indicators which may be helpful in capturing ecosystem properties of the southern Benguela ecosystem in more detail. The aim of this chapter is therefore to extract indicators from current and past southern Benguela ecosystem trophic models, and from these models, compile a trophic indicator list that would be most appropriate for use within management plans for the southern Benguela ecosystem.

3.2. Trophic Indicator Selection

The model groups used in the trophic model representing the southern Benguela ecosystem were aggregated to form functional groups (Table 3.1). The functional groups used were Pelagic-caught fish (PEL), Demersal-caught Fish (DEM), Small Fish (SMF), Large Fish (LAF), Planktivorous Fish (PLA) and Piscivorous Fish (PIS), and were modelled after those used in Cury *et al.* (2005) and Shannon *et al.* (2009a). The functional groups describe important ecosystem components, such as all predatory fish (PIS) and all forage fish (PLA) within the southern Benguela ecosystem. Changes occurring within and across the functional groups can be related to changes in ecosystem structure and function (Cury *et al.* 2005). The functional groups PEL and DEM were largely separated according to the type of fishery in which fish were caught, i.e. pelagic fishery (purse-seine, line-fishery, long line, other) or demersal fishery (midwater trawl, demersal trawl, long line, other) (Appendix Table 7.3). Although midwater trawl is a pelagic fishing gear, it has been included in the demersal fishery classification because it targets adult horse mackerel, which are also caught within the demersal trawl fishery (Appendix Table 7.3). The functional group separation would aid in the differentiation of fishing vs. natural environmental pressures driving changes in a functional group. Other groups included for easier characterisation of the southern Benguela ecosystem are System (all model groups except phytoplankton, benthic producers, micro-, meso-, macro and gelatinous zooplankton, meio- and macro-benthos, and detritus), Fin Fish (PEL and DEM) and Chondricthyans (apex, pelagic- and benthic-feeding).
Indicators have been grouped according to the properties of the southern Benguela ecosystem which they describe. Nine groups of indicators were extracted: Biomass, Production, Consumption, Catch, Trophic Level, Turnover Rate, Catch: Production, Catch: Biomass and System Indices.
Indicators generated from model outputs, as is the case with this study, allow for the opportunity to extract indicators which express ecosystem properties not usually available

through the data-based indicators extracted from research surveys. These include production and consumption ratios which are important for understanding the underlying dynamics of the system (Cury *et al.* 2005), thus providing a more complete picture of the ecosystem and its properties.

Table 3.1: Functional groups of the southern Benguela ecosystem used in the calculation of trophic indicators.

Functional Group	Code	Individual Model Groups
Pelagic-caught Fish	PEL	anchovy, sardine, redeye , other small pelagic fish, juvenile horse mackerel, chub mackerel, mesopelagic fish, all large pelagic fish (snoek & other large pelagic fish, e.g. yellowtail, tuna, etc. - See Chapter 2 Section 2.1.1.1)
Demersal-caught Fish	DEM	adult horse mackerel, all hake (small & large *M. capensis* and small & large *M. paradoxus*), pelagic- & benthic-feeding demersal fish
Small Fish	SMF	anchovy, sardine, redeye, other small pelagic fish, juvenile horse mackerel, small hake
Large Fish	LAF	large hake, all large pelagic fish (snoek & other large pelagic fish, e.g. yellowtail, tuna, etc. - See Chapter 2 Section 2.1.1.1)
Planktivorous Fish	PLA	anchovy, sardine, redeye, other small pelagic fish, adult & juvenile horse mackerel, mesopelagic fish, small hake
Piscivorous Fish	PIS	chub mackerel, all large pelagic fish (see above), large hake, pelagic- & benthic-feeding demersal fish
Pelagic Fish Predators	PFP	chub mackerel, all large pelagic fish (see above), large hake, seals, cetaceans, seabirds

3.2.1. Biomass (B) (t.km^{-2})

Model-estimated biomasses of functional groups can be used to generate model-estimated biomass ratios comparing functional groups within the southern Benguela ecosystem. Changes in functional group ratios can be related to changes within communities which translate into changes in ecosystem functioning (Cury *et al.* 2005). The indicator "proportion of predatory fish" is a measure of fish diversity and can reflect effects of fishing on ecosystem functioning (Shin *et al.* 2010). Calculations of the indicators are shown in Table 3.2.

Table 3.2: Calculation of Biomass (B) indicators.

Biomass Indicator	**Calculation**
B PEL/DEM	$\frac{\sum Model\ Biomass\ of\ PEL}{\sum Model\ Biomass\ of\ DEM}$
B SMF/LAF	$\frac{\sum Model\ Biomass\ of\ SMF}{\sum Model\ Biomass\ of\ LAF}$
B PLA/PIS	$\frac{\sum Model\ Biomass\ of\ PLA}{\sum Model\ Biomass\ of\ PIS}$
Proportion of predatory fish	$\frac{Model\ Biomass\ of\ PIS}{Model\ Biomass\ of\ (PEL + DEM + Cephalopods)}$

3.2.2. Production (P) ($t.km^{-2}.yr^{-1}$)

Model-estimated production by functional groups can be used to generate Production ratios comparing functional groups within the southern Benguela ecosystem. Production ratios reflect the biological dynamics of the functional groups (Cury *et al.* 2005). Calculations of the indicators are shown in Table 3.3.

Table 3.3: Calculation of Production (P) indicators.

Production Indicator	**Calculation**
P	$Model\ Biomass\ \times Model\ \frac{P}{B}$
P PEL/DEM	$\frac{\sum Model\ Production\ of\ PEL}{\sum Model\ Production\ of\ DEM}$
P SMF/LAF	$\frac{\sum Model\ Production\ of\ SMF}{\sum Model\ Production\ of\ LAF}$
P PLA/PIS	$\frac{\sum Model\ Production\ of\ PLA}{\sum Model\ Production\ of\ PIS}$

3.2.3. Consumption (Q) ($t.km^{-2}.yr^{-1}$)

Consumption indicators characterise the importance of prey and predator groups in the southern Benguela ecosystem (Cury *et al.* 2005). The consumption by a functional group describes what the functional group needs to sustain itself (how much needs to be consumed), whereas consumption of a functional group describes how important the functional group is to trophic groups higher up the food web (how much is consumed). Calculations of the indicators are shown in Table 3.4.

Table 3.4: Calculation of Consumption (Q) indicators.

Consumption Indicator	Calculation
Q	$Model\ Consumption$ (t.km^{-2}.yr^{-1})
Q by PEL Predators/DEM Predators	$\frac{\sum Q\ by\ PEL\ Predators}{\sum Q\ by\ DEM\ Predators}$
Q of PEL Prey/DEM Prey	$\frac{\sum Q\ of\ PEL\ Prey}{\sum Q\ of\ DEM\ Prey}$
Q by PLA Predators/PIS Predators	$\frac{\sum Q\ by\ PLA\ Predators}{\sum Q\ by\ PIS\ Predators}$
Q of PLA Prey/PIS Prey	$\frac{\sum Q\ of\ PLA\ Prey}{\sum Q\ of\ PIS\ Prey}$

3.2.4. Catch (Y) (t.km^{-2}.yr^{-1})

Catches of functional groups can be used to generate catch ratios comparing functional groups within the southern Benguela ecosystem. The catch ratios are expected to capture potential "fishing down the food web" (Pauly *et al.* 1998) effects as a result of the removal of the large, predatory, high trophic level fish from the system (Shannon *et al.* 2009a). Calculations of the indicators are shown in Table 3.5.

Table 3.5: Calculation of Catch (Y) indicators.

Catch Indicator	Calculation
Y PEL/DEM	$\frac{\sum Catch\ of\ PEL}{\sum Catch\ of\ DEM}$
Y SMF/LAF	$\frac{\sum Catch\ of\ SMF}{\sum Catch\ of\ LAF}$
Y PLA/PIS	$\frac{\sum Catch\ of\ PLA}{\sum Catch\ of\ PIS}$

3.2.5. Trophic Level (TL)

The position of a group within the food web can be described by its trophic level (TL). The trophic level can be calculated for each functional group and can describe changes within the functional group trophic positioning (Shannon *et al.* 2009a), which may be a result of the pressures acting upon the system. The mean trophic level of the catch (TL of the Y) measures the weighted mean TL of all model groups exploited by the fishery (Shin *et al.* 2010), and can therefore track fishing down of the food web (Pauly *et al.* 1998). The model groups, plankton (phytoplankton, benthic producers, micro-, meso-, macro- and gelatinous zooplankton), benthos (meio- and macrobenthos) and detritus were excluded when calculating the trophic level of the System. Calculations of the indicators are shown in Table 3.6.

Table 3.6: Calculation of trophic level (TL) indicators.

TL Indicator	Calculation
Mean TL of the Y	$\frac{\sum Individual\ (TL\ \times Y)}{Total\ Y}$
System TL	$\frac{\sum Individual\ (TL\ \times Model\ Biomass)(excl. plankton, benthos\ \&\ detritus)}{System\ Model\ Biomass\ (excl. plankton, benthos\ \&\ detritus)}$
PEL TL	$\frac{\sum Individual\ (TL\ \times Model\ Biomass)}{PEL\ B}$
DEM TL	$\frac{\sum Individual\ (TL\ \times Model\ Biomass)}{DEM\ B}$
PLA TL	$\frac{\sum Individual\ (TL\ \times Model\ Biomass)}{PLA\ B}$
PIS TL	$\frac{\sum Individual\ (TL\ \times Model\ Biomass)}{PIS\ B}$
PFP TL	$\frac{\sum Individual\ (TL\ \times Model\ Biomass)}{PFP\ B}$

3.2.6. Turnover Rate (P/B) (yr^{-1})

Turnover rates describe ecosystem bioenergetics (Christensen 1995). Odum (1985) and Christensen (1995) propose that the turnover rates in mature systems would be low since biomass has accumulated over time as a result of the efficient conversion of energy into biomass. Turnover rates of functional groups can therefore be used to determine whether a system is under stress (Odum 1985, Christensen 1995). Calculations of the indicators are shown in Table 3.7.

Table 3.7: Calculation of turnover rate (P/B) indicators.

Turnover Rate Indicator	Calculation
Primary P/Primary B	$\frac{Total\ Primary\ P}{Total\ System\ B\ (excluding\ detritus)}$
Fin Fish P/Fin Fish B	$\frac{\sum Fin\ Fish\ P}{\sum Fin\ Fish\ B}$
PEL P/PEL B	$\frac{\sum PEL\ P}{\sum PEL\ B}$
DEM P/DEM B	$\frac{\sum DEM\ P}{\sum DEM\ B}$
SMF P/SMF B	$\frac{\sum SMF\ P}{\sum SMF\ B}$
LAF P/LAF B	$\frac{\sum LAF\ P}{\sum LAF\ B}$
PLA P/PLA B	$\frac{\sum PLA\ P}{\sum PLA\ B}$
PIS P/PIS B	$\frac{\sum PIS\ P}{\sum PIS\ B}$

3.2.7. Catch: Production (Y/P)

Catch: production ratio indicators are a description of how much production is removed from the functional groups through their respective fishery sectors, i.e. how hard the system is being fished. Calculations of the indicators are shown in Table 3.8.

Table 3.8: Calculation of Catch: Production (Y/P) indicators.

Y/P Indicator	Calculation
Fishery Y/Fishery P	$\frac{Y(PEL + DEM + Cephalopods + Chondrichthyans)}{P\ (PEL + DEM + Cephalopods + Chondrichthyans)}$
Fin Fish Y/Fin Fish P	$\frac{Y(PEL + DEM)}{P\ (PEL + DEM)}$
Functional group* Y/P	$\frac{Functional\ Group\ Y}{Functional\ Group\ P}$

* as detailed in previous tables

3.2.8. Catch: Biomass (Y/B) (yr^{-1})

Catch: biomass ratio indicators are a description of how much biomass is removed from the functional groups, and ultimately the ecosystem, through their respective fishery sectors. Calculations of the indicators are shown in Table 3.9.

Table 3.9: Calculation of Catch: Biomass (Y/B) Indicators.

Y/B Indicator	Calculation
Fishery Y/Fishery B	$\frac{Y(PEL + DEM + Cephalopods + Chondrichthyans)}{B\ (PEL + DEM + Cephalopods + Chondrichthyans)}$
Fin Fish Y/Fin Fish B	$\frac{Y(PEL + DEM)}{B\ (PEL + DEM)}$
Functional group* Y/B	$\frac{Functional\ Group\ Y}{Functional\ Group\ B}$

* as detailed in previous tables

3.2.9. System Indices

Finn's mean path length represents the average number of groups that an inflow or outflow passes through (Finn 1980 as cited by Christensen *et al.* 2005). According to Shin *et al.* (2010), System Y/System B indicates global fishing pressure at the community level. This indicator measures the resource potential of the system because it represents how much of the community biomass is removed through fishing (Shin *et al.* 2010). Trophic models do not directly measure the size of organisms in a system. However, a proxy for size can be obtained from the inverse of the production/biomass ratio (Odum 1985, Christensen 1995), the Average Longevity, which is measured in years. It is expected that mature systems would have a higher proportion of long-lived, slow growing organisms while the opposite is true for newer systems (Odum 1985). The average longevity can therefore be used as an indicator of ecosystem stress. Calculations of the system indices are shown in Table 3.10.

Table 3.10: Calculation of System Indices.

System Indicator	Calculation
Finn's mean path length	$\frac{Throughput}{(\sum of\ Exports + \sum of\ Respiration)}$
System Y/ System B	$\frac{Y(PEL + DEM + Cephalopods + Chondrichthyans + Whales)}{B\ (PEL + DEM + Cephalopods + Chondrichthyans + Whales)}$
Average longevity	$\frac{Total\ System\ B\ (excluding\ detritus)}{Total\ Primary\ P}$

3.3. Results

The Trophic Indicators extracted from the 2004-2008 model representing the current state of the southern Benguela ecosystem were compared to those extracted from models of previous time periods, i.e. past ecosystem states. The three historic time periods considered were the 1900s “Pristine”, 1960s “Industrial” and 1980s “Anchovy Period”. The 1900s and 1960s models were compiled by Watermeyer *et al.* (2008a) and the 1980s model was constructed by Shannon *et al.* (2003). The four models and indicators derived from these models were comparable because the same individual model groups were used and the functional group aggregations were therefore the same across the four time periods. In this manner, an assessment could be made about the state and trend of the southern Benguela ecosystem. Trophic Indicators describing properties of the southern Benguela ecosystem are displayed graphically in Figures 3.1- 3.9. Although the indicator values are displayed as line graphs with markers for the four time periods, it must be remembered that they are not continuous time series. The lines are used merely to emphasise the trends between the four model time periods, i.e. an increase or decrease. Trophic Indicator values are shown in Appendix Table 7.6.

3.3.1. Biomass (B) ($t.km^{-2}.yr^{-1}$)

Biomass indicators are displayed in Figure 3.1. Biomass of the entire southern Benguela ecosystem (Total System B), excluding detritus, was at its highest value for the 2004-2008 period, with an overall increase of 10% from the “pristine” to current period (Figure 3.1; Appendix Table 7.6). Functional groups which also displayed maximum biomass values during the current period are Total Fin Fish (6% overall increase), Total Pelagic-caught Fish (PEL) (12% overall increase), Total Small Fish (SMF) (19% overall increase) and Total Planktivorous Fish (PLA) (9% overall increase) (Figure 3.1; Appendix Table 7.6). Four functional groups displayed a decrease in biomass from the 1900s to the current period: Total Demersal-caught Fish (DEM) (5% overall decrease), Total Large Fish (LAF) (40% overall decrease), Total Piscivorous Fish (PIS) (2% overall decrease) and Total Pelagic Fish Predators (PFP) (38% overall decrease) (Figure 3.1; Appendix Table 7.6). Total Chondrichthyan biomass underwent a significant decline between 1900 and 1960, but reached a maximum in the 1980s and has remained relatively stable since then with an overall increase of 6% (Figure 3.1; Appendix Table 7.6).

Only one of the four biomass indicator ratios calculated, Small Fish: Large Fish (SMF/LAF) showed a consistent increasing pattern over time (overall 55% increase) (Figure 3.1; Appendix Table 7.6). The three remaining biomass indicator ratios displayed fluctuating patterns over the four time periods (Figure 3.1). Biomass of All Pelagic-caught Fish: Demersal-caught Fish (PEL/DEM) and Biomass of Planktivorous Fish: Piscivorous Fish

(PLA/PIS) had overall increases of 17% and 11% respectively, whereas the Proportion of predatory fish (Prop. of pred. fish) had an overall decrease of 9% (Appendix Table 7.6). However, Prop. of pred. fish had opposite trends to that displayed by PEL/DEM and PLA/PIS, i.e. when the Prop of pred. fish ratio was higher (1960 -1980), both the PEL/DEM and PLA/PIS ratios were lower, and vice versa for the other time periods (Figure 3.1).

3.3.2. Production (P) ($t.km^{-2}.yr^{-1}$)

Production indicators are displayed in Figure 3.2. The highest production was calculated to occur in the current 2004-2008 period for the following groups: System, Total Fin Fish, PEL, SMF, PLA and PIS (Figure 3.2; Appendix Table 7.6). These six groups experienced overall increases in production of 18%, 4%, 8%, 10%, 3% and 10% respectively (Appendix Table 7.6). The functional groups which experienced decreases in production over the four time periods were DEM, LAF and PFP (overall decrease: 5%, 42% and 38% respectively; Figure 3.2; Appendix Table 7.6), with PFP experiencing the lowest production during the current period. Two production ratios were highest during the current period, PEL/DEM and SMF/LAF (14% and 51% overall increase respectively), whereas PLA/PIS was highest during 1900 (7% overall decrease) (Figure 3.2, Appendix Table 7.6).

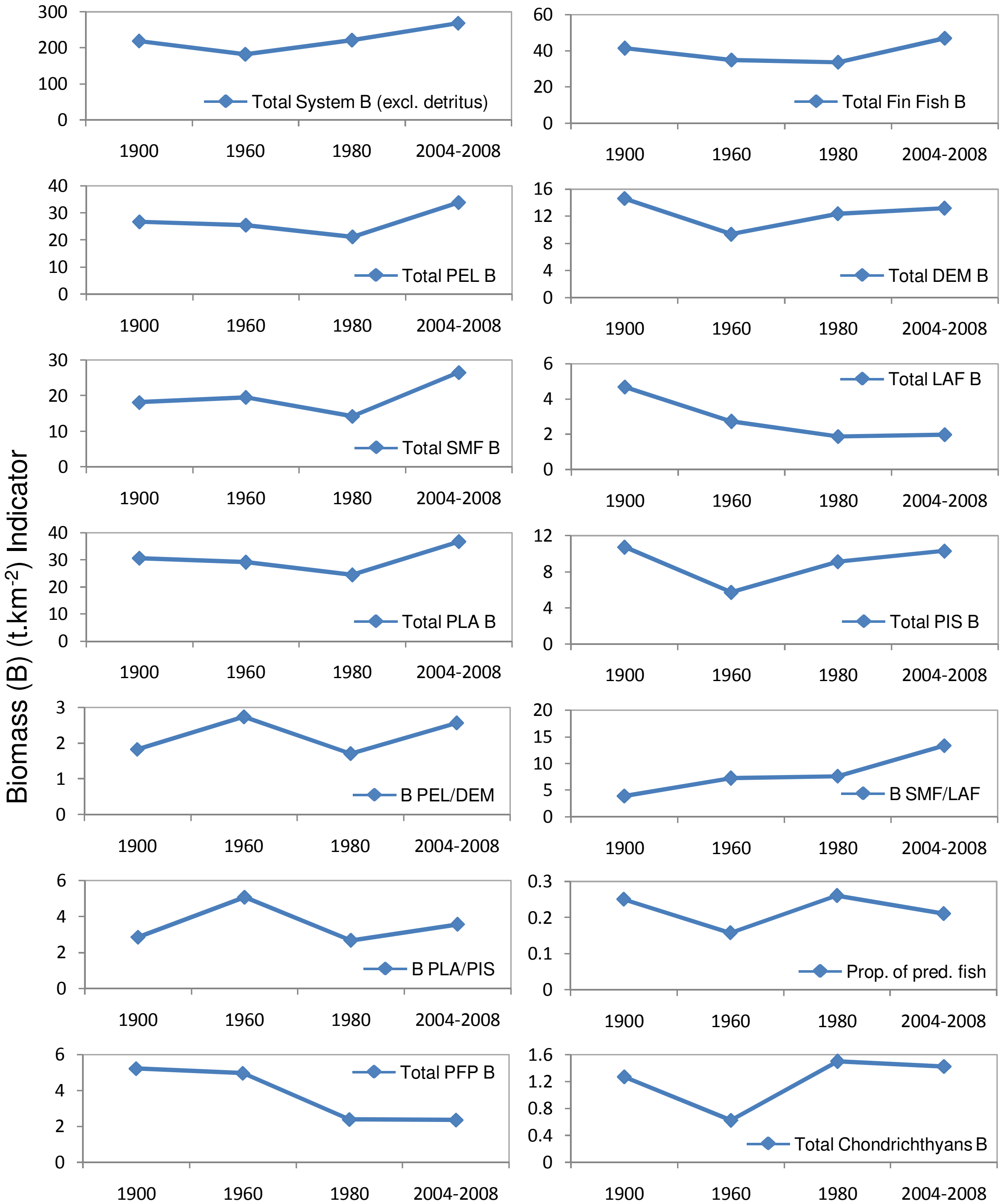


Figure 3.1: Biomass (B; t.km^{-2}) indicators of the southern Benguela ecosystem over the time periods 1900, 1960, 1980 and 2004-2008. Data for 1980 were sourced from Shannon *et al.* (2003) and for 1900 & 1960 from Watermeyer *et al.* (2008a). Total Fin Fish = Pelagic-caught & Demersal-caught Fish; Pelagic-caught Fish (PEL) = anchovy, sardine, redeye (ASR), other small pelagic fish, juvenile horse mackerel, mesopelagic fish, chub mackerel, all large pelagic fish (snoek & other large pelagic fish); Demersal-caught Fish (DEM) = all hake (small & large *M. capensis*, small & large *M. paradoxus*), pelagic- & benthic-feeding demersal fish, adult horse mackerel; SMF = Small Fish (ASR, other small pelagic fish, juvenile horse mackerel, small hake); LAF = Large Fish (large hake, all large pelagic fish); PLA = Planktivorous Fish (ASR, other small pelagic fish, all horse mackerel, mesopelagic fish, small hake); PIS = Piscivorous Fish (large hake, all large pelagic fish, pelagic- & benthic-feeding demersal fish, chub mackerel); Prop. of pred. fish = Proportion of predatory fish; PFP = Pelagic Fish Predators (seabirds, seals, cetaceans, all large pelagic fish, large hake, chub mackerel); Chondrichthyans = apex, pelagic- & benthic-feeding chondrichthyans.

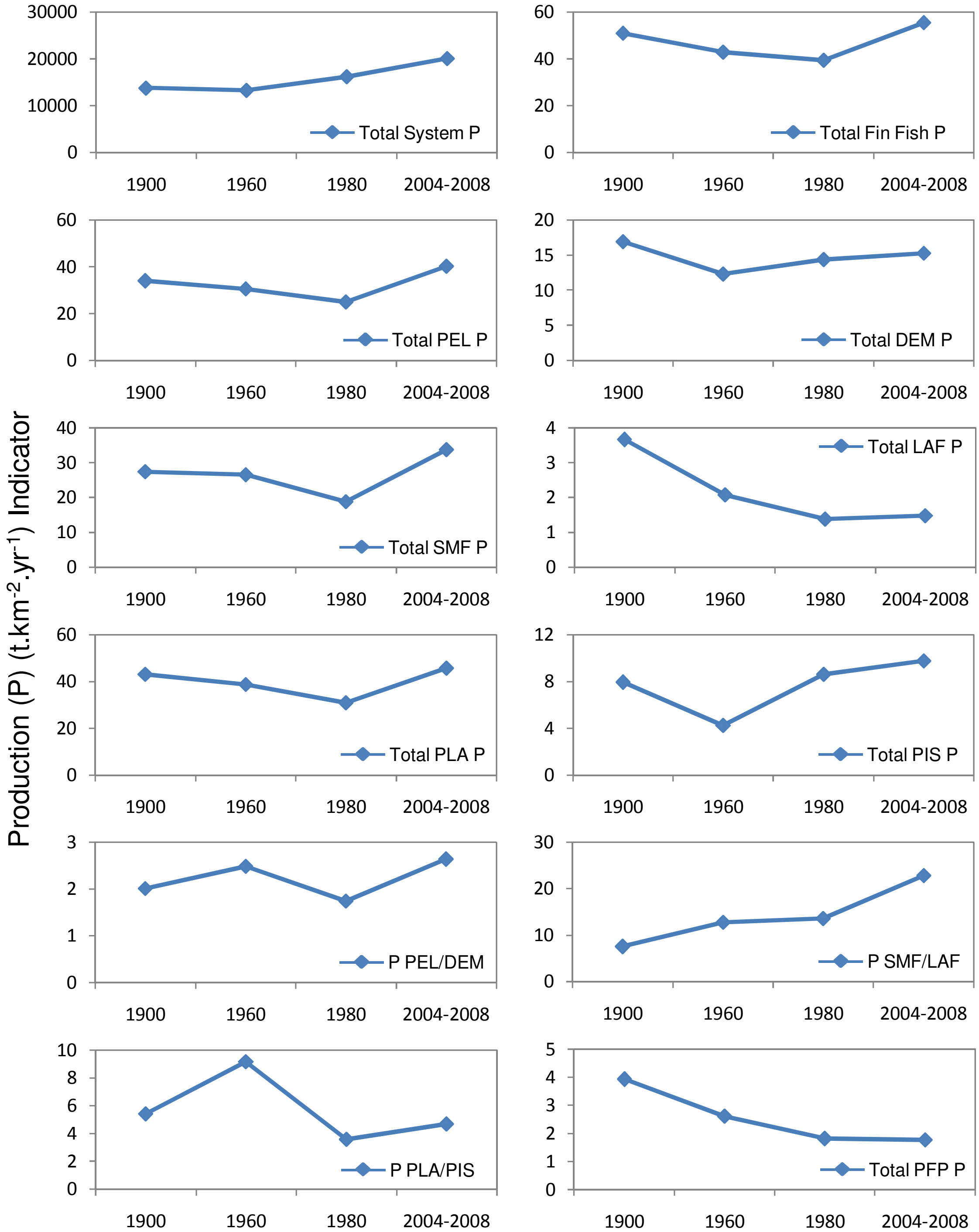


Figure 3.2: Production (P; t.km^{-2}.yr^{-1}) indicators of the southern Benguela ecosystem over the time periods 1900, 1960, 1980 and 2004-2008. Data for 1980 were sourced from Shannon *et al.* (2003) and for 1900 & 1960 from Watermeyer *et al.* (2008a). Total Fin Fish = Pelagic-caught & Demersal-caught Fish; Pelagic-caught Fish (PEL) = anchovy, sardine, redeye (ASR), other small pelagic fish, juvenile horse mackerel, mesopelagic fish, chub mackerel, all large pelagic fish (snoek & other large pelagic fish); Demersal Fish (DEM) = all hake (small & large *M. capensis*; small & large *M. paradoxus*), pelagic- & benthic-feeding demersal fish, adult horse mackerel; SMF = Small Fish (ASR, other small pelagic fish, juvenile horse mackerel, small hake); LAF = Large Fish (large hake, all large pelagic fish); PLA = Planktivorous Fish (ASR, other small pelagic fish, all horse mackerel, mesopelagic fish, small hake); PIS = Piscivorous Fish (large hake, all large pelagic fish, pelagic- & benthic-feeding demersal fish, chub mackerel); PFP = Pelagic Fish Predators (seabirds, seals, cetaceans, all large pelagic fish, large hake, chub mackerel).

3.3.3. Consumption (Q) ($t.km^{-2}.yr^{-1}$)

Consumption indicators are displayed in Figure 3.3. Consumption by PEL Predators (Q by PEL Predators) and of PEL Prey (Q of PEL Prey) followed similar trends over the four time periods (Figure 3.3). From 1900 to 1980 there was decline in consumption by PEL Predators and of PEL Prey (15% and 18% decrease respectively). However, from 1980 to2004-2008, increases in consumption for both, by PEL Predators and of PEL Prey, have occurred (24% and 9% increase respectively) (Figure 3.3). Consumption patterns by DEM Predators (Q by DEM Predators) and of DEM Prey (Q of DEM Prey) have also followed similar trends to each other (Figure 3.3). There was a decrease in consumption of 14% and 11% by DEM Predators and of DEM Prey respectively, from 1900 to 1960. Since the 1960s to the current period, consumption has increased by 8% for the DEM Predators and by 10% of the DEM Prey (Figure 3.3).

All eight functional group consumption indicators displayed minimum values in one of two time periods, the 1960s or the 1980s. The consumption indicators which were at minimum values in the 1960s were Q by DEM Predators, Q of DEM Prey, Q by PIS Predators and Q of PIS Prey (Figure 3.3; Appendix Table 7.6). The consumption indicators which were at minimum values in the 1980s were Q by PEL Predators, Q of PEL Prey, Q by PLA Predators and Q of PLA Prey (Figure 3.3; Appendix Table 7.6).

The four consumption indicator ratios calculated were all highest during the 1960s period and then lowest during the 1980s period (Figure 3.3). The three consumption indicator ratios, Q by PEL/DEM Predators, Q of PEL/DEM Prey and Q by PLA/PIS Predators showed an increase from the 1980s to current period of 22%, 8% and 15% respectively. The consumption indicator ratio Q of PLA/PIS Prey remained stable since the 1980s with an increase of only 3% till the current period.

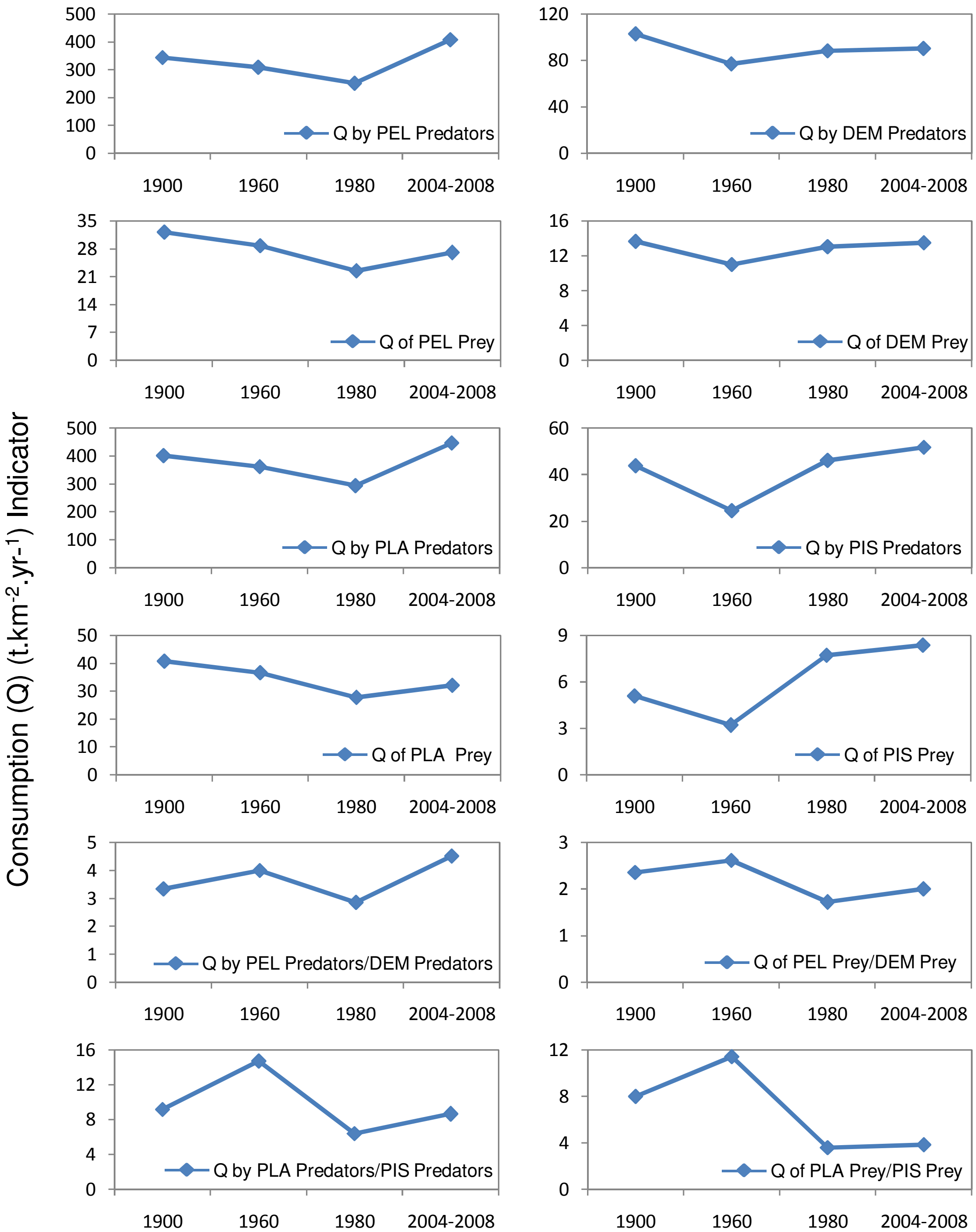


Figure 3.3: Consumption (Q; t.km^{-2}.yr^{-1}) indicators of the southern Benguela ecosystem over the time periods 1900, 1960, 1980 and 2004-2008. Data for 1980 were sourced from Shannon *et al.* (2003) and for 1900 & 1960 from Watermeyer *et al.* (2008a). Pelagic-caught Fish (PEL) = anchovy, sardine, redeye (ASR), other small pelagic fish, juvenile horse mackerel, mesopelagic fish, chub mackerel, all large pelagic fish (snoek & other large pelagic fish); Demersal-caught Fish (DEM) = all hake (small & large *M. capensis*, small & large *M. paradoxus*), pelagic- & benthic-feeding demersal fish, adult horse mackerel; PLA = Planktivorous Fish (ASR, other small pelagic fish, all horse mackerel, mesopelagic fish, small hake); PIS = Piscivorous Fish (large hake, all large pelagic fish, pelagic- & benthic-feeding demersal fish, chub mackerel).

3.3.4. Catch (Y) ($t.km^{-2}.yr^{-1}$)

Catch indicators are displayed in Figure 3.4. The 1900s Y indicator value for all groups displays as zero because either there were no harvests for the functional group, or there were harvests, but they were very minimal, i.e. approximately zero (Figure 3.4; Appendix Table 7.6). For this reason, the overall change in Y indicator value was calculated from the 1960s, the start of the industrial fishing era, to the current 2004-2008 period (Appendix Table 7.6). Maximum catches were recorded during the 2004-2008 period for the groups: Total System, Total Fin Fish, PEL, SMF and PLA (Figure 3.4). Functional groups which displayed a decrease in recorded catch from the 1960s to the current period were DEM, LAF and PIS (15%, 8% and 12% respectively) (Figure 3.4; Appendix Table 7.6). The three catch ratios calculated, PEL/DEM, SMF/LAF and PLA/PIS, have maximum values during the current period (Figure 3.4) and experienced overall increases from the 1960s to the current period of 39%, 35% and 33% respectively (Appendix Table 7.6).

3.3.5. Trophic Level (TL)

The trophic levels of various groups occurring in the southern Benguela ecosystem are displayed in Figure 3.5. The trophic level of the Catch (Y), System (excluding plankton, benthos and detritus) and all functional groups (PEL, DEM, PLA, PIS, PFP) have all decreased relative to that calculated for the 1900s (Figure 3.5). The lowest TL occurred in the current period for the Y, System, DEM and PIS groups (Figure 3.5; Appendix Table 7.6). The TLs of the System, PEL and PLA have fluctuated over the four time periods, but do display similar trends, i.e. TLs of all three groups increase and decrease in correspondence with each other (Figure 3.5). TL of PFP experienced a decline from the 1900 to the 1960s (2%), but has increased slightly from the 1980s to the current period (0.5%) (Figure 3.5).

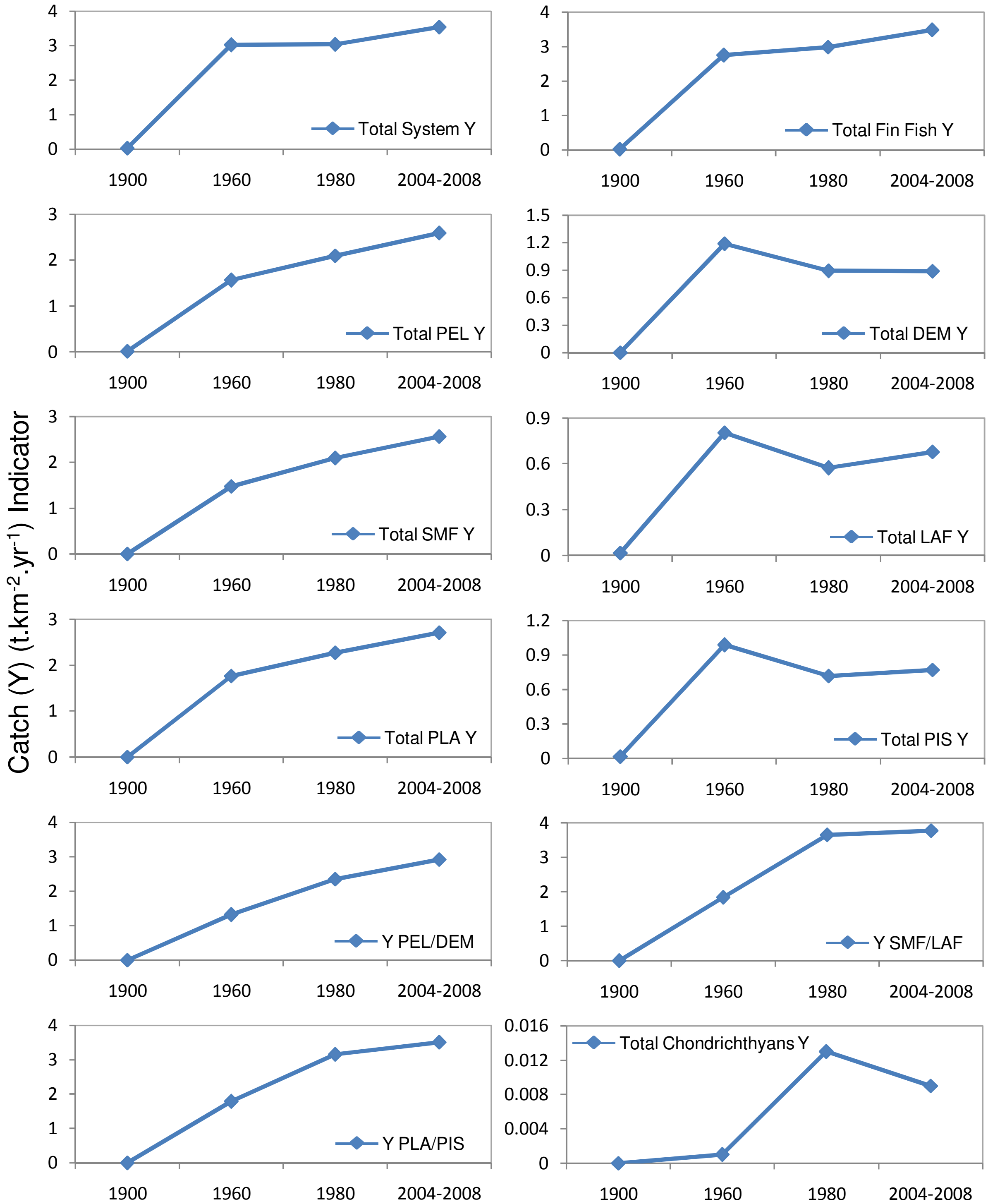


Figure 3.4: Catch (Y; t.km^{-2}.yr^{-1}) indicators of the southern Benguela ecosystem over the time periods 1900, 1960, 1980 and 2004-2008. Data for 1980 were sourced from Shannon *et al.* (2003) and for 1900 & 1960 from Watermeyer *et al.* (2008a). Total Fin Fish = Pelagic-caught & Demersal-caught Fish; Pelagic-caught Fish (PEL) = anchovy, sardine, redeye (ASR), other small pelagic fish, juvenile horse mackerel, mesopelagic fish, chub mackerel, all large pelagic fish (snoek & other large pelagic fish); Demersal-caught Fish (DEM) = all hake (small & large *M. capensis*, small & large *M. paradoxus*), pelagic- & benthic-feeding demersal fish, adult horse mackerel; SMF = Small Fish (ASR, other small pelagic fish, juvenile horse mackerel, small hake); LAF = Large Fish (large hake, all large pelagic fish); PLA = Planktivorous Fish (ASR, other small pelagic fish, all horse mackerel, mesopelagic fish, small hake); PIS = Piscivorous Fish (large hake, all large pelagic fish, pelagic- & benthic-feeding demersal fish, chub mackerel); Chondrichthyans = apex, pelagic- & benthic-feeding chondrichthyans.

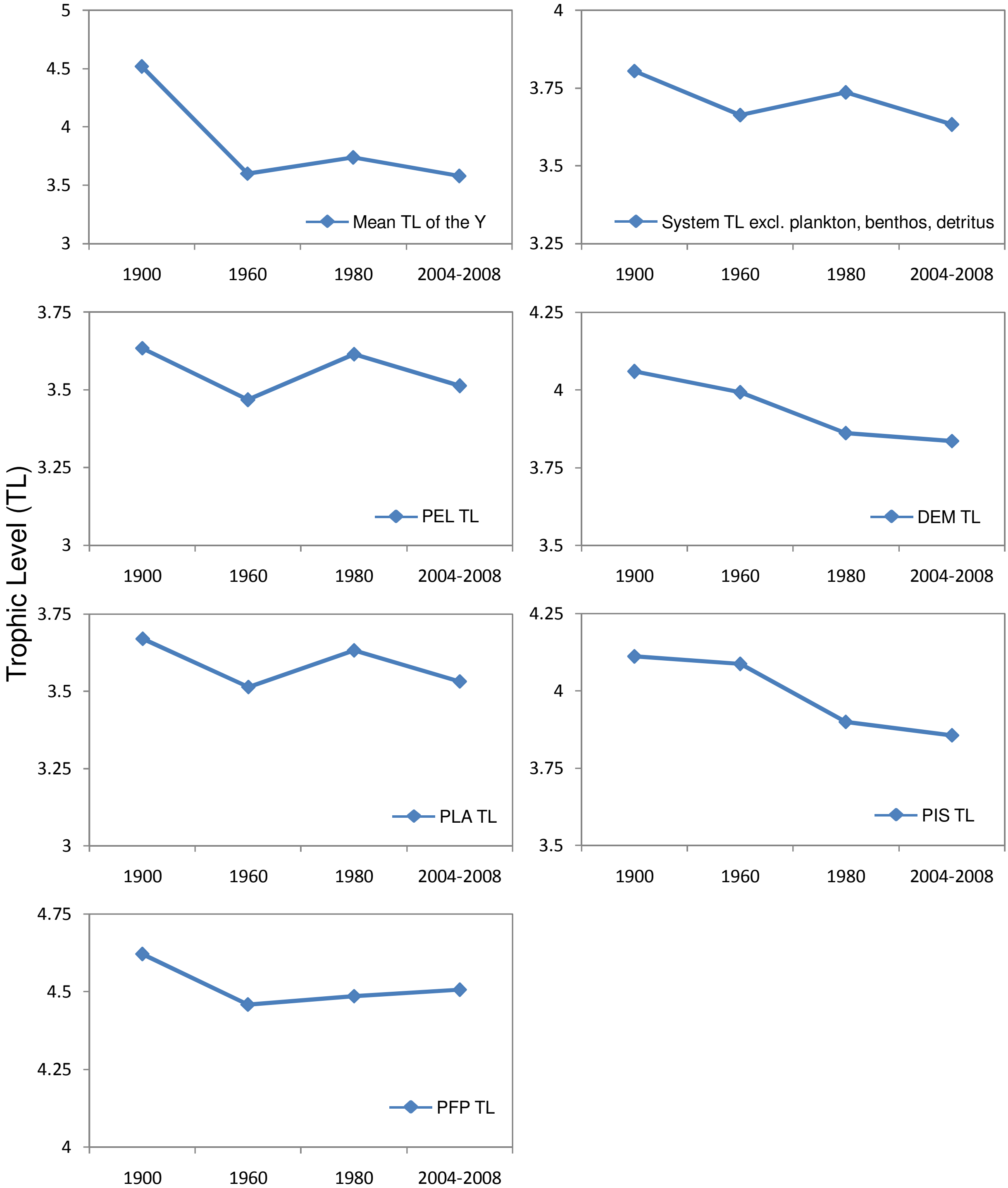


Figure 3.5: Trophic levels (TL) of functional groups in the southern Benguela ecosystem over the time periods 1900, 1960, 1980 and 2004-2008. Data for 1980 were sourced from Shannon *et al.* (2003) and for 1900 & 1960 from Watermeyer *et al.* (2008a). Y = catch (t.km^{-2}.yr^{-1}); System = all model groups except phytoplankton, benthic producers, micro-, meso-, macro- and gelatinous zooplankton, meio- & macrobenthos, detritus; Pelagic-caught Fish (PEL) = anchovy, sardine, redeye (ASR), other small pelagic fish, juvenile horse mackerel, mesopelagic fish, chub mackerel, all large pelagic fish (snoek & other large pelagic fish); Demersal-caught Fish (DEM) = all hake (small & large *M. capensis*, small & large *M. paradoxus*), pelagic- & benthic-feeding demersal fish, adult horse mackerel; PLA = Planktivorous Fish (ASR, other small pelagic fish, all horse mackerel, mesopelagic fish, small hake); PIS = Piscivorous Fish (large hake, all large pelagic fish, pelagic- & benthic-feeding demersal fish, chub mackerel); PFP = Pelagic Fish Predators (seabirds, seals, cetaceans, all large pelagic fish, large hake, chub mackerel).

3.3.6. Turnover Rate (P/B) (yr^{-1})

Turnover rate indicators are displayed in Figure 3.6. All groups except DEM P/DEM B and PIS P/PIS B experienced declines in their turnover rate from the 1900s (Figure 3.6). The greatest overall decline was by SMF P/SMF B (9%), followed by PLA P/PLA B (6%), PEL P/PEL B and LAF P/LAF B (both 3%), and lastly Total Fin Fish P/Total Fin Fish B and Total Primary P/Total Primary B (both 2%) (Appendix Table 7.6). The DEM turnover rate increased from the 1900s to a maximum in the 1960s (1.32 yr^{-1}; 6% increase), after which it declined and is estimated to have remained at a constant level in the 1980s and current periods as that of the 1900s (1.20 yr^{-1}) (Figure 3.6; Appendix Table 7.6). On the other hand, turnover rate was at a minimum in the 1900s for the group PIS, but has increased by 12% to a maximum value of 0.95 yr^{-1} during the current period (Figure 3.6; Appendix Table 7.6).

3.3.7. Catch: Production (Y/P)

Catch: Production indicators are displayed in Figure 3.7. The 1900s Y/P indicator value for all groups displays as zero because either there were no harvests for the functional group, or there were harvests, but they were very minimal with the result that the indicator value was approximately zero (Figure 3.7; Appendix Table 7.6). For this reason, the overall change in Y/P indicator value was calculated from the 1960s, the start of the industrial fishing era, to the current 2004-2008 period (Appendix Table 7.6).

Four groups displayed overall decreases in Y/P ratios since the 1960s, and these groups were Total Fishery, Total Fin Fish, DEM and PIS (5%, 1%, 25% and 49% decline respectively since the 1960s; Figure 3.7; Appendix Table 7.6). Only the LAF group displayed a constant increase in Y/P ratio from one period to the next (1960s vs. 1980s: 3% increase; 1980s vs. 2004-2008: 5% increase; 9% overall increase). The remaining groups, PEL, SMF and PLA, had Y/P ratios which increased from the 1960s to reach a maximum in the 1980s, after which they declined again (Figure 3.7). The overall change in Y/P indicator value from the 1960s to the current period experienced by PEL, SMF and PLA, were increases of 12%, 16% and 13% respectively (Appendix Table 7.6).

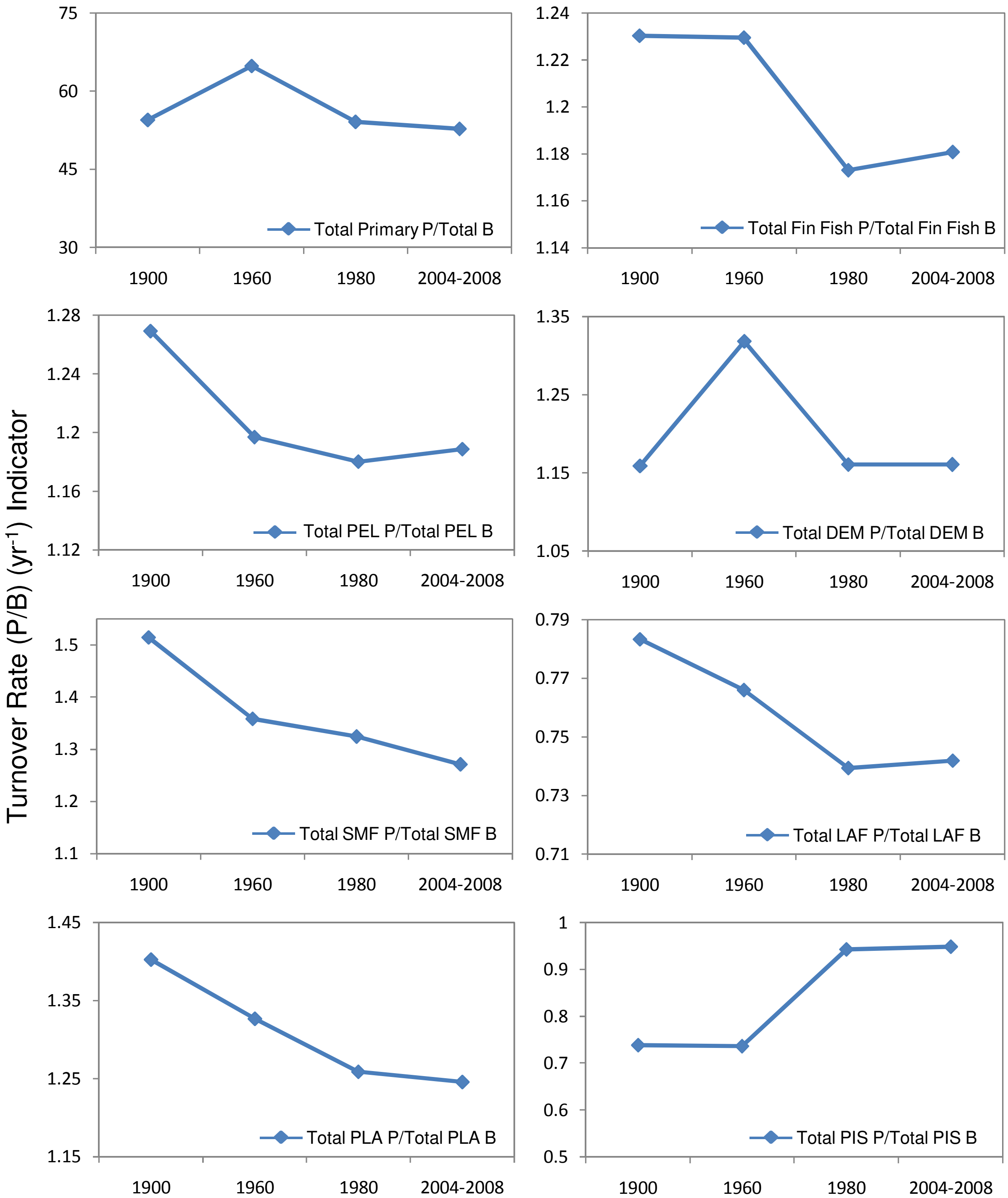


Figure 3.6: Turnover Rate (P/B; yr^{-1}) indicators of the southern Benguela ecosystem over the time periods 1900, 1960, 1980 and 2004-2008. Data for 1980 were sourced from Shannon *et al.* (2003) and for 1900 & 1960 from Watermeyer *et al.* (2008a). P = Production ($t.km^{-2}.yr^{-1}$); B = Biomass ($t.km^{-2}$); Total Fin Fish = Pelagic-caught & Demersal-caught Fish; Pelagic-caught Fish (PEL) = anchovy, sardine, redeye (ASR), other small pelagic fish, juvenile horse mackerel, mesopelagic fish, chub mackerel, all large pelagic fish (snoek & other large pelagic fish); Demersal-caught Fish (DEM) = all hake (small & large *M. capensis*, small & large *M. paradoxus*), pelagic- & benthic-feeding demersal fish, adult horse mackerel; SMF = Small Fish (ASR, other small pelagic fish, juvenile horse mackerel, small hake); LAF = Large Fish (large hake, all large pelagic fish); PLA = Planktivorous Fish (ASR, other small pelagic fish, all horse mackerel, mesopelagic fish, small hake); PIS = Piscivorous Fish (large hake, all large pelagic fish, pelagic- & benthic-feeding demersal fish, chub mackerel).

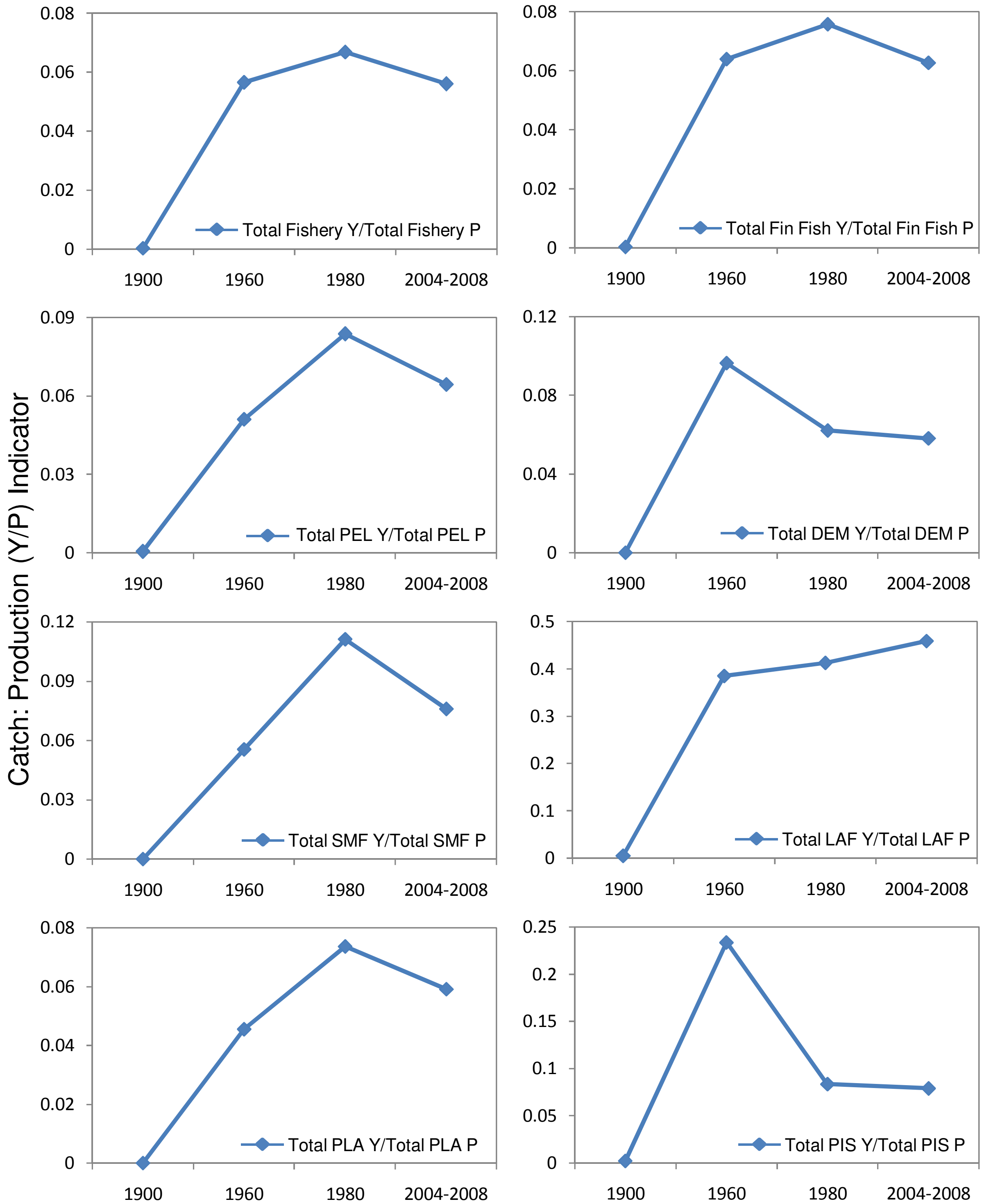


Figure 3.7: Catch: Production (Y/P) indicators of the southern Benguela ecosystem over the time periods 1900, 1960, 1980 and 2004-2008. Data for 1980 were sourced from Shannon *et al.* (2003) and for 1900 & 1960 from Watermeyer *et al.* (2008a). Y = Catch ($t.km^{-2}.yr^{-1}$); P = Production ($t.km^{-2}.yr^{-1}$); Total Fishery = Fin Fish, Cephalopods & Chondrichthyans (apex, pelagic- & benthic-feeding) caught; Total Fin Fish = Pelagic-caught & Demersal-caught Fish; Pelagic-caught Fish (PEL) = anchovy, sardine, redeye (ASR), other small pelagic fish, juvenile horse mackerel, mesopelagic fish, chub mackerel, all large pelagic fish (snoek & other large pelagic fish); Demersal-caught Fish (DEM) = all hake (small & large *M. capensis*, small & large *M. paradoxus*), pelagic- & benthic-feeding demersal fish, adult horse mackerel; SMF = Small Fish (ASR, other small pelagic fish, juvenile horse mackerel, small hake); LAF = Large Fish (large hake, all large pelagic fish); PLA = Planktivorous Fish (ASR, other small pelagic fish, all horse mackerel, mesopelagic fish, small hake); PIS = Piscivorous Fish (large hake, all large pelagic fish, pelagic- & benthic-feeding demersal fish, chub mackerel).

3.3.8. Catch: Biomass (Y/B) (yr^{-1})

Catch: Biomass indicators are displayed in Figure 3.8. The overall percentage change in the Y/B indicators was calculated from the 1960s to the 2004-2008 period for the same reasons as mentioned in section 3.3.7 Catch: Production. The Y/B indicators displayed similar trends to that of the Y/P indicators. The same four groups which displayed overall decreases in Y/P ratios displayed overall decreases in Y/B ratios. These groups were Total Fishery, Total Fin Fish, DEM and PIS (3%, 3%, 31% and 39% decline respectively; Figure 3.8; Appendix Table 7.6). The LAF group was again the only group which displayed a constant increase in Y/B ratio from one period to the next (1960s vs. 1980s: 2% increase; 1980s vs. 2004-2008: 6% increase; 7% overall increase). The three remaining functional groups, PEL, SMF and PLA, again had Y/B ratios which increased from the 1960s to reach a maximum in the 1980s, after which they declined (Figure 3.8). All three groups displayed an overall increase in Y/B indicator value (PEL = 11%, SMF = 12%, PLA = 10%; Appendix Table 7.6).

3.3.9. System Indices

Three system indices, Finn's mean path length, System Y/System B (yr^{-1}) and Proportion of r-strategists (B/P) are displayed for the southern Benguela ecosystem across four time periods in Figure 3.9. Finn's mean path length decreased from the 1900s to a minimum value of 2.4 in the 1960s, but then increased to a maximum (3.4) in the current period (overall increase of 2%; Figure 3.9; Appendix Table 7.6). The indicator System Y/System B is displayed as zero in the 1900s, but this is due to minimal harvests during this period, after which it increased to a maximum in the 1960s, the start of the industrial fishing era, and then declined (Figure 3.9). The overall change in the System Y/System B indicator was a decrease of 11% (Appendix Table 7.6). The average longevity indicator declined from the 1900s to a minimum in the 1960s. The indicator increased after that to a maximum value in the current period (0.02) (overall increase of 14%; Figure 3.9; Appendix Table 7.6).

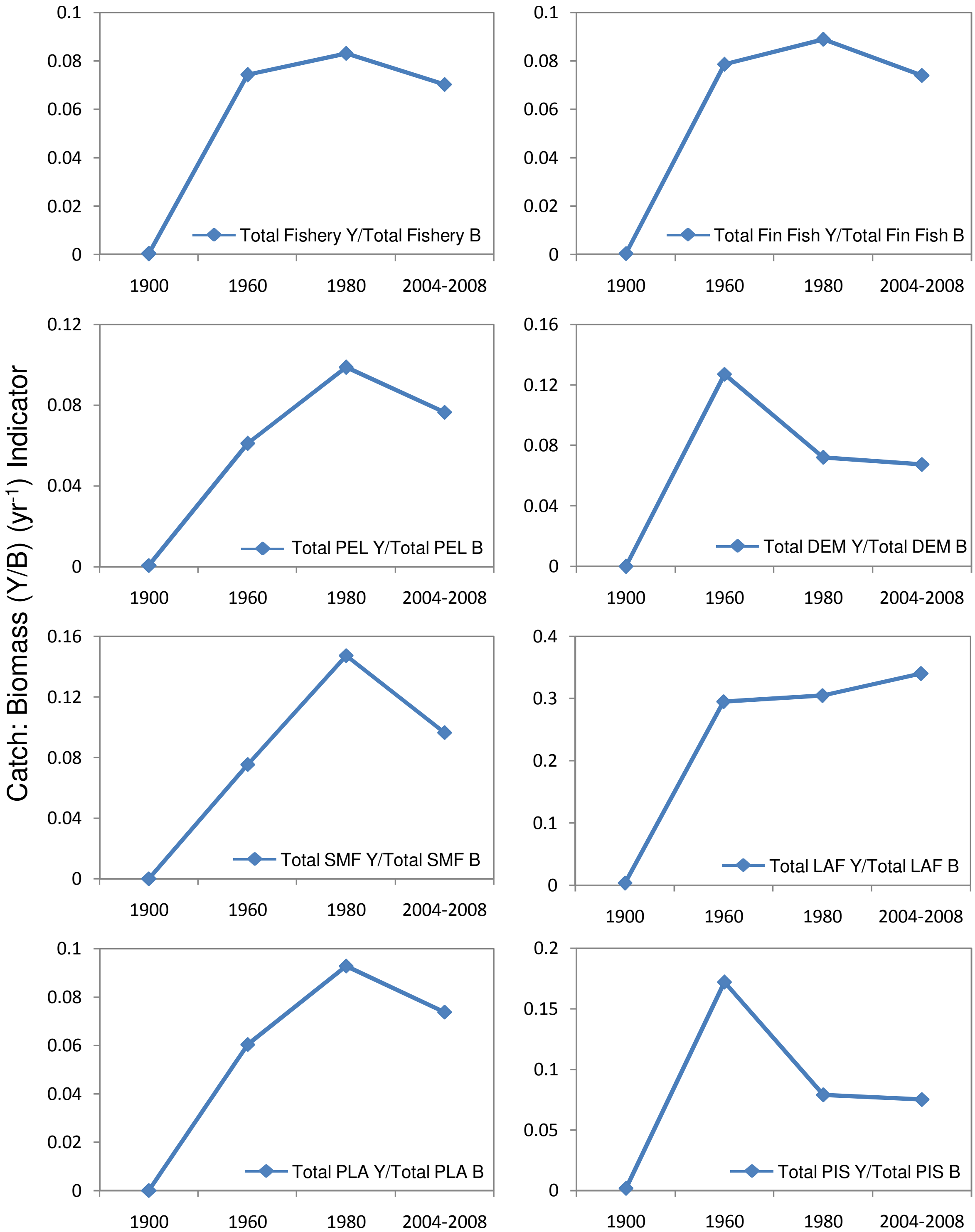


Figure 3.8: Catch: Biomass (Y/B; yr^{-1}) indicators of the southern Benguela ecosystem over the time periods 1900, 1960, 1980 and 2004-2008. Data for 1980 were sourced from Shannon *et al.* (2003) and for 1900 & 1960 from Watermeyer *et al.* (2008a). Y = Catch ($t.km^{-2}.yr^{-1}$); B = Biomass ($t.km^{-2}$); Total Fishery = Fin Fish, Cephalopods & Chondrichthyans (apex, pelagic- & benthic-feeding) caught; Total Fin Fish = Pelagic-caught & Demersal-caught Fish; Pelagic-caught Fish (PEL) = anchovy, sardine, redeye (ASR), other small pelagic fish, juvenile horse mackerel, mesopelagic fish, chub mackerel, all large pelagic fish (snoek & other large pelagic fish); Demersal-caught Fish (DEM) = all hake (small & large *M. capensis*, small & large *M. paradoxus*), pelagic- & benthic-feeding demersal fish, adult horse mackerel; SMF = Small Fish (ASR, other small pelagic fish, juvenile horse mackerel, small hake); LAF = Large Fish (large hake, all large pelagic fish); PLA = Planktivorous Fish (ASR, other small pelagic fish, all horse mackerel, mesopelagic fish, small hake); PIS = Piscivorous Fish (large hake, all large pelagic fish, pelagic- & benthic-feeding demersal fish, chub mackerel).

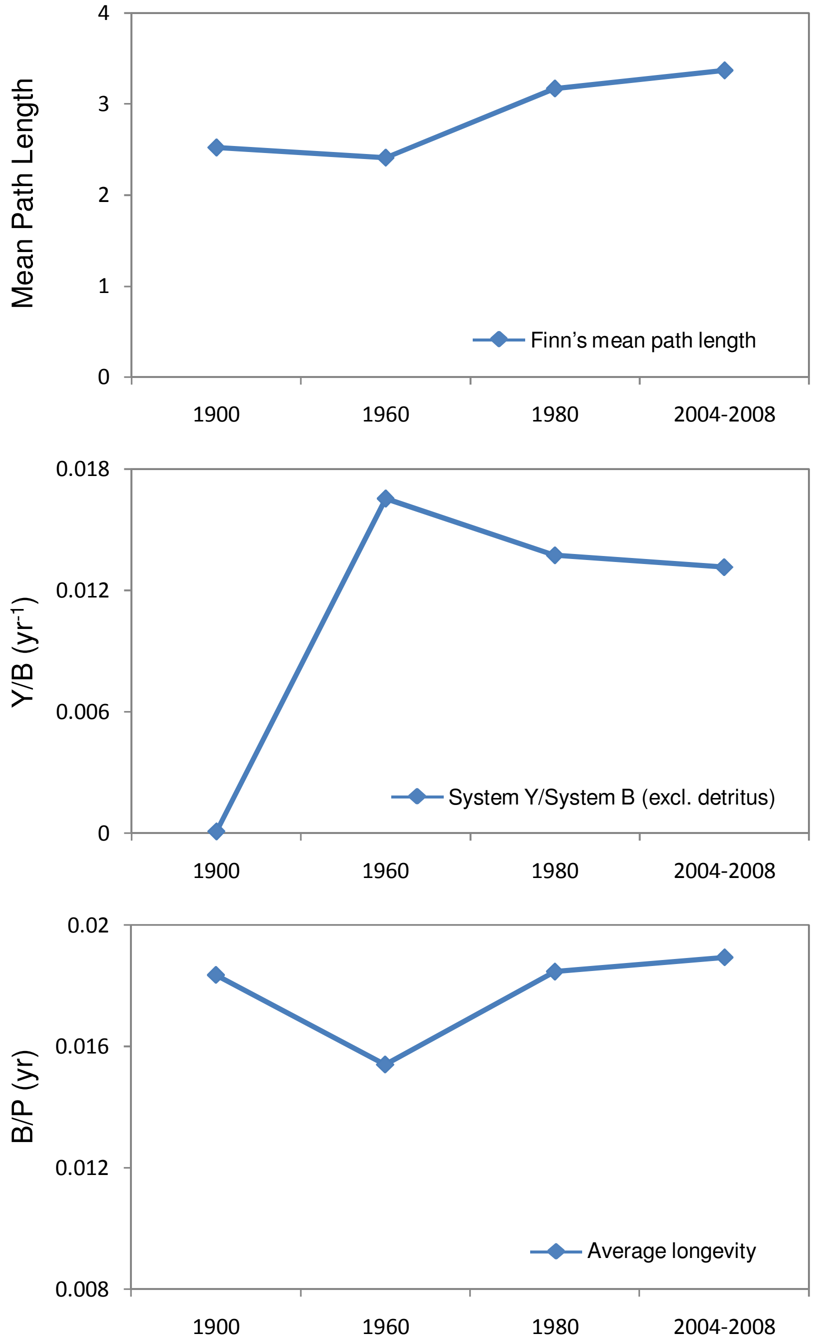


Figure 3.9: System indices of the southern Benguela ecosystem over the time periods 1900, 1960, 1980 and 2004-2008. Data for 1980 were sourced from Shannon *et al.* (2003) and for 1900 & 1960 from Watermeyer *et al.* (2008a). B = Biomass ($t.km^{-2}$); P = Production ($t.km^{-2}.yr^{-1}$); Y = Catch ($t.km^{-2}.yr^{-1}$).

3.4. Discussion

The indicators calculated here are used to assess the state of an ecosystem which has been altered either due to fishing or other anthropogenic pressures, natural environmental pressures or a combination of pressure types. Nine groups of indicator types were extracted so as to describe the overall state and trend of the southern Benguela ecosystem.

3.4.1. Biomass

The biomass indicators calculated reflect a change in abundance of functional groups in the southern Benguela ecosystem. Although Total Fin Fish biomass is at a maximum during the current period, this biomass is dominated by the functional groups PEL, SMF and PLA. On average, the groups PEL, SMF and PLA represent 68%, 50% and 77% of the Total Fin Fish biomass in the southern Benguela ecosystem over the four time periods examined. Although the PEL functional group includes All Large Pelagic Fish (snoek and other large pelagic fish), this group represents <2% of the total functional group biomass during all four time periods. The remaining 98% comprise small pelagic fish (anchovy, sardine, redeye, other small pelagic fish, juvenile horse mackerel, mesopelagic fish and chub mackerel). Thus we can infer that a change in ecosystem food web structure has occurred, with small, planktivorous fish comprising the majority of the biomass in the southern Benguela ecosystem, especially during the current 2004-2008 period. This pattern is also repeated in the biomass ratios calculated. The ratios SMF/LAF, PEL/DEM and PLA/PIS all increased over time, whereas Prop. of pred. fish decreased, confirming the change in functional group abundance within the southern Benguela ecosystem over time, i.e. increase of small, planktivorous fish and decrease of large, predatory/piscivorous fish.

3.4.2. Production

Production indicators point towards an overall increase in production of functional groups lower down the food web (PEL, SMF, PLA), whereas overall production of functional groups higher up the food web (DEM, LAF, PFP) has decreased. The production ratio SMF/LAF indicates that small fish have increased in abundance resulting in the greater estimated production relative to that of large fish in the system. What is interesting is the overall increase in PIS production which can be explained by the increase in model-estimated biomass of pelagic- and benthic-feeding demersal fish (Chapter 2 Figure 2.1). The increase in model-estimated biomass of pelagic-feeding demersal fish is supported by the increasing biomass index calculated from unpublished MCM research survey data. Although the research surveys suggests an overall decrease of 9% in the biomass index for the periods 1980 to 2004-2008 for the benthic-feeding demersal fish, model-estimated benthic-feeding demersal fish biomass required to sustain model predators is estimated to have increased by 10% over the same time period (1980 to 2004-2008). This model-estimated increase is not unrealistic given that demersal surveys are specifically directed at hake. The dip in the production ratio PLA/PIS is explained by the low abundance (and comparable fish productivity) of small pelagic fish in the 1980s, despite the slight increase in demersal fish abundance (and comparable fish productivity) since the 1960s.

3.4.3. Consumption

The Consumption ratio indicators reflect small changes in the consumption patterns of and by the various functional groups. Consumption by PEL Predators/DEM Predators displays a clear increasing trend over time. PEL Predators consumption is much greater relative to the consumption of DEM Predators, which suggests that PEL Predators have become much more important in the southern Benguela ecosystem because PEL have increased in abundance. This is supported by the increasing consumption trend by the individual functional group, PEL Predators. The consumption of PEL prey and PLA prey display a decreasing pattern over time. The two ratios calculated, Q of PEL Prey/DEM Prey and Q of PLA Prey/PIS Prey, point towards a decrease (<10%) in abundance of groups which feed on PEL and PLA fish. The ratio, consumption of PLA Predators/PIS Predators, has shown a dramatic decline since the 1960s. This decline is attributable to the much higher modelled-biomass of PLA Predators in the 1960s, specifically cetaceans (Chapter 2 Figure 2.1), which decreased thereafter. Other than this dramatic decline, the consumption patterns of the higher-level trophic groups in the southern Benguela have remained relatively stable.

3.4.4. Catch

The catch indicators are proof that fishing sectors in the southern Benguela ecosystem have shifted towards small, pelagic and planktivorous fish which occur lower in the food web. The catches of PEL, SMF and PLA have all increased over time, and in the current period they represent 74%, 73% and 78% of the Total Fish biomass removed from the system through the various fishing sectors. Catches of DEM, LAF and PIS have decreased since the 1960s. However, the catch ratio SMF/LAF increased between the 1960 and 1980 reflecting the increase in SMF catch, but has remained at a constant value since the 1980s. This indicates that the LAF Fishery (hake and linefish) is catching as much fish as that of the SMF Fishery, even though the LAF biomass has decreased and SMF biomass has increased over time (Figure 3.1). The catch ratios PEL/DEM and PLA/PIS, display increasing trends over time reinforcing the increase of a fishery based on pelagic and planktivorous fish.

3.4.5. Trophic Level

Functional groups which displayed a consistent decrease in trophic level over time are DEM and PIS. Benthic-feeding demersal fish have the lowest TL of the functional group DEM (average TL = 3.4; Chapter 2 Figure 2.5). The model-estimated biomass of benthic-feeding demersal fish was the highest within the functional group during three of the four time periods (1900, 1980, 2004-2008) and since TL is weighted by biomass, the group contributing most towards the decline in TL of DEM is benthic-feeding demersal fish. This is an ambiguous result because the biomass of this model group has been estimated by the model and is in actual fact, one of the major uncertainties associated with the model. The demersal fish biomass indices calculated from unpublished research survey data support the model estimation, which points towards the usefulness of trophic modelling because the biomass estimations appear to be within realistic ecosystem limits. However, more substantial and current diet studies of the higher trophic level groups would strengthen the model outputs, especially with regard to the calculation of trophic levels.

The declining TL of PIS can be attributed to three features: the increase in the lower trophic level benthic- and pelagic-feeding demersal fish abundance as estimated by the model; the reduced large hake biomass since the 1980s (pre-1980: >2.4 t.km^{-2} vs. post-1980: <1.6 t.km^{-2}) and the increase in sardine (average TL = 2.95; Chapter 2 Figure 2.5) consumption by large hake between the 1980s and current period (1980 = 0 t.km^{-2}.yr^{-1} vs. 2004-2008 = 0.195 t.km^{-2}.yr^{-1}).

The fluctuating TL of PEL and PLA are a result of the alternating abundances of small pelagic fish, specifically anchovy and sardine. The 1900s and 1980s periods were modelled as anchovy-dominated periods. This explains the higher PEL TL and PLA TL during the 1900s and 1980s, since anchovy occupies a higher trophic level (average TL = 3.54; Chapter 2 Figure 2.5) than sardine (average TL = 2.95; Chapter 2 Figure 2.5). However, although anchovy is also the dominant small pelagic fish during the current period, sardine biomass has increased by 80% since the 1980s and is responsible for the dip in TL of PEL and PLA.

The sharp decline in PFP TL between the 1900s and 1960s is a result of the decreasing biomass of large hakes in the ecosystem between the two time periods (*M. capensis* = 50% decrease, *M. paradoxus* = 20% decrease). The hakes were in the top three trophic levels of the PFP functional group in the 1900s and occupied the highest trophic levels in the 1960s when the other pelagic fish predators (specifically mammals) were consuming more of the lower trophic level sardine.

The mean TL of the Y has remained relatively constant from the 1960s to the 2004-2008 period, after the initial sharp decline from the 1900s. This seems to support the assessment by Cury *et al.* (2005) that no further “fishing down of the food web” (Pauly *et al.* 1998) has occurred since the 1960s. The recent DEM and PIS catch indicators seem to suggest that the harvesting of these groups has remained constant and conservative since the 1960s, such that complete removal of the higher trophic level groups has not taken place. This is supported by the DEM and PIS biomass indicators which convey a recent increase. However, these trends are contradicted by the LAF catch and biomass indicators. These contrasting trends highlight the importance of examining a suite of indicators when assessing an ecosystem (Daan *et al.* 2005 and contributors therein) especially when using trophic level indicators. Furthermore, the stable TL of the Y might also be a result of the fisheries shifting towards the lower trophic, small, planktivorous pelagic fish, since their abundance has increased dramatically in recent years as a result of a more favourable environment.

3.4.6. Turnover Rate

The turnover rate describes how fast production is converted to biomass. The only functional group which does not show an overall decrease in turnover rate was PIS. This is surprising because the functional group DEM displays the opposite trend, when both functional groups consist of similar individual model groups. Although DEM displayed an initial increase in turnover rate, this was a result of a biomass decrease of large hake (*M. capensis* and *M. paradoxus*) and estimated biomass decrease for the demersal fish (pelagic- and benthic-feeders). The model groups which are responsible for the post-1960s decline in DEM turnover rate and the changing turnover rate within the PIS functional group, are the pelagic- and benthic-feeding demersal fish. As discussed previously, the current model-estimated demersal fish (pelagic- and benthic-feeders) biomass has approximately tripled since the 1960s (Chapter 2 Figure 2.1), which is when the turnover rate increased. This suggests that the demersal fish community may have undergone a change from historic time periods. Following from Odum (1985) and Christensen's (1995) hypothesis that mature systems would have low turnover rates; it would seem that the demersal fish community of the southern Benguela ecosystem has deteriorated since the 1960s and is possibly deteriorating further. Atkinson (2010) has confirmed two shifts in the demersal fish community in the southern

Benguela ecosystem. The first of the shifts occurred in the 1990s (increasing fish density) and the second in the mid-2000s (decreasing fish density). The shifts observed by Atkinson (2010) reinforce the changing turnover rates of the PIS functional group observed in this study and thus the changing demersal fish community of the southern Benguela ecosystem.

3.4.7. Catch: Production

The Y/P ratios for the groups Total Fishery, Fin Fish, PEL, SMF and PLA were at maximum values in the 1980s. This implies that fishing intensities during the 1980s were particularly high and were operating on low production levels (biomasses), i.e. not necessarily at ecologically optimal levels. The declines in Y/P ratios of the functional groups PEL, SMF and PLA from the 1980s indicate that the production by small, planktivorous, pelagic fish has increased substantially (i.e. much more produced than what is removed) and sustains the currently higher fishing intensities. This suggests that after the 1980s period, the fishery sectors concentrating on small, planktivorous, pelagic fish are operating at more ecologically optimal levels. The Y/P ratios for the functional groups PIS and DEM suggest that the fishery sectors concentrating on these functional groups have also been operating at ecologically optimal levels after the 1960s period. However, these two functional groups are dominated by the less well parameterised benthic- and pelagic-feeding demersal fish model groups which, as discussed previously, are estimated to have substantially increased in production levels since the 1980s and combined with the perceived stable harvesting levels of PIS since the 1980s (Figure 3.4; Appendix Table 7.6), has resulted in the appearance of an ecologically optimal fishery. In fact, zooming in on the DEM and PIS groups, and extracting LAF, it becomes clear that the benthic- and pelagic-feeding demersal fish are masking the fishing effects within the DEM and PIS functional groups. The LAF Y/P ratio has continually increased since the 1960s, suggesting that the LAF fishery sectors, i.e. hake and linefish, have not been operating at ecologically optimal levels since the 1960s because production has decreased substantially since that period (Figure 3.2).

3.4.8. Catch: Biomass

The Catch: biomass ratios display the same trends as those of catch: production, which is expected because production is calculated from the biomass. The two indicator groups, Catch: Production vs. Catch: Biomass, are merely two viewpoints of the same system. The Catch: Production indicator is more tangible to ecosystem scientists who wish to understand the dynamics of the ecosystem whereas Catch: Biomass is likely to be more tangible to fisheries managers who are more concerned with the practical nature concerning harvesting levels, i.e. relative to biomass. The Catch: Biomass indicators reinforce the points highlighted in section 3.4.7 Catch: Production.

3.4.9. System Indices

Finn's mean path length suggests that there was a change in the southern Benguela ecosystem food web between the 1960s and 1980s periods. This change is supported by the findings of Howard *et al.* (2007). Howard *et al.* (2007) detected two regime shifts within the southern Benguela ecosystem, the first occurring in the 1960s as a result of intense fishing, and the second in the early 2000s (this time period was not considered in this study) as a result of environmental forcing. The increase in path length suggests that the southern Benguela ecosystem does not seem to be under stress (Christensen 1995, Odum 1985).

The System Y/ System B indicator has decreased since the 1960s, suggesting that the resource potential of the southern Benguela ecosystem is not being degraded. However, small pelagic fish dominate upwelling ecosystems such as the southern Benguela, and the documented increase in small pelagic fish biomass is most probably masking any potential fishing effects on the system. The System Y/ System B indicator should therefore be looked at in conjunction with specific functional group catch: biomass indicators which can provide a more accurate depiction of the southern Benguela ecosystem, instead of just an averaged overview.

The average longevity indicator suggests that the southern Benguela ecosystem was severely stressed in the 1960s, when industrial fishing first started. Since that period, the system has adapted and the increase in the indicator implies that the southern Benguela ecosystem as a whole, is coping with current stress levels. Nevertheless, functional groups should be carefully scrutinised for specific fishing effects and potential stress on specific species or groups.

3.5. Trophic Indicator List for the southern Benguela ecosystem

A simplified but complimentary suite of indicators is needed for management within the southern Benguela ecosystem. The indicators need to effectively capture the observed changes within the southern Benguela ecosystem, without losing any information through over-aggregation. The indicator groups generated above were examined for their ability to detect change within the southern Benguela ecosystem and those deemed suitable were selected for initial consideration within the decision tree to be formulated (Chapter 4).

3.5.1. Biomass

The biomass indicators which have been selected are LAF B, PFP B, B PEL/DEM, B SMF/LAF and Prop. of pred. fish. LAF B conveys information about the commercially important fisheries in the southern Benguela ecosystem, hake and linefish, which are not explicitly captured by other biomass indicators. PFP B is currently the only indicator which captures trends about the higher trophic level groups, specifically the mammals and seabirds. B PEL/DEM conveys which functional group is dominating the ecosystem, i.e. the pelagic component vs. the demersal component. B SMF/LAF is an indicator which classifies the fish within the ecosystem in terms of size. It is a useful indicator because it provides information about the state of the ecosystem in terms of the size of fish dominating the ecosystem, i.e. more large fish is indicative of a healthy ecosystem. The proportion of predatory fish was included because it captures information about the predatory (PIS) and forage (PLA) fish groups in the ecosystem in one indicator and is a reflection of fish diversity within the ecosystem (Shin *et al.* 2010).

The biomass indicators discarded were System B, Fin Fish B, PEL B, DEM B, SMF B, PLA B, PIS B, B PLA/PIS and Chondrichthyan B. System B was excluded because it includes model groups which are poorly parameterised within the model such as the plankton and detritus groups. Fin Fish B was excluded because it over-aggregated the information available. This indicator suggests conservative management of the Fin Fishery because it displays an increasing trend, but in actual fact, the favourable environment has resulted in the higher abundance of fin fish in the southern Benguela ecosystem. PEL B and DEM B were discarded because they could be combined to form the single indicator B PEL/DEM which has been included. SMF B was discarded because the information it captures is included in the indicator B SMF/LAF. PLA B, PIS B and B PLA/PIS were all discarded because the information they convey is captured by the single indicator Prop. of pred. fish, which has been selected.

3.5.2. Production

None of the production indicators have been included because they display the same trend as the biomass indicators. It seems that the productivity of the model groups has not changed over time, and in the absence of periodic productivity updates, it is simpler to use the biomass indicators mentioned previously since they would be more easily understood by stakeholders.

3.5.3. Consumption

The consumption indicators compare the feeding habits of the lower and higher level trophic fish groups within the ecosystem. The indicators selected were Q of PLA Prey, Q of PIS Prey and Q of PLA Prey/PIS Prey. Q of PLA Prey is an important indicator because it quantifies how much of the forage fish (anchovy, sardine and redeye) is being eaten and thus how important the forage fish are within the ecosystem. Q of PIS Prey quantifies the food requirements necessary to sustain the higher trophic level model groups. Q of PLA Prey/PIS Prey provides an overall picture of the feeding habits of the southern Benguela ecosystem, i.e. feeders of planktivorous fish vs. feeders of piscivorous fish. Consumption indicators which quantified consumption of the plankton groups (Q by PLA Predators, Q by PLA Predators/PIS Predators) were excluded from selection because they included the plankton groups which are poorly quantified in the model. No other consumption indicator has been selected at this point because it is unclear what would be needed by the decision tree model to clarify the consumption patterns of the components within the southern Benguela ecosystem.

3.5.4. Catch

The indicators selected are Total System Y, Fin Fish Y, DEM Y and Y PEL/DEM. The System Y and Fin Fish Y follow similar trends and points to the fact that system harvests are dominated by fish. The southern Benguela has therefore not undergone the dramatic changes like that of the South Catalan Sea ecosystem where invertebrates (cephalopods) have become an exclusive and very important fishery sector (Shannon *et al.* 2009a). The Y PEL/DEM indicator illustrates the dominance of the fishery sectors in the southern Benguela ecosystem and whether there has been a change of functional groups within the ecosystem. The DEM Y indicator was also selected to clarify whether the possible change displayed by Y PEL/DEM could be a result of a change within the DEM Y.

3.5.5. Trophic Level

Trophic level can be considered a measure of ecosystem structure and function (Shin *et al.* 2010). Trophic levels, along with production and consumption, can only be calculated using trophic models and thus highlights the importance of trophic modelling. The indicators included were Mean TL of the Y, System TL and PIS TL. The mean TL of the Y can be used to detect whether fishing down of the food web has occurred (Pauly *et al.* 1998). System TL, which excludes the poorly parameterised groups (plankton, benthos and detritus – Section 3.2.5) gives the trophic position of the main ecosystem components, i.e. fish, cephalopods and mammals which are crucial for maintaining optimal ecosystem structure and function.

3.5.6. Turnover Rate

Apart from Total Primary P/Total B, the indicator list is not defined with regard to turnover rate indicators. The expert system and decision rules are needed to clarify which turnover rate indicators would be most useful for clarification of an ecosystem trend/state.

3.5.7. Catch: Production

None of the Catch: Production indicators were selected because no production indicators were selected.

3.5.8. Catch: Biomass

The Catch: Biomass indicators provide information about the yield per biomass for each functional group. They are useful for detecting whether the fishing pressure on a particular group is too high and can therefore serve as warning signals. The indicators selected are Total Fishery Y/Total Fishery B, DEM Y/DEM B and LAF Y/LAF B. Fin Fish Y/Fin Fish B, PEL Y/PEL B, SMF Y/SMF B and PLA Y/PLA B were excluded because they displayed similar trends to that of Total Fishery Y/Total Fishery B and therefore the information has been captured in the one indicator. PIS Y/PIS B was also excluded because it was felt that the information it captured, i.e. harvests of piscivorous fish (large hake, all large pelagic fish, pelagic- and benthic-feeding demersal fish, chub mackerel) have been included in the previous indicators selected.

3.5.9. System Indices

The system indices, Finn's mean path length, System Y/System B and Average Longevity were all excluded because they over-aggregated the lower trophic level groups (phytoplankton, zooplankton and benthos). Until a complete modelling technique of these lower trophic level groups is achieved, such that they are more accurately represented within the ecosystem models, these indicators will not be very useful to management.

Chapter 4

Developing a Decision Tree and Expert System for Fisheries Management within the Southern Benguela Ecosystem

4.1. Introduction

An important element of science is the dissemination of findings to a varied audience. This also forms a central component of an Ecosystem Approach to Fisheries (EAF), i.e. the engagement of and communication amongst all stakeholders. This requires integrating different types of information and communicating the results to all stakeholders in a manner that does not intimidate or confuse. From a scientific perspective this involves combining the available data and model-based indicators that are being applied into a tool that can be used to effectively communicate ecosystem characteristics/properties/trends among the stakeholders (Jarre *et al.* 2006).

Jarre *et al.* (2006) proposed that expert systems would be suitable for this purpose since an expert system contains "*a high degree of expertise in a form which makes it accessible to a novice*" (Starfield and Louw 1986). Expert systems are simple models in the form of computerised decision trees which are able to provide help functions (the user can ask 'why?'); trace the questions asked, answers given and rules triggered, thereby allowing the user to review the thought process within the decision tree; and are easier to update and modify (Starfield and Louw 1986). Many expert systems use the basics of communication, i.e. words, to convey the scientific principles and applications. The expert system can then be used to inform management groups about the state or trend of the ecosystem/resource and can therefore be used to aid management decisions.

The aim of this chapter is to develop an expert system based on a decision tree for the southern Benguela ecosystem. The decision tree could inform fisheries managers and all other stakeholders about trends displayed by the southern Benguela ecosystem and its components largely in response to fishing, based on indicators developed during the present study.

4.2. Decision Tree Development

It was initially decided that classification of the southern Benguela ecosystem would require one decision tree that would combine the community and system indicators identified.

However, during the development process, this approach was impractical because it was difficult to separate the community and system indicators when a particular trend (system or community) needed to be clarified. It was therefore decided to develop three separate decision trees.

4.2.1. Community decision trees: Pelagic-caught fish (PEL) and Demersal-caught fish (DEM)

The southern Benguela ecosystem consists of pelagic and demersal fish communities. Both fish communities are targeted by various fishing sectors and are harvested using different gear types. Two decision trees were developed for the two fish communities, largely separating them according to fishery type, i.e. pelagic (purse-seine, line fishery, long line, other) and demersal (midwater trawl, demersal trawl, line fishery, long line, other) (Appendix Table 7.3). Although midwater trawl is a pelagic fishing gear, it has been included in the demersal fishery classification because it targets adult horse mackerel, which are also caught within the demersal trawl fishery (Appendix Table 7.3). Hence, the Pelagic-caught fish (PEL) community decision tree and Demersal-caught fish (DEM) community decision tree were developed. Fish which are harvested within the PEL community are anchovy, sardine, redeye, other small pelagic fish, chub mackerel, juvenile horse mackerel, mesopelagic fish, snoek and other large pelagic fish. Fish harvested within the DEM community are adult horse mackerel, small *M. capensis*, large *M. capensis*, small *M. paradoxus*, large *M. paradoxus*, pelagic- and benthic-feeding demersal fish.

The two community indicators used in each community decision tree were Biomass (B) and Catch: Biomass (Y/B) (Table 4.1). The indicators were examined to determine whether they displayed one of three trends: Increase, Same or Decrease. Indicator trends were verified using a 5% limit, i.e. <5% change between the two time periods was classified as the same, whereas a ≥5% change between two time periods was classified as an increasing/decreasing trend.

Three classification trends were chosen for the end-point of the community decision tree: Improving, Not Improving or Deteriorating. The general rule applied was that if one indicator displayed a trend in the wrong direction (e.g. B decrease), and the other indicator did not compensate accordingly (e.g. Y/B decrease), the community would receive a deteriorating classification.

4.2.2. Southern Benguela ecosystem decision tree

The southern Benguela ecosystem decision tree used a combination of community and system indicators (Table 4.1). Classification of the southern Benguela ecosystem components, i.e. the PEL and DEM community, were first completed using the PEL and DEM community decision trees. If the assessments displayed by the PEL and DEM community were not the same, a definitive ecosystem classification could not be reached, and system level clarification indicators would be used for the component displaying the least positive trend. The trends for the indicators used in the community decision trees were also used in the ecosystem decision tree, i.e. Increase, Same or Decrease; and the 5% limit was also employed. However, four classification trends were used for the end point of the ecosystem decision tree: Improving, Not Improving, Deteriorating or Can't Say. The classification 'Can't Say' was included in the ecosystem decision tree because more indicators are used, which could result in contradictory trends, no trends or difficulty distinguishing between two ecosystem classifications.

Table 4.1: Final list of trophic model-generated indicators selected/rejected for the southern Benguela ecosystem with reasons. System = all model groups except plankton (phytoplankton, benthic producers micro-, meso-, macro- and gelatinous zooplankton), benthos (meio- and macro-benthos), detritus; Fin Fish = Pelagic-caught and Demersal-caught fish; Pelagic-caught fish (PEL) = anchovy, sardine, redeye, other small pelagic fish, juvenile horse mackerel, mesopelagic fish, chub mackerel, all large pelagic fish (snoek and other large pelagic fish); Demersal-caught fish (DEM) = adult horse mackerel, all hake (small and large *M. capensis*, small and large *M. paradoxus*), pelagic- and benthic-feeding demersal fish; SMF = Small fish (anchovy, sardine, redeye, other small pelagic fish, juvenile horse mackerel, small hake); LAF = Large fish (large hake, all large pelagic fish); PLA = Planktivorous fish (anchovy, sardine, redeye, other small pelagic fish, all horse mackerel, mesopelagic fish, small hake); PIS = Piscivorous fish (large hake, all large pelagic fish, pelagic- and benthic-feeding demersal fish, chub mackerel); Prop. of pred. fish = Proportion of predatory fish; PFP = Pelagic fish predators (seabirds, seals, cetaceans, all large pelagic fish, large hake, chub mackerel); Chondrichthyans = apex, pelagic- and benthic-feeding chondrichthyans; B = biomass ($t.km^{-2}$); Y = catch ($t.km^{-2}.yr^{-1}$); TL = trophic level.

Group	Selected Indicators	Reason	Rejected Indicators	Reason
Biomass (B)	PEL B	Needed to classify PEL community biomass trends	System B	Includes the poorly parameterised groups, i.e. plankton
	DEM B	Needed to classify DEM community biomass trends	Fin Fish B	Over-aggregates information across PEL & DEM groups
	B SMF/LAF	Needed to capture biomass trends regarding size structure of the fish community within the ecosystem	B PEL/DEM	Clarification of each community was needed rather than a comparison between the two
	Prop. of pred. fish	Needed to capture biomass trends regarding predatory (piscivorous) fish within the ecosystem	LAF B	Information is captured by the single indicator B SMF/LAF
	PFP B	Needed to capture biomass trends regarding pelagic fish predators	SMF B	
			PLA B	Information is captured by the single indicator Prop. of pred. fish
			PIS B	
			B PLA/PIS	
			Chondrichthyan B	Chondrichthyan group not adequately represented in the model

Table 4.1 continued...

Group	Selected Indicators	Reason	Rejected Indicators	Reason
Production (P)	No production indicators included since they display the same trend as the biomass indicators*			
Consumption (Q)	No consumption indicators were needed to classify ecosystem trends			
Catch (Y)	Total catch was considered over-aggregated for purposes of classifying detailed ecosystem trends in this study. Further, rather than using group-specific catches in their own right, we related them to biomass and production (see below)			
Catch: Biomass (Y/B)	DEM Y/DEM B	Needed to classify fishing pressure trends in the PEL community	Fishery Y/Fishery B	Fishing pressure trends in each community within the ecosystem deemed more appropriate
	PEL Y/PEL B	Needed to classify fishing pressure trends in the DEM community	Fin Fish Y/Fin Fish B	
			LAF Y/LAF B	
			SMF Y/SMF B	More appropriate to use catch indicators which are classified according to the fishing sectors in operation within the ecosystem
			PLA Y/PLA B	
			PIS Y/PIS B	
Catch: Production (Y/P)	No Catch: Production indicators included since they display the same trend as the Catch: Biomass indicators*			
Trophic Level (TL)	System TL	Needed to capture possible "fishing down the food web" effects	PEL TL	Fluctuates according to which small pelagic fish is dominating the ecosystem
	DEM TL	Needed to clarify trophic positioning of the DEM community	Mean TL of the Y	System TL deemed more appropriate for capturing possible "fishing down the food web" effects
			PLA TL	Fluctuates according to which small pelagic fish is dominating the ecosystem
			PIS TL	Clarification of DEM community trophic position rather than functional group PIS was needed
			PFP TL	Indistinctive trend displayed (mammals largely opportunistic feeders)

*See Figures in Chapter 3

Table 4.1 continued...

Group	Selected Indicators	Reason	Rejected Indicators	Reason
Turnover Rate (P/B)	No turnover rate indicators were needed to classify ecosystem trends			
System Indices			Finn's mean path length	Includes poorly parameterised groups, e.g. plankton & chondrichthyans, and over-aggregates lower trophic level groups
			System Y/System B	
			Average Longevity	

4.2.3. Decision Tree Tests

The decision tree developed was applied to the southern Benguela, as well as other upwelling ecosystems, to check that the decision tree logic was sound, consistent and robust. The first test, i.e. the Observation Test, was applying the decision tree to the southern Benguela ecosystem to determine if any of the decision outcomes had occurred previously, and to identify the possible mechanism driving the changes. Five time periods were tested: the 1900s, 1960s, 1980s, 1990s and 2004-2008. The data needed to calculate the indicators for the various time periods were sourced from Shannon *et al.* (2003) (1980s and 1990s trophic model), and Watermeyer *et al.* (2008a) (1900s and 1960s trophic model). Data for 2004-2008 indicator calculation were compiled in this study. Comparisons were made between two subsequent time periods, i.e. 1960s compared to 1900s, 1980s compared to 1960s, 1990s compared to 1980s and 2004-2008 compared to 1990s. An additional comparison was made between the 2004-2008 and 1980s periods because both these time periods have been modelled as anchovy-dominated and it would be interesting to note any ecosystem changes. The second test, i.e. the Ranking Test, was to determine whether the decision tree ranked upwelling ecosystems consistently compared to other studies. The data used in this test were sourced from Shannon *et al.* (2009a), in which three ecosystems, the southern Benguela, southern Humboldt and south Catalan Sea, were compared in terms of fishing impacts. The model-derived indicators available in Shannon *et al.* (2009a) are not the exact ones used within the decision tree. It was therefore necessary to use the indicators available in Shannon *et al.* (2009a) as "surrogate indicators" which would most closely represent the indicators used in the decision tree. Table 4.2 lists the surrogate indicators as well as their associated model groups. It is assumed that since Shannon *et al.* (2009a) undertook a comparative study of the three ecosystems; the aggregations of modelled species/groups used by them had been standardised, and therefore the indicators resulting from them can be used in this study.

Since a continuous time series of data was not used in this study, the significance of a trend displayed by an indicator and the decision tree could not be assessed statistically. Indeed, this form of statistical analysis does not form part of the objective when developing this decision tree. The decision trees are intended as communication tools between and amongst scientists, fisheries managers and other stakeholders. The source texts for the community and ecosystem decision trees were therefore loaded into WinExp (Small Expert System for Windows v2.11) (Quadling and Quadling 1995). WinExp is a computer-based electronic platform with a userfriendly interface that makes the interaction with the computer (for the user) and use of the decision tree (for the developer) very straightforward. Explanations must be provided at each step within the expert system and in this manner, the user is continuously guided along the route of the decision tree.

Table 4.2: The "surrogate" indicators, and their associated model groups, used in the Ranking decision tree test. Surrogate indicators were sourced from Shannon *et al.* (2009a).

This study		**Shannon *et al.* (2009a)**			
Decision Tree Indicator	**Southern Benguela model groups**	**Surrogate Indicator**	**Southern Benguela model groups**	**Southern Humboldt model groups**	**South Catalan Sea model groups**
PEL catch: biomass (Y/B)	anchovy, sardine, redeye, other small pelagic fish, juvenile horse mackerel, mesopelagic fish, chub mackerel, all large pelagic fish (snoek & other large pelagic fish)	Pelagic fish catch (C)	anchovy, sardine, redeye, other small pelagic fish, chub mackerel, adult & juvenile horse mackerel, mesopelagic fish, snoek & other large pelagic fish	anchovy, common sardine, mesopelagic, horse mackerel, pelagic I (hoki), pelagic II (sword fish)	benthopelagic fishes, European anchovy, sardine, other small pelagic fishes, horse mackerel, Atlantic bonito, swordfish & Tuna
DEM catch: biomass (Y/B)	adult horse mackerel, all hake (small & large *M. capensis*, small & large *M. paradoxus*), pelagic- & benthic-feeding demersal fish	Demersal fish and chondrichthyans catch (C)	small & large *M. capensis*, small & large *M. paradoxus*, pelagic- & benthic-feeding demersal fish, pelagic- & benthic-feeding chondrichthyans, apex chondrichthyans	juvenile (0-3 yrs old) & adult 4+ yr old) Chilean hake, pelagic- & benthic-feeding fish, benthic chondrichthyans	mullets, conger, eel, anglerfish, flatfishes, poor cod, juvenile & adult hake, blue whiting, various demersal fishes, demersal sharks
Small Fish (SMF)	anchovy, sardine, redeye, other small pelagic fish, juvenile horse mackerel, small hake	Forage fish biomass (B)	anchovy, sardine, redeye, other small pelagic fish, adult & juvenile horse mackerel, mesopelagic fish	anchovy, common sardine, mesopelagics, horse mackerel, pelagic fish I (hoki)	poor cod, blue whiting, benthopelagic fishes, European anchovy, sardine, other small pelagic fishes
Large Fish (LAF)	large hake, all large pelagic fish	Predatory fish including chondrichthyans biomass (B)	chub mackerel, snoek, & other large pelagic fish, hake, pelagic- & benthic-feeding demersal fish, pelagic- & benthic-feeding chondrichthyans, apex chondrichthyans	sword fish, juvenile & adult Chilean hake, pelagic & benthic feeding demersal fish, benthic-feeding chondrichthyans	mullets, conger eel, anglerfish, flatfishes, juvenile hake, adult hake, various demersal fishes, demersal sharks, horse mackerel, mackerel, Atlantic bonito, swordfish & tuna
B SMF/LAF	SMF B/LAF B	forage/ predatory B*	*Shannon *et al.* (2009a) calculates this indicator as predatory/forage B. However, the trend displayed by this indicator was inverted to reflect the indicator, forage/predatory B, which most closely represents B SMF/LAF.		
Pelagic fish predators (PFP) B	seabirds, seals, cetaceans, all large pelagic fish, large hake, chub mackerel	top 5 TL fish or chondrichthyans	snoek, large *M. paradoxus*, large *M. capensis*, apex chondrichthyans, pelagic-feeding demersal fish	pelagic fish II (sword fish), demersal fish II, demersal fish I, hake (adults) & hake (juveniles)	anglerfish, conger eel, Swordfish and tuna, adult hake & Atlantic bonito
DEM Trophic level (TL)	adult horse mackerel, all hake (small & large *M. capensis* & *M. paradoxus*), pelagic- & benthic-feeding demersal fish	TL of model community	all model groups except producers, detritus, benthic invertebrates & zooplankton		

4.3. Results

4.3.1. Community Decision Trees

Flow diagrams of the PEL and DEM community decision trees are displayed in Figures 4.1 and 4.2 respectively. A total of five rules were used to arrive at nine possible outcomes. The explanation for each rule, for both community decision trees, is displayed in Table 4.3. There were five cases of Not Improving and two cases each of Improving and Deteriorating, for both community decision trees (Figures 4.1 and 4.2).

4.3.2. Ecosystem Decision Tree

The entire flow diagram for the southern Benguela ecosystem decision tree can be viewed in Figure 4.3. The three branches of the decision tree (Improving PEL community branch, Not Improving PEL community branch, Deteriorating PEL community branch) are also displayed in Figures 4.4a-c respectively, for clarity. The ecosystem decision tree displayed 40 possible outcomes after evaluating 29 rules (Figures 4.3 and 4.4). The explanations for the rules reaching the final decisions are explained in Table 4.4. There were two cases of Improving, 15 cases of Not Improving, 13 cases of Deteriorating and 10 cases of Can't Say.

The source code for the PEL, DEM and southern Benguela ecosystem decision trees which were loaded into WinExp, can be found in Appendix 7.7-7.9 respectively. The code contains the indicators, decisions and explanations included in Tables 4.3 and 4.4, but in an expanded format required by WinExp, such that more guidance and support is provided to the user of the expert system. The three WinExp expert system files (PELTREE, DEMTREE and SBTREE) and the software needed to run them can be found on the compact disc (Wisaal Osman MSc 2010) submitted with this dissertation.

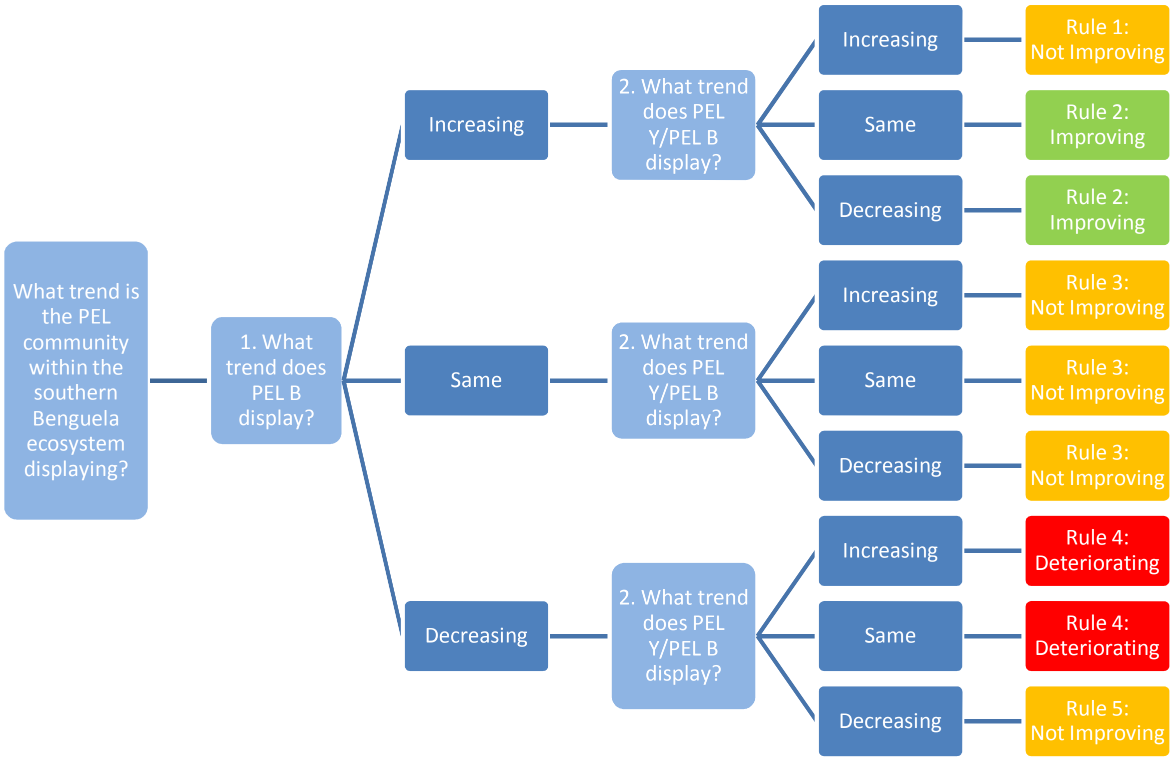


Figure 4.1: Pelagic-caught fish (PEL) community decision tree for the southern Benguela ecosystem. B = biomass (t.km^{-2}), Y = catch (t.km^{-2}.yr^{-1}).

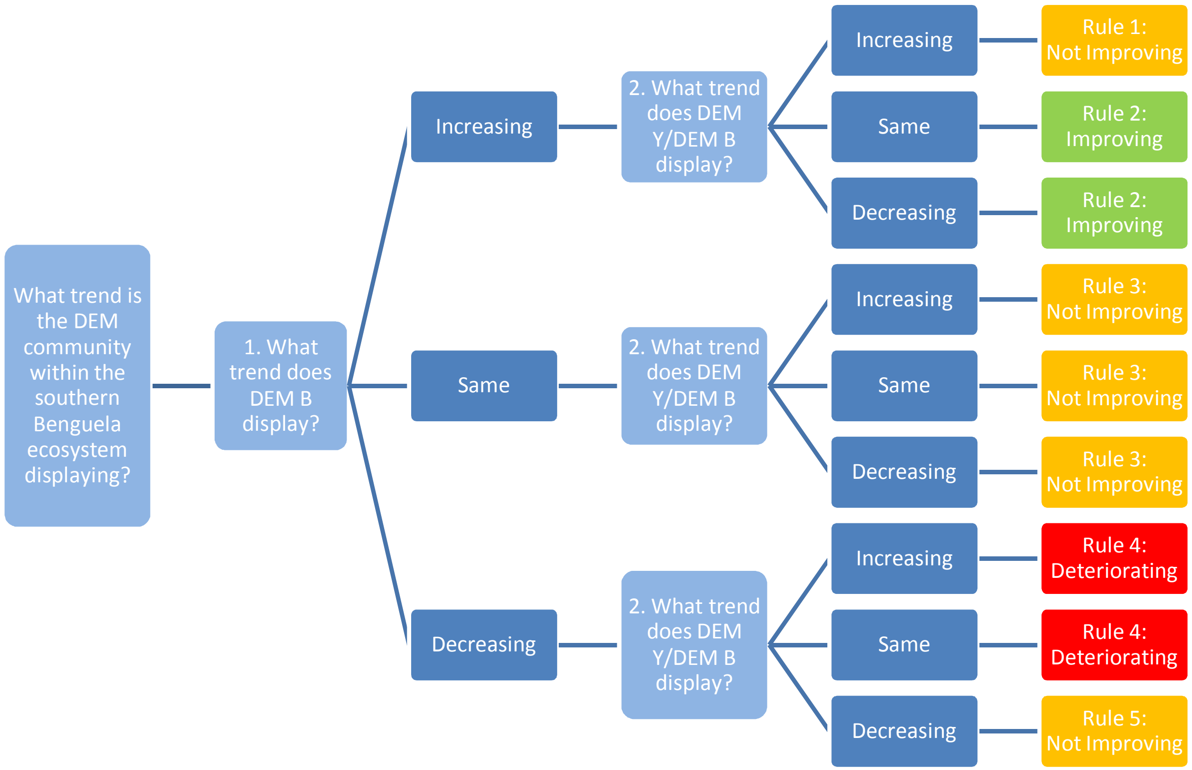
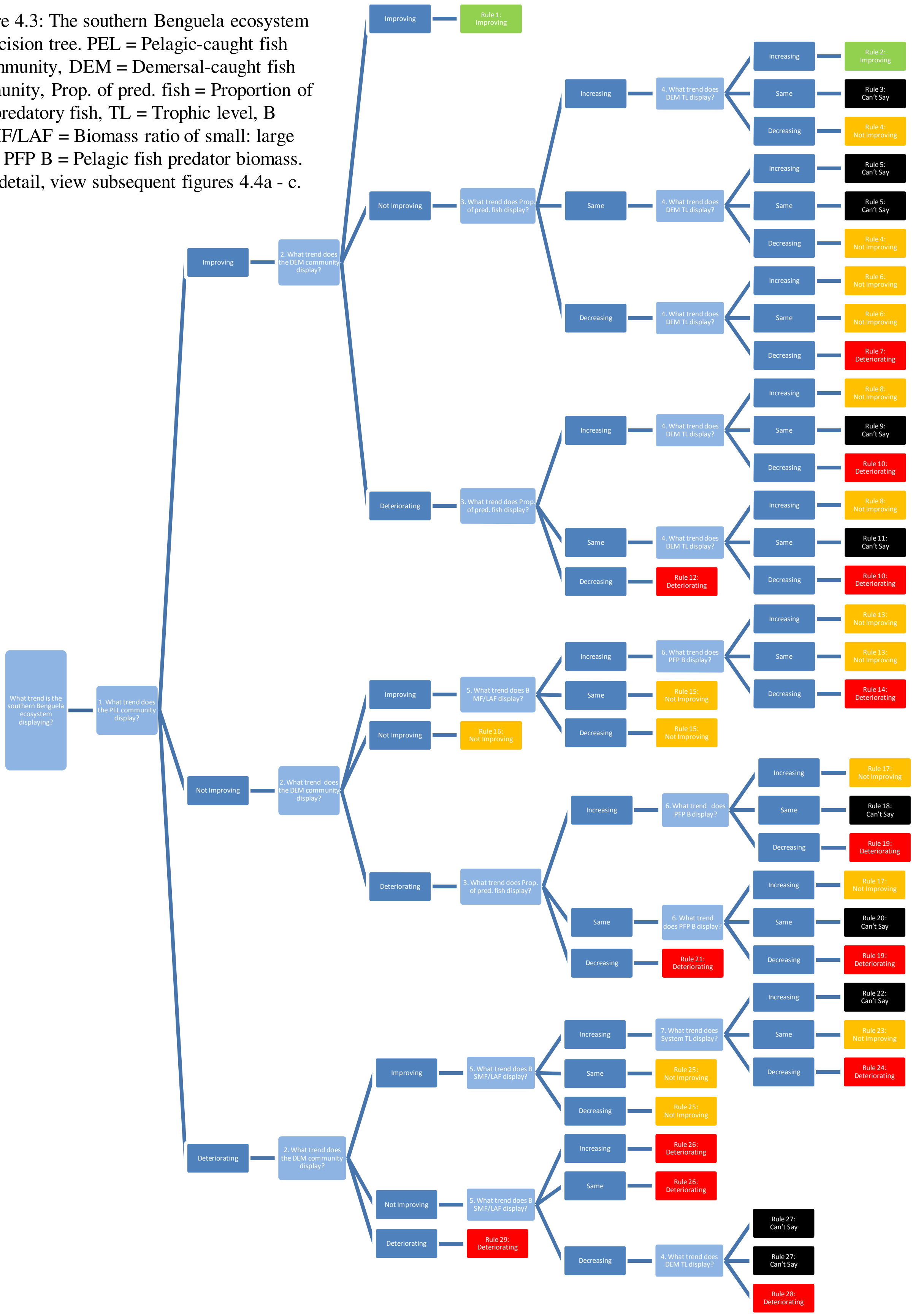


Figure 4.2: Demersal-caught fish (DEM) community decision tree for the southern Benguela ecosystem. B = biomass (t.km^{-2}), Y = catch (t.km^{-2}.yr^{-1}).

Table 4.3: Rules and explanations for the decisions reached within the Pelagic-caught fish (PEL) and Demersal-caught fish (DEM) community decision trees.

Community	Rule No.	Indicator	Trend	Decision	Explanation
Pelagic-caught fish (PEL)	1	PEL B PEL Y/B	incr incr	Not Improving	The PEL community can sustain the current fishing pressure. Be aware of possible changing environmental conditions or fishing practices that could negatively affect the PEL community.
	2	PEL B PEL Y/B	incr same/ decr	Improving	The PEL community biomass is increasing and the PEL community can sustain the current fishing pressure. Be aware of possible changing environmental conditions or fishing practices that could negatively affect the PEL community.
	3	PEL B PEL Y/B	same incr/ same/ decr	Not Improving	The PEL community can sustain the current fishing pressure. Be aware of possible changing environmental conditions or fishing practices that could negatively affect the PEL community.
	4	PEL B PEL Y/B	decr incr/ same/ decr	Deteriorating	The current fishing pressure is too high to be sustained by the PEL community.
	5	PEL B PEL Y/B	decr decr	Not Improving	The PEL community can sustain the current fishing pressure. Be aware of possible changing environmental conditions or fishing practices that could negatively affect the PEL community.
Demersal-caught fish (DEM)	1	DEM B DEM Y/B	incr incr	Not Improving	The DEM community can sustain the current fishing pressure. Be aware of possible changing environmental conditions or fishing practices that could negatively affect the DEM community.
	2	DEM B DEM Y/B	incr same/ decr	Improving	The DEM community biomass is increasing and can the DEM community sustain the current fishing pressure. Be aware of possible changing environmental conditions or fishing practices that could negatively affect the DEM community.
	3	DEM B DEM Y/B	same incr/ same/ decr	Not Improving	The DEM community can sustain the current fishing pressure. Be aware of possible changing environmental conditions or fishing practices that could negatively affect the DEM community.
	4	DEM B DEM Y/B	decr incr/ same/ decr	Deteriorating	The current fishing pressure is too high to be sustained by the DEM community.
	5	DEM B DEM Y/B	decr decr	Not Improving	The DEM community can sustain the current fishing pressure. Be aware of possible changing environmental conditions or fishing practices that could negatively affect the DEM community.

Figure 4.3: The southern Benguela ecosystem decision tree. PEL = Pelagic-caught fish community, DEM = Demersal-caught fish community, Prop. of pred. fish = Proportion of predatory fish, TL = Trophic level, B SMF/LAF = Biomass ratio of small: large fish, PFP B = Pelagic fish predator biomass. For detail, view subsequent figures 4.4a - c.



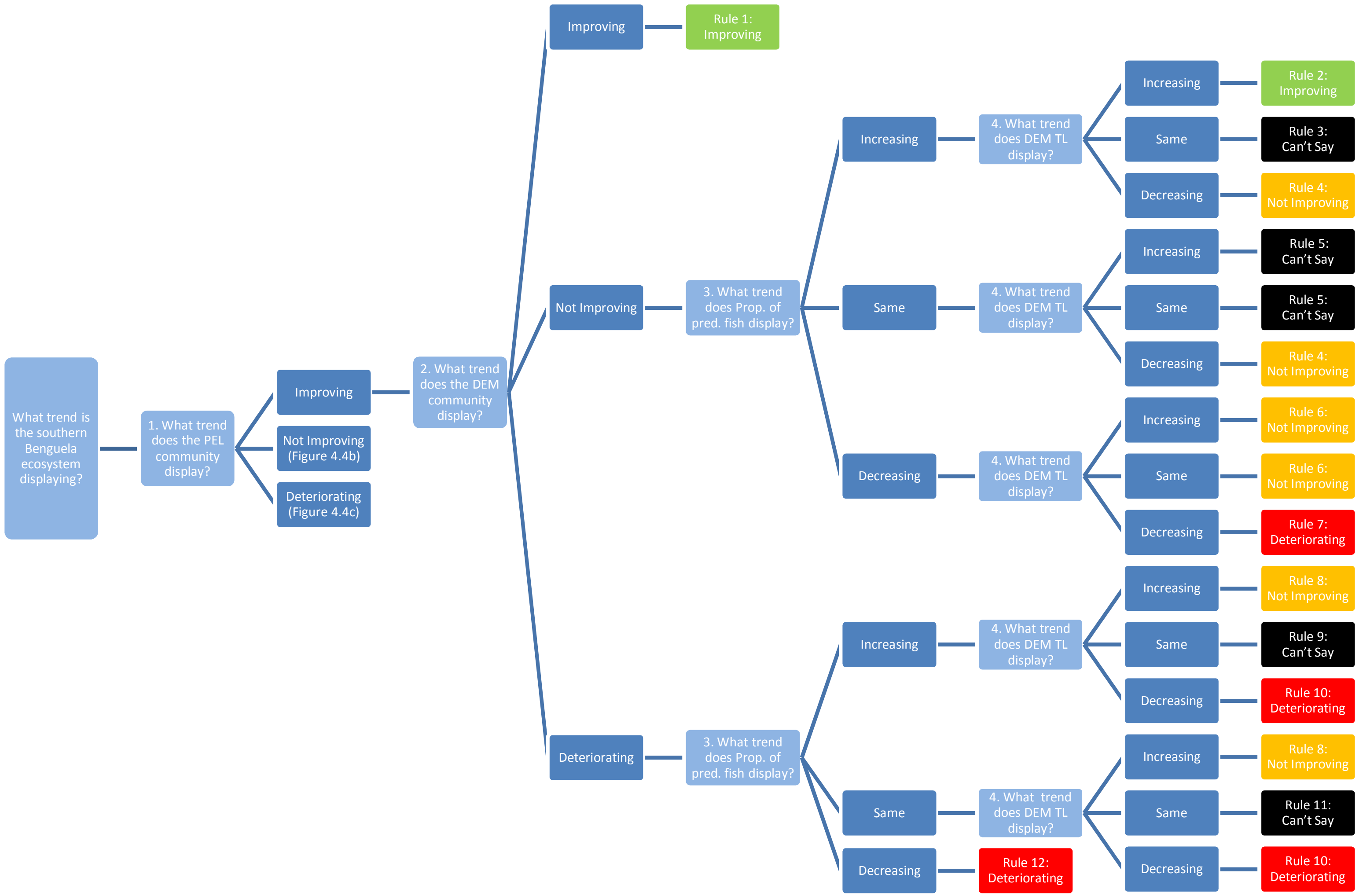


Figure 4.4a: The southern Benguela ecosystem decision tree – Improving PEL community branch. PEL = Pelagic-caught fish community, DEM = Demersal-caught fish community, Prop. of pred. fish = Proportion of predatory fish, TL = Trophic level, B SMF/LAF = Biomass ratio of small: large fish, PFP B = Pelagic fish predator biomass.

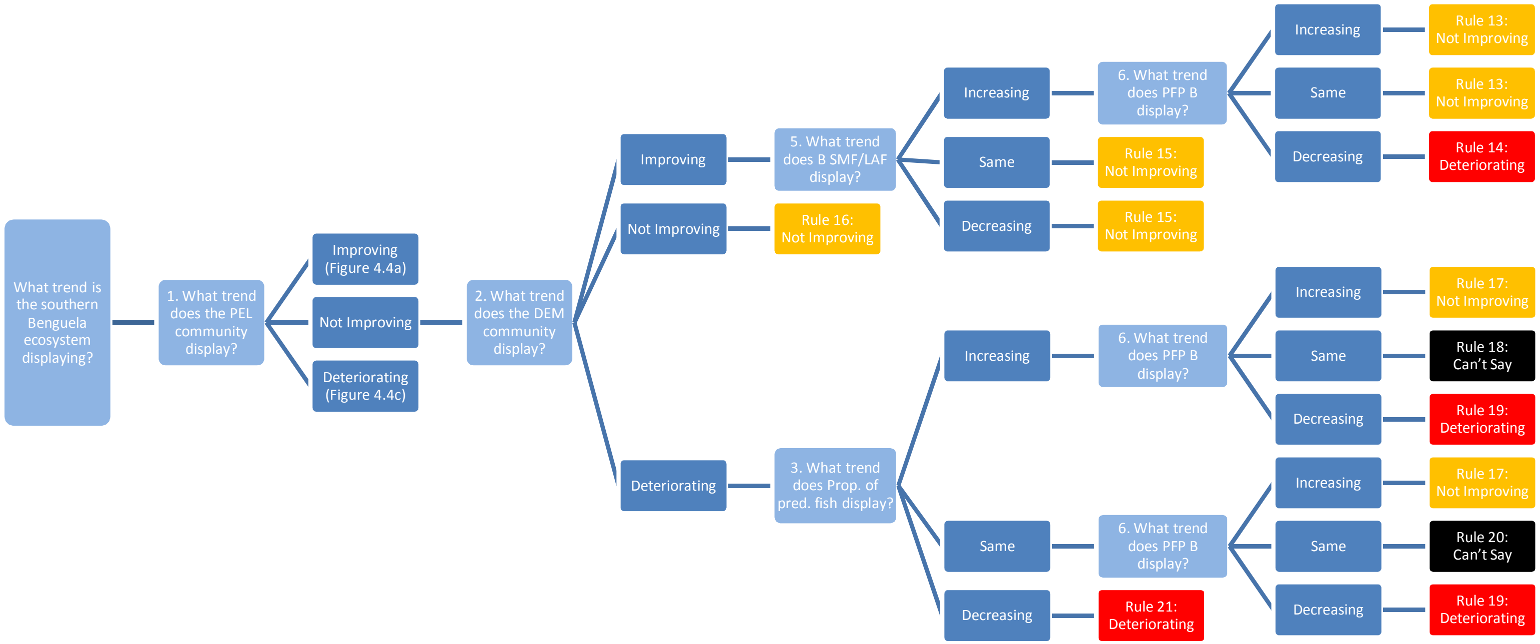


Figure 4.4b: The southern Benguela ecosystem decision tree – Not Improving PEL community branch. PEL = Pelagic-caught fish community, DEM = Demersal-caught fish community, Prop. of pred. fish = Proportion of predatory fish, TL = Trophic level, B SMF/LAF = Biomass ratio of small: large fish, PFP B = Pelagic fish predator biomass.

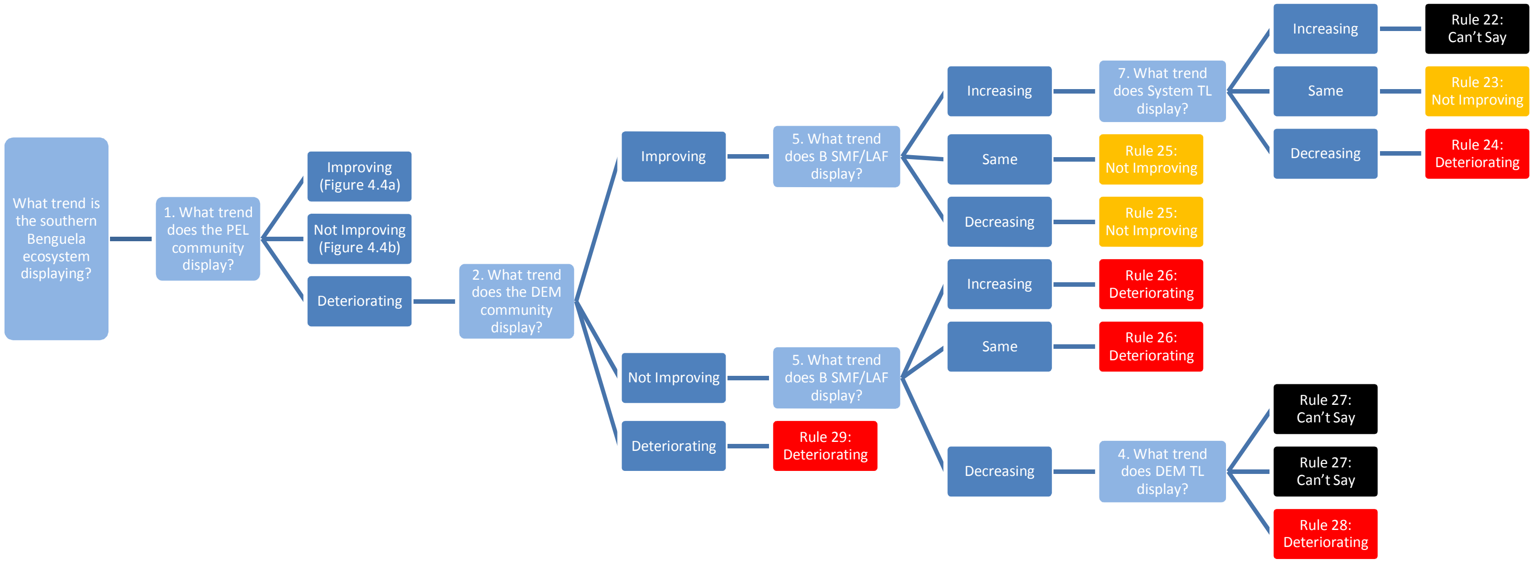


Figure 4.4c: The southern Benguela ecosystem decision tree – Deteriorating PEL community branch. PEL = Pelagic-caught fish community, DEM = Demersal-caught fish community, Prop. of pred. fish = Proportion of predatory fish, TL = Trophic level, B SMF/LAF = Biomass ratio of small: large fish, PFP B = Pelagic fish predator biomass.

Table 4.4: Rules and explanations for the decisions reached within the southern Benguela ecosystem decision tree. PEL = Pelagic-caught fish; DEM = Demersal-caught fish; comm. = community; Prop. of pred. fish = Proportion of predatory fish; DEM TL = DEM community trophic level; B SMF/LAF = biomass ratio of small: large fish; PFP B = Pelagic fish predator biomass; System TL = ecosystem trophic level (excludes plankton, benthos and detritus); imp = improving; not = not improving; det = deteriorating; incr = increase; decr = decrease.

Rule No.	1st Indicator Pair	Trend	2nd indicator	Trend	3rd Indicator	Trend	Decision	Reason
1	PEL comm. DEM comm.	imp imp					Improving	Both fish communities are improving, thus the southern Benguela ecosystem is improving.
2	PEL comm. DEM comm.	imp not	Prop. of pred. fish	incr	DEM TL	incr	Improving	More predatory fish within ecosystem and DEM community is not negatively affected by fishing.
3						same	Can't Say	More predatory fish within ecosystem, but fishing likely to be negatively affecting DEM community. Net effect cannot be clarified, i.e. Improving or Not Improving? Components within DEM community require further examination.
4						decr	Not Improving	More predatory fish within ecosystem, but fishing negatively affecting DEM community. Be aware of possible changing environmental conditions or fishing practices that could negatively affect the fish community and ecosystem.
5	PEL comm. DEM comm.	imp not	Prop. of pred. fish	same	DEM TL	incr	Can't Say	Predatory fish present within ecosystem and fishing not negatively affecting DEM community. Net effect cannot be clarified, i.e. Not Improving or Deteriorating? Components within DEM community require further examination.
5						same	Can't Say	Predatory fish present within ecosystem and fishing unlikely to be negatively affecting DEM community. Net effect cannot be clarified, i.e. Not Improving or Deteriorating? Components within DEM community require further examination.
4						decr	Not Improving	Predatory fish present within ecosystem, but fishing negatively affecting DEM community. Be aware of possible changing environmental conditions or fishing practices that could negatively affect the fish community and ecosystem.

Table 4.4 continued...

Rule No.	1st Indicator Pair	Trend	2nd indicator	Trend	3rd Indicator	Trend	Decision	Reason
6	PEL comm. DEM comm.	imp not	Prop. of pred. fish	decr	DEM TL	incr	Not Improving	Fewer predatory fish within ecosystem, but fishing not negatively affecting DEM community. Be aware of possible changing environmental conditions or fishing practices that could negatively affect the fish community and ecosystem.
6						same	Not Improving	Fewer predatory fish within ecosystem, but fishing unlikely to be negatively affecting DEM community. Be aware of possible changing environmental conditions or fishing practices that could negatively affect the fish community and ecosystem.
7						decr	Deteriorating	Fewer predatory fish within the ecosystem and within DEM community.
8	PEL comm. DEM comm.	imp det	Prop. of pred. fish	incr	DEM TL	incr	Not Improving	More predatory fish within ecosystem and fishing not negatively affecting DEM community. Be aware of possible changing environmental conditions or fishing practices that could negatively affect the fish community and ecosystem.
9						same	Can't Say	More predatory fish within ecosystem, but fishing likely to be negatively affecting DEM community. Net effect cannot be clarified, i.e. Not Improving or Deteriorating? Components within DEM community require further examination.
10						decr	Deteriorating	More predatory fish within ecosystem, but fishing negatively affecting DEM community.
8	PEL comm. DEM comm.	imp det	Prop. of pred. fish	same	DEM TL	incr	Not Improving	Predatory fish present within ecosystem, but not increasing. Although DEM TL increasing, DEM community deteriorating, therefore overall system Not Improving. Be aware of possible changing environmental conditions or fishing practices that could negatively affect the fish community and ecosystem.
11						same	Can't Say	Predatory fish present within ecosystem, but DEM community likely to be negatively affected by fishing. Net effect cannot be clarified, i.e. Not Improving or Deteriorating? Components within DEM community require further examination.
10						decr	Deteriorating	Predatory fish present within ecosystem, but fishing negatively affecting DEM community.
12	PEL comm. DEM comm.	imp det	Prop. of pred. fish	decr			Deteriorating	Fewer predatory fish within the ecosystem and DEM community deteriorating.

Table 4.4 continued...

Rule No.	1st Indicator Pair	Trend	2nd indicator	Trend	3rd Indicator	Trend	Decision	Reason
13	PEL comm. DEM comm.	not imp	B SMF/LAF	incr	PFP B	incr	Not Improving	Good recruitment of small fish and more large pelagic fish predators within the ecosystem, but PEL community deteriorating. Be aware of possible changing environmental conditions or fishing practices that could negatively affect the fish community and ecosystem.
13						same	Not Improving	Good recruitment of small fish and sufficient large pelagic fish predators within the ecosystem, but PEL community deteriorating. Be aware of possible changing environmental conditions or fishing practices that could negatively affect the fish community and ecosystem.
14						decr	Deteriorating	More small fish present within the ecosystem, but the ecosystem is lacking large pelagic fish predators.
15	PEL comm. DEM comm.	not imp	B SMF/LAF	same			Not Improving	Size structure of fish within ecosystem is reasonable, i.e. sufficient large fish to ensure an optimally functioning ecosystem. Be aware of possible changing environmental conditions or fishing practices that could negatively affect the fish community and ecosystem.
15	PEL comm. DEM comm.	not imp	B SMF/LAF	decr			Not Improving	Size structure of fish within ecosystem is reasonable, i.e. more large fish to ensure an optimally functioning ecosystem. Be aware of possible changing environmental conditions or fishing practices that could negatively affect the fish community and ecosystem.
16	PEL comm. DEM comm.	not not					Not Improving	Both fish communities are not improving, thus the southern Benguela ecosystem is Not Improving. Be aware of possible changing environmental conditions or fishing practices that could negatively affect the fish community and ecosystem.
17	PEL comm. DEM comm.	not det	Prop. of pred. fish	incr	PFP B	incr	Not Improving	More large demersal and pelagic predatory fish present within the ecosystem, but DEM community deteriorating. Be aware of possible changing environmental conditions or fishing practices that could negatively affect the fish community and ecosystem.
18						same	Can't Say	More predatory fish within ecosystem, but increase not due to presence of pelagic fish predators within the ecosystem. Net effect cannot be clarified, i.e. Not Improving or Deteriorating? Components within fish community require further examination.
19						decr	Deteriorating	More predatory fish within ecosystem, but ecosystem falls short on pelagic fish predators and DEM community deteriorating.

Table 4.4 continued...

Rule No.	1st Indicator Pair	Trend	2nd indicator	Trend	3rd Indicator	Trend	Decision	Reason
17						incr	Not Improving	Some large demersal predatory fish and more large pelagic predatory fish present within the ecosystem, but DEM community deteriorating. Be aware of possible changing environmental conditions or fishing practices that could negatively affect the fish community and ecosystem.
20	PEL comm. DEM comm.	not det	Prop. of pred. fish	same	PFP B	same	Can't Say	Large demersal and pelagic predatory fish present within the ecosystem, but no trend apparent from indicators. Net effect cannot be clarified, i.e. Not Improving or Deteriorating? Components within fish community require further examination.
19						decr	Deteriorating	Predatory fish present within ecosystem, but ecosystem falls short on pelagic fish predators and DEM community deteriorating.
21	PEL comm. DEM comm.	not det	Prop. of pred. fish	decr			Deteriorating	No predatory fish present within the ecosystem.
22						incr	Can't Say	Fewer large fish within the ecosystem and fishing down of food web not occurring. Trends are contradictory since large fish occupy a high trophic level (TL) within food web and their absence should lower the TL of the ecosystem. Definitely not an Improving ecosystem trend.
23	PEL comm. DEM comm.	det imp	B SMF/LAF	incr	System TL	same	Not Improving	Fewer large fish within ecosystem and fishing down of pelagic food web may be occurring. Be aware of possible changing environmental conditions or fishing practices that could negatively affect the fish community and ecosystem.
24						decr	Deteriorating	Fewer large fish within ecosystem and fishing down of pelagic food web is occurring.
25	PEL comm. DEM comm.	det imp	B SMF/LAF	same			Not Improving	Size structure of fish community within ecosystem is reasonable (large fish present), but PEL community deteriorating. Be aware of possible changing environmental conditions or fishing practices that could negatively affect the fish community and ecosystem.
25	PEL comm. DEM comm.	det imp	B SMF/LAF	decr			Not Improving	Size structure of fish community within ecosystem is improving, but PEL community deteriorating. Be aware of possible changing environmental conditions or fishing practices that could negatively affect the fish community and ecosystem.

Table 4.4 continued...

Rule No.	1st Indicator Pair	Trend	2nd indicator	Trend	3rd Indicator	Trend	Decision	Reason
26	PEL comm. DEM comm.	det not	B SMF/LAF	incr			Deteriorating	Size structure of fish community skewed towards small fish. PEL community is deteriorating, indicating small fish present can only be small demersal fish, most likely small hake.
26	PEL comm. DEM comm.	det not	B SMF/LAF	same			Deteriorating	Size structure of fish community likely skewed towards small fish. PEL community is deteriorating indicating small fish present can only be small demersal fish, likely to be small hake.
27	PEL comm. DEM comm.	det not	B SMF/LAF	decr	DEM TL	incr	Can't Say	More large fish within ecosystem and larger demersal fish not negatively affected by fishing. However, PEL community deteriorating. Net effect cannot be clarified, i.e. Not Improving or Deteriorating? Components within PEL community require further examination.
27						same	Can't Say	More large fish within ecosystem and larger demersal fish unlikely to be negatively affected by fishing. However, PEL community deteriorating. Net effect cannot be clarified, i.e. Not Improving or Deteriorating? Components within PEL community require further examination.
28						decr	Deteriorating	More large fish within ecosystem, but fishing down of demersal food web occurring and PEL community deteriorating.
29	PEL comm. DEM comm.	det det					Deteriorating	Both fish communities are deteriorating, thus the southern Benguela ecosystem is Deteriorating.

4.3.3. Decision Tree Tests

The results of the Observation test as well as the explanations are displayed in Table 4.5. The decision tree observed two different decision outcomes in the history of the southern Benguela ecosystem: one Deteriorating (1960s vs.1900s) and four cases of Not Improving (1980s vs. 1960s, 1990s vs. 1980s, 2004-2008 vs. 1990s and 2004-2008 vs. 1980s) (Table 4.5). For simplicity, only these five observations are shown in the table.

The results of the Ranking test are displayed in Table 4.6 and were consistent with the overall ranks considering trends (1970s – 2003) in model-derived indicators of Shannon *et al.* (2009a). Shannon *et al.* (2009a) ranked the three ecosystems from lowest to highest in terms of fishing impacts as: southern Humboldt, southern Benguela and South Catalan Sea. This pattern was repeated in this study, with the South Catalan Sea being classified as in a worse condition (Deteriorating) than the southern Humboldt and southern Benguela, which were both classified as Not Improving.

Table 4.5: Results of the Observation Test when classifying the five time periods modelled (1900s, 1960s, 1980s, 1990s, 2004-2008) within the southern Benguela ecosystem using the ecosystem decision tree. PEL = Pelagic-caught fish; DEM = Demersal-caught fish; comm. = community; Prop. of pred. fish = Proportion of predatory fish; B SMF/LAF = biomass ratio of small: large fish; TL = trophic level; imp = improving; not = not improving; det = deteriorating; incr = increase; decr = decrease.

Rule No.	1st Indicator Pair	Trend	2nd indicator	Trend	3rd Indicator	Trend	Decision	Observation/Mechanism
21	PEL comm. DEM comm.	not det	Prop. of pred. fish	decr			Deteriorating	1960s vs. 1900s. The period when large-scale industrial fishing started within the southern Benguela. Fish which were targeted were from the demersal community (hake, adult horse mackerel, demersal fish) with the result that the DEM community deteriorated.
25	PEL comm. DEM comm.	det imp	B SMF/LAF	same			Not Improving	1980s vs. 1960s. The era when industrial fishing expanded such that all potentially exploitable species were harvested. Management measures had been put in place in view of rebuilding sardine and hake stocks.
15	PEL comm. DEM comm.	not imp	B SMF/LAF	decr			Not Improving	1990s vs. 1980s. Hake biomass was increasing in response to management measures. Size structure of fish within ecosystem was improving, i.e. more large fish to ensure a functioning ecosystem.
8						incr	Not Improving	2004-2008 vs. 1990s. System had undergone a geographical shift from west coast to south coast. High biomasses of small pelagic fish. Predatory fish present within ecosystem, but not increasing. Although DEM TL increasing, DEM community deteriorating, therefore overall system Not Improving.
11	PEL comm. DEM comm.	imp det	Prop. of pred. fish	same	DEM TL	same	Can't Say	Not observed.
10						decr	Deteriorating	Not observed.
6						incr	Not Improving	Not observed.
6	PEL comm. DEM comm.	imp not	Prop. of pred. fish	decr	DEM TL	same	Not Improving	2004-2008 vs. 1980s. System had undergone a geographical shift from west coast to south coast. The increase in small pelagic fish biomass is responsible for the improving PEL community classification. However, linefish are overexploited which has resulted in fewer predatory fish being present in the ecosystem.
7						decr	Deteriorating	Not observed.

Table 4.6: Results of the Ranking Test when three upwelling ecosystems (southern Benguela, southern Humboldt, South Catalan Sea) were classified using data and surrogate indicators* sourced from Shannon *et al.* (2009)[1]. PEL = Pelagic-caught fish; DEM = Demersal-caught fish; B SMF/LAF = biomass ratio of small: large fish; PFP B = Pelagic fish predator biomass; TL = trophic level; C = catch; Y = catch; incr = increasing; decr = decreasing.

Ecosystem	Indicator	Trend	Community Classification	Indicator	Trend	Indicator	Trend	Classification
Southern Benguela	Pelagic B[1] (PEL B) Pelagic C[1] (PEL Y/PEL B) Demersal B[1] (DEM B) Demersal C[1] (DEM Y/DEM B)	incr incr incr same	PEL Not Improving DEM Improving	forage/ predatory B[1] (B SMF/LAF)	incr	Top 5 TL fish or chondrichthyans[1] (PFP B)	same	Not Improving
Southern Humboldt	Pelagic B[1] (PEL B) Pelagic C[1] (PEL Y/PEL B) Demersal B[1] (DEM B) Demersal C[1] (DEM Y/DEM B)	incr incr incr decr	PEL Not Improving DEM Improving	forage/ predatory B[1] (B SMF/LAF)	incr	Top 5 TL fish or chondrichthyans[1] (PFP B)	incr	Not Improving
South Catalan Sea	Pelagic B[1] (PEL B) Pelagic C[1] (PEL Y/PEL B) Demersal B[1] (DEM B) Demersal C[1] (DEM Y/DEM B)	decr incr same incr	PEL Deteriorating DEM Not Improving	forage/ predatory B[1] (B SMF/LAF)	decr	TL of model community[1] (DEM TL)	decr	Deteriorating

*See section 4.2.3 for details

4.4. Discussion

The decision tree is intended as a communication tool between scientists, fisheries managers and other stakeholders to inform the various groups about the dynamics within the southern Benguela ecosystem. This was achieved by loading the decision tree, in the form of an expert system, within the WinExp program. The expert system promotes disciplined thinking because explanations for the use of the indicators, the characteristics they describe and final decision outcomes must be provided (Starfield and Louw 1986).

This was the first attempt at a southern Benguela ecosystem specific decision tree. Emphasis was placed on the reasons for indicator use and the interpretation of trends rather than applying statistics to try and validate significant trends. The development process essentially consisted of three steps. The first was choosing what the final decision outcomes would be, which would guide formulation of the decision tree. The second step was the approach envisioned for the decision tree, e.g. top-down, bottom-up, etc. This second step required some careful thought because it was quite easy to get stuck in a loop where it became necessary to use an indicator twice which would have been counter-productive. The final approach decided upon was first assessing the fish communities (PEL and DEM), and then having an overall classification based upon these community assessments and the additional indicators needed to clarify trends on the scale of an entire ecosystem. In this manner, warning signals regarding species or functional groups could also be detected because information was conveyed about the two fish communities and the overall ecosystem.

The decision tree was not designed to explicitly compare ecosystems to one another, for example, to be able to say that the southern Humboldt ecosystem is in a better state than the southern Benguela ecosystem, as was done in Shannon *et al.* (2009a). The Ranking test conducted was an exercise in validating the logic used in the decision tree to guide the decision tree outcomes. In order to achieve the level of detail reported by Shannon *et al.* (2009a), a quantitative method would be needed to examine the trends in indicators as well as those displayed by communities and the ecosystem.

The majority of decision outcomes obtained in all three decision trees were Not Improving. This was expected since conditions for an Improving/Deteriorating outcome were stringent; with the result that the majority of outcomes would be Not Improving. This is not necessarily a bad situation, since if the community or ecosystem started in a “good” situation, a Not Improving classification would make the most sense, since it is unlikely that a community/ecosystem would improve on an already good situation. The question then arises regarding how good a “Not Improving” situation is, since the trends are all relative to a predetermined standard of what is thought to be a desirable situation (e.g. the 1900s). This first prototype demonstrates the principles of use of the indicators in line with current understanding. As our understanding of community and ecosystem indicators improves, reference levels should be developed that will be reflected in later versions of the expert system.

It must still be borne in mind that a Not Improving classification for either the community or ecosystem does not imply that all species or functional groups are in good condition. In fact, the decision tree classifies the community and ecosystem in terms of the bigger picture, i.e. overall functioning of the community and ecosystem. Vigilance is required on the part of scientists, fisheries managers and stakeholders with regard to Not Improving trends to constantly monitor the fish communities and overall ecosystem processes because changing environmental conditions or fishing practices could negatively affect the individual species and/or functional groups within the community and/or ecosystem. For example, the current period for the southern Benguela ecosystem has been classified as Not Improving (Table 4.5), but the Proportion of predatory fish indicator shows a decreasing trend of predatory fish within the ecosystem which is a result of the overexploitation of linefish (LAF Indicator - Chapter 3). Thus, expanding or even maintaining the current state of the linefishery is not a viable option because the remaining stocks, which currently seem able to support a functioning ecosystem, would be further decimated, opening the potential for a community collapse.

If the rules were formulated so that more Deteriorating outcomes were reached, it would not bode well for building communication relationships between scientists, fisheries managers and other stakeholders. This approach would constantly portray a negative outlook no matter the conditions employed when managing fishing sectors and activities within an ecosystem, and would undermine the objective of the decision tree, i.e. to generate support for an Ecosystem Approach to Fishing (EAF).

Indicators provide assistance for the implementation of an EAF management plan (Degnbol and Jarre 2004). Suitable indicators therefore need to be generated and selected for a particular ecosystem. Pauly and Watson (2005) encourage using a Marine Trophic Index with a cut-off trophic level (TL) of 3.25 for fish when attempting to detect fishing down food web effects within an ecosystem. However, in this study, the indicator System TL, rather than Mean TL of Y, was used as a warning signal for possible fishing down food web (Pauly *et al.*

1998) effects (Table 4.1). The southern Benguela is an upwelling ecosystem and is dominated by mid-trophic level fishes such as anchovy (TL = 3.54; Chapter 2 Figure 2.5) and sardine (TL = 2.99; Chapter 2 Figure 2.5). Pauly and Watson's (2005) suggestion would hold in global ecosystem comparative studies since a standardised method for calculating the indicator will be required. This study was specifically aimed at the southern Benguela ecosystem and therefore, methods most appropriate for this ecosystem were considered when choosing indicators.

The positive outcome achieved with the development of this decision tree was the synthesis of knowledge through the use of the trophic model constructed (Chapter 2) and the indicators extracted (Chapter 3), which is recognised as a current gap in Benguela ecosystem science (Jarre *et al.* 2006). In fact, one of the more difficult aspects during the decision tree development process was the distillation of scientific results and literature into a form that would be most appropriate and usable for fisheries managers and stakeholders. This distillation process is one of the hurdles hampering effective management and was the most time consuming during the development process. It was essential to ensure that unnecessary scientific jargon was not used and that each and every thought process was recorded so that the user may be guided through the logic employed by the decision tree.

The next step in the decision tree development process would be the presentation (use) of the decision tree to (by) fisheries managers as a training exercise. To facilitate this process, visual representations of the indicators and the decision tree such as illustrated in Figure 4.5, should also be considered. The various tools available (expert systems, graphics) should be used side-by-side when presenting to fisheries managers so that the message is communicated effectively. The aim of this training exercise would be to generate feedback regarding the decision tree's usefulness and clarity. The decision tree is not cast in stone, if necessary; it should be modified so that the dynamic nature of the southern Benguela ecosystem may be better reflected. However, this step lies outside the scope of this project.

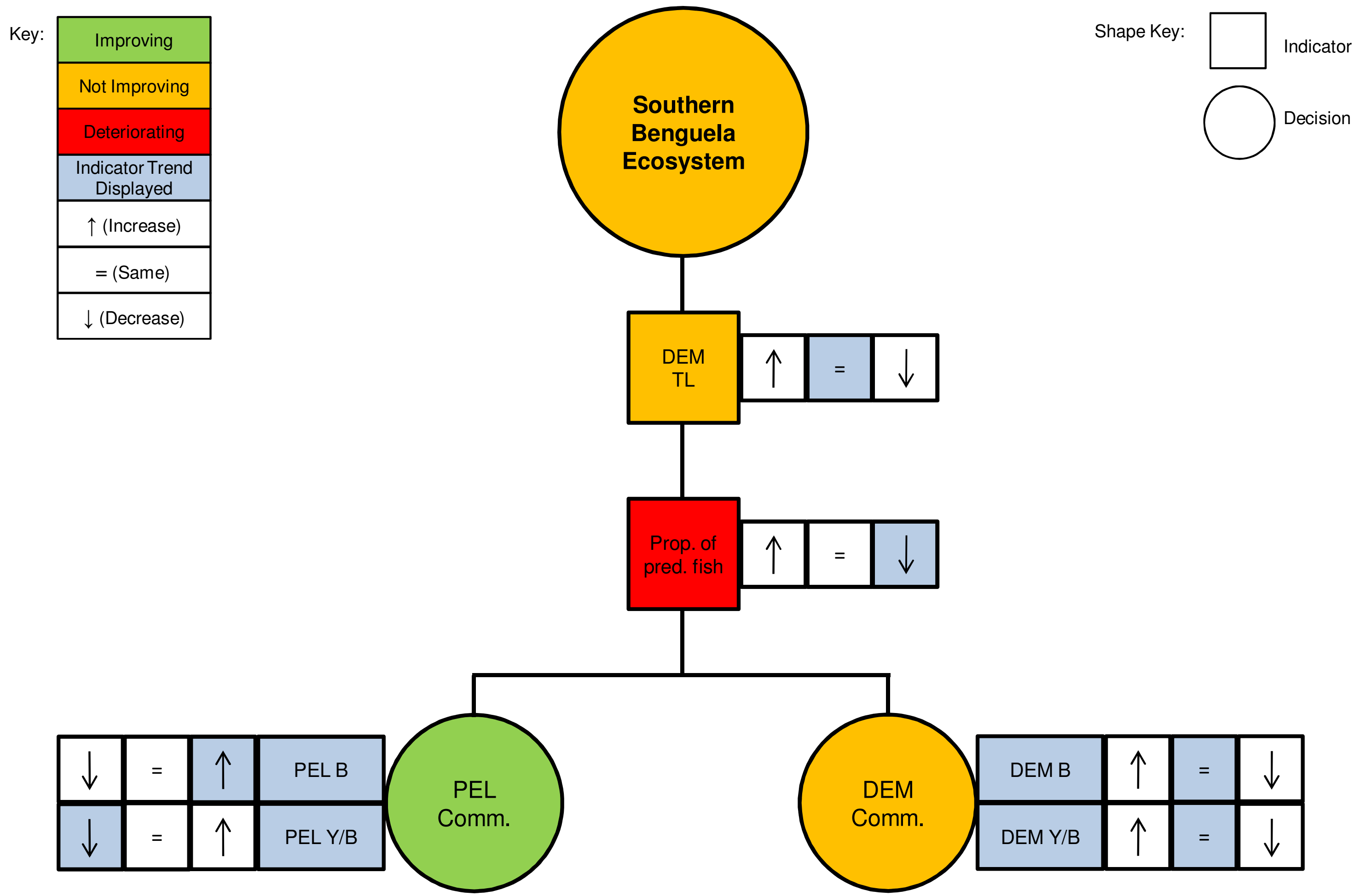


Figure 4.5: Visual representation of the 2004-2008 vs. 1980s trend displayed by the southern Benguela ecosystem when using the Pelagic-caught fish (PEL) community decision tree, the Demersal-caught fish (DEM) community decision tree and the southern Benguela ecosystem decision tree and their associated indicators. Comm. = Community; B = biomass; Y/B = catch per biomass; Prop. of pred. fish = Proportion of predatory fish; TL = Trophic level.

Chapter 5

Synthesis and Conclusions

The southern Benguela ecosystem is a highly dynamic and productive upwelling system that supports a great diversity of marine life (Gibbons *et al.* 1999) and provides a number of ecosystem services. It is also able to support a number of commercial fishery sectors because of its productive nature. This poses a challenge to management because a multitude of objectives, including those of exploitation versus conservation, need to be balanced within the one ecosystem. The new management paradigm considered for ecosystems worldwide is one of an ecosystem approach, i.e. an Ecosystem Approach to Fisheries (EAF). It gained popularity in the 1990s and South Africa committed to it by signing the 2001 Rejkavík Declaration, which was reinforced at the 2002 World Summit on Sustainable Development (Cochrane *et al.* 2004).

Ecosystem modelling is one of the tools used towards achieving an EAF. Trophic (food web) models are based on the interactions between ecosystem components and therefore represent the complexity of food webs within an ecosystem. In this manner, scientists, managers and other stakeholders are able to view the connections between and among the different ecosystem components and it can be analysed how pressures, be they environmental or anthropogenic, affect the ecosystem as a whole, as well as its individual components. In this study, an updated 2004-2008 ecosystem trophic model was developed using the Ecopath with Ecosim (EwE v5.1) software developed by Pauly *et al.* (2000). The current model complements the historic 1900s, 1960s 1980s and 1990s southern Benguela ecosystem trophic models developed by Shannon *et al.* (2003) and Watermeyer *et al.* (2008a), such that a series of snapshots of the southern Benguela ecosystem from the largely unfished era to the current period is now available. The results of these modelling exercises denote a change in the southern Benguela ecosystem food web structure over time. Biomasses of the lower trophic level groups, i.e. small pelagic fish, have increased, whereas biomasses of the higher trophic level groups (e.g. hake, mammals, seabirds) have decreased. Even within specific model groups, such as large pelagic fish, changes have become evident. Modelled large pelagic fish biomass has increasingly become dominated by the faster growing and more productive snoek. Model results indicate that changes in the consumption patterns of natural predators have also taken place since the various fishing sectors have expanded and become significant consumers of potential food sources of the natural predators. This has occurred in conjunction with natural environmental fluctuations which have shifted the food sources for certain groups, such as the changing geographical distribution of small pelagic fish within the southern Benguela ecosystem (van der Lingen *et al.* 2002, Fairweather *et al.* 2006, van der Lingen *et al.* 2006b), which is also reflected in the increased cephalopod consumption of small pelagic fish in the model.

Ecosystem models are very useful, but they do not lend themselves to be completely meaningful to fisheries managers and non-academic stakeholders, because they are very technical. Indicators have been recognised as an aid for the implementation of an EAF within various fishing sectors if they are related to specific fisheries management objectives (Degnbol and Jarre 2004). Their properties include that they should be observable and they should be understood by stakeholders (Degnbol and Jarre 2004, Rice and Rochet 2005). A suite of indicators are needed when assessing potential ecosystem states and trends (Daan *et al.* 2005 and contributors therein). Model-generated indicators are an additional source of information to that of data-based indicators. They are able to capture ecosystem properties in more detail, such as production and consumption ratios as well as trophic level patterns, which are important for understanding the underlying dynamics of the ecosystem (Cury *et al.* 2005). In this study, indicators were extracted from the range of southern Benguela ecosystem trophic models available so that assessments could be made about the state of the southern Benguela ecosystem and how it has changed over time. Biomass-based indicators suggest that the southern Benguela ecosystem has undergone a change in food web structure over time with small, planktivorous fish becoming more abundant whereas the large, predatory/piscivorous fish have decreased in abundance. Catch-based indicators provide support for this change in ecosystem food web structure. Catch-based indicators of the small, pelagic planktivorous fish have all increased over time whereas those of the large, demersal, piscivorous fish have decreased. In accordance with the findings of Cury *et al.* (2005), the mean trophic level of the catch suggests that no further fishing down of the food web (Pauly *et al.* 1998) has occurred since the 1960s, and that harvesting of the higher level trophic groups has been conservative. However, this result is contradicted by the Large Fish functional group (linefish and hake) catch-based and biomass-based indicators, which is line with the current poor status of the linefish community (Griffiths 2000, Southern African Sustainable Seafood Initiative (SASSI): www.wwf.org.za/sassi) and deep-water hake (MSC

2010), and suggests that specifically the hake and linefish fishing sectors have not been operating at ecologically optimal levels.

Indicators which were deemed most meaningful for management groups in the southern Benguela ecosystem were selected for use within decision trees to assess trends in ecosystem status as a result of fishing. These decision trees examined the southern Benguela ecosystem on a different scale to that which is currently addressed within management, i.e. it focussed on the community (Pelagic-caught fish and Demersal-caught fish community decision trees) and system perspective (ecosystem decision tree) of the southern Benguela ecosystem. In this way, they are intended to complement the single-species assessments in operation. A summary of the classifications of the southern Benguela ecosystem across time periods is displayed in Table 5.1.

Table 5.1: Summary of the classification of the southern Benguela ecosystem across time periods using the community and ecosystem decision trees developed. For details see Chapter 4.

Time period compared	1st Indicator Pair	Trend	2nd indicator	Trend	3rd Indicator	Trend	Decision
1960s vs. 1900s	Pelagic-caught fish community	not improving	Proportion of predatory fish	decreasing			Deteriorating
	Demersal-caught fish community	deteriorating					
1980s vs. 1960s	Pelagic-caught fish community	deteriorating	Biomass of small: large fish	same			Not Improving
	Demersal-caught fish community	improving					
2004-2008 vs. 1980s	Pelagic-caught fish community	improving	Proportion of predatory fish	decreasing	Demersal-caught fish community trophic level	same	Not Improving
	Demersal-caught fish community	not improving					

Except for the Deteriorating classification of the southern Benguela ecosystem 1960s vs. 1900s periods when industrial fishing first started, all ecosystem decisions were Not Improving. This indicates that this first prototype of the decision trees and the associated indicators is conservative and robust. The decision tree is intended as a communication tool amongst stakeholders and therefore a 5% limit used to assess indicator trends was deemed appropriate, since emphasis was placed on interpreting the trends in a positive light. This was also the reason for loading the decision tree as an expert system, which provides a logical framework whereby fisheries managers and other stakeholders are able to access the information and the reasoning behind the conclusions reached. Tests of the ecosystem decision tree were conducted and these validated the logic employed within the decision tree because it ranked other upwelling ecosystems in a consistent fashion to the study conducted by Shannon *et al.* (2009a), in which a more quantitative approach was used. Given that so many ecosystems around the world are in a poor condition, the management employed within the offshore fisheries of the southern Benguela ecosystem has ensured that the offshore ecosystem, which was the focus of this study, has not deteriorated further. The next step in the decision tree development process would be the presentation of the expert system and decision trees to fisheries managers to generate feedback regarding its usefulness and clarity. In addition, incorporation of reference levels for the indicators selected from this study should be a priority for further research.

Chapter 6
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Chapter 7
Appendices

Appendix Table 7.1: Initial input parameters for the 31 living trophic groups used in the 2004-2008 southern Benguela ecosystem trophic model. Parameter values were taken from those sourced by Shannon (2001) and published in Shannon *et al.* (2003). Where updated values are available, sources are indicated. Biomass (B) is in t.km^{-2}, P/B and Q/B are per year (yr^{-1}), and catch (Y) is in t.km^{-2}.yr^{-1}.

Model Group No.	Model Group	Parameter	Value	Source
1	Phytoplankton	B	57.797	Barlow *et al.* 2009
		P/B	154.400	Shannon *et al.* (2003)
2	Benthic producers	P/B	15.000	Shannon *et al.* (2003)
3	Microzooplankton	P/B	482.000	Shannon *et al.* (2003)
		P/Q	0.250	Shannon *et al.* (2003)
		U	0.200	Shannon *et al.* (2003)
4	Mesozooplankton	P/B	40.000	Shannon *et al.* (2003)
		P/Q	0.300	Shannon *et al.* (2003)
		U	0.350	Shannon *et al.* (2003)
5	Macrozooplankton	P/B	13.000	Shannon *et al.* (2003)
		P/Q	0.410	Shannon *et al.* (2003)
		U	0.200	Shannon *et al.* (2003)
6	Gelatinous zooplankton	B	5.000	M. Gibbons (UWC), pers. comm., assume no change from Shannon *et al.* (2003)
		P/B	0.584	Shannon *et al.* (2003)
		P/Q	0.350	Shannon *et al.* (2003)
		U	0.200	Shannon *et al.* (2003)
7	Anchovy	B	11.445	Cunningham & Butterworth (2007); de Moor & Butterworth (2009)
		P/B	1.200	Shannon *et al.* (2003)
		Q/B	12.300	Shannon *et al.* (2003)
		Y	1.126	MCM unpublished data
8	Sardine	B	5.381	Coetzee *et al.* (2008)
		P/B	1.200	Shannon *et al.* (2003)
		P/Q	0.097	Shannon *et al.* (2003)
		Y	1.165	MCM unpublished data
9	Redeye	B	6.638	Fairweather (2009)
		P/B	1.200	Shannon *et al.* (2003)
		P/Q	0.100	Shannon *et al.* (2003)
		Y	0.209	Coetzee (2009)
10	Other small pelagic fish	B	0.364	Shannon *et al.* (2003)
		P/B	1.000	Shannon *et al.* (2003)
		P/Q	0.100	Shannon *et al.* (2003)
		Y	0.001	MCM unpublished data
11	Chub mackerel	B	0.063	Twatwa *et al.*(2009)
		P/B	0.900	Shannon *et al.* (2003)
		P/Q	0.100	Shannon *et al.* (2003)
		U	0.250	Shannon *et al.* (2003)
		Y	0.002	MCM unpublished data
12	Juvenile horse mackerel	B	0.298	Merkle & Coetzee (2007)
		P/B	1.200	Shannon *et al.* (2003)
		Q/B	12.000	Shannon *et al.* (2003)
		U	0.350	Shannon *et al.* (2003)
		Y	0.015	MCM unpublished data

Appendix Table 7.1 continued...

Model Group No.	Model Group	Parameter	Value	Source
13	Adult horse mackerel	B	0.967	Fairweather (2009)
		P/B	1.000	Shannon *et al.* (2003)
		Q/B	10.000	Shannon *et al.* (2003)
		U	0.300	Shannon *et al.* (2003)
		Y	0.148	Johnston & Butterworth (2009)
14	Mesopelagic fish	P/B	1.200	Shannon *et al.* (2003)
		P/Q	0.100	Shannon *et al.* (2003)
		U	0.350	Shannon *et al.* (2003)
		Y	0.003	MCM unpublished data
15	Snoek	P/B	0.500	Shannon *et al.* (2003)
		P/Q	0.100	Shannon *et al.* (2003)
		U	0.200	Shannon *et al.* (2003)
		Y	0.042	MCM unpublished data
16	Other large pelagic fish	B	0.106	MCM unpublished data
		P/B	0.480	Shannon *et al.* (2003)
		P/Q	0.056	Shannon *et al.* (2003)
		U	0.200	Shannon *et al.* (2003)
		Y	0.032	MCM unpublished data
17	Cephalopods	B	1.773	MCM unpublished data
		P/B	3.500	Shannon *et al.* (2003)
		P/Q	0.350	Shannon *et al.* (2003)
		U	0.200	Shannon *et al.* (2003)
		Y	0.041	MCM unpublished data
18	Small *M. capensis*	P/B	2.000	Shannon *et al.* (2003)
		P/Q	0.150	Shannon *et al.* (2003)
		U	0.350	Shannon *et al.* (2003)
		Y	0.000	Rademeyer & Butterworth (2009)
19	Large *M. capensis*	B	0.653	Fairweather & Leslie (2009)
		P/B	0.800	Shannon *et al.* (2003)
		P/Q	0.180	Shannon *et al.* (2003)
		U	0.200	Shannon *et al.* (2003)
		Y	0.130	Rademeyer & Butterworth (2009)
20	Small *M. paradoxus*	P/B	2.000	Shannon *et al.* (2003)
		P/Q	0.150	Shannon *et al.* (2003)
		U	0.350	Shannon *et al.* (2003)
		Y	0.045	Rademeyer & Butterworth (2009)
21	Large *M. paradoxus*	B	0.959	Fairweather & Leslie (2009)
		P/B	0.800	Shannon *et al.* (2003)
		P/Q	0.170	Shannon *et al.* (2003)
		U	0.200	Shannon *et al.* (2003)
		Y	0.474	Rademeyer & Butterworth (2009)

Appendix Table 7.1 continued...

Model Group No.	Model Group	Parameter	Value	Source
22	Pelagic-feeding demersal fish	P/B	1.000	Shannon *et al.* (2003)
		P/Q	0.200	Shannon *et al.* (2003)
		U	0.200	Shannon *et al.* (2003)
		Y	0.037	MCM unpublished data
23	Benthic-feeding demersal fish	P/B	1.000	Shannon *et al.* (2003)
		P/Q	0.200	Shannon *et al.* (2003)
		U	0.200	Shannon *et al.* (2003)
		Y	0.056	MCM unpublished data
24	Pelagic-feeding chondrichthyans	B	0.176	MCM unpublished data
		P/B	0.500	Shannon *et al.* (2003)
		Q/B	4.500	Shannon *et al.* (2003)
		U	0.200	Shannon *et al.* (2003)
		Y	0.007	MCM unpublished data
25	Benthic-feeding chondrichthyans	B	1.210	MCM unpublished data
		P/B	1.000	Shannon *et al.* (2003)
		P/Q	0.100	Shannon *et al.* (2003)
		U	0.200	Shannon *et al.* (2003)
		Y	0.002	MCM unpublished data
26	Apex chondrichthyans	B	0.042	Shannon *et al.* (2003)
		P/B	0.500	Shannon *et al.* (2003)
		P/Q	0.100	Shannon *et al.* (2003)
		U	0.200	Shannon *et al.* (2003)
		Y	0.0000145	MCM unpublished data
27	Seals	B	0.133	Kirkman *et al.* (2007), Kirkman (MCM) pers. comm.
		P/B	0.946	Shannon *et al.* (2003)
		Q/B	19.300	Shannon *et al.* (2003)
		U	0.200	Shannon *et al.* (2003)
		Y	0.003	Shannon *et al.* (2003)
28	Cetaceans	B	0.082	Shannon *et al.* (2003)
		P/B	0.600	Shannon *et al.* (2003)
		Q/B	10.000	Shannon *et al.* (2003)
		U	0.210	Shannon *et al.* (2003)
29	Seabirds	B	0.011	Crawford *et al.* (1991), Underhill *et al.* (2002), Crawford *et al.* (2006), Crawford *et al.* (2007a), Crawford *et al.* (2007b), Kemper *et al.* (2007)
		P/B	0.123	Shannon *et al.* (2003)
		Q/B	118.000	Shannon *et al.* (2003)
		U	0.260	Shannon *et al.* (2003)
30	Meiobenthos	P/B	4.000	Shannon *et al.* (2003)
		P/Q	0.120	Shannon *et al.* (2003)
		U	0.100	Shannon *et al.* (2003)
31	Macrobenthos	P/B	1.200	Shannon *et al.* (2003)
		P/Q	0.120	Shannon *et al.* (2003)
		U	0.100	Shannon *et al.* (2003)

Appendix Table 7.2: The biomasses calculated for each resident species of seabird included in the 2004-2008 southern Benguela ecosystem trophic model. Data for the species were sourced from Crawford *et al.* (1991), Underhill *et al.* (2002), Crawford *et al.* (2006), Crawford *et al.* (2007a), Crawford *et al.* (2007b) and Kemper *et al.* (2007).

Common Name	**Scientific Name**	**Biomass (t)**
African Penguin	*Spheniscus demersus*	433.640
Bank Cormorant	*Phalacrocorax neglectus*	3.977
Cape Cormorant	*Phalacrocorax capensis*	317.034
Cape Gannet	*Morus capensis*	1544.746
Caspian Tern	*Sterna caspia*	0.023
Crowned Cormorant	*Phalacrocorax coronatus*	7.343
Damara Tern	*Sterna balaenarum*	0.035
Great White Pelican	*Pelecanus onocrotalus*	10.276
Greyheaded Gull	*Larus cirrocephalus poicephalus*	2.132
Hartlaub's Gull	*Larus hartlaubii*	3.145
Kelp Gull	*Larus dominicanus vetula*	35.325
Leach's Storm Petrel	*Oceanodroma leucorhoa*	0.000
Roseate Tern	*Sterna dougallii*	0.067
Swift Tern	*Sterna bergii bergii*	7.395
White-breasted Cormorant	*Phalacrocorax lucidus*	18.605

Appendix Table 7.3: The catch ($t.km^{-2}.yr^{-1}$) calculated for each model group per fleet and grouped according to fishing gear used in the 2004-2008 southern Benguela ecosystem trophic model. Data were sourced from Coetzee (2009), Johnston & Butterworth (2009), Rademeyer & Butterworth (2009), Shannon *et al.* (2003) and unpublished MCM data. These catch values exclude discard amounts.

	Model Fishing Gear	**Purse-seine**	**Midwater trawl**	**Demersal trawl**				**Line fishery**
Model group no.	**Model group \ Fleet**	Purse-seine	Midwater Trawl	Demersal Trawl	Hake Trawl	Inshore	Offshore	Linefish & Tuna Pole
7	Anchovy	1.024						
8	Sardine	0.971						
9	Redeye	0.209						
10	Other small pelagic fish	0.001						
11	Chub mackerel	0.002						
12	Juvenile horse mackerel	0.015						
13	Adult horse mackerel	0.0189	0.0987	0.0302				
14	Mesopelagic fish	0.003						
15	Snoek				0.0184502			0.0235253
16	Other large pelagic fish				0.0003855			0.0233175
17	Cephalopods				0.0023932			0.0302828
18	Small *M. capensis*					0.0001092		
19	Large *M. capensis*					0.0337079	0.0668273	
20	Small *M. paradoxus*						0.0451877	
21	Large *M. paradoxus*						0.4568976	
22	Pelagic-feeding demersal fish				0.0364784			0.0003646
23	Benthic-feeding demersal fish				0.0537619			0.0004175
24	Pelagic-feeding chondrichthyans				0.0026420			0.0009026
25	Benthic-feeding chondrichthyans				0.0015297			0.0004724
26	Apex chondrichthyans							0.0000145
27	Seals							

Appendix Table 7.3 continued...

	Model Fishing Gear	**Long Line**			**Other**					
Model group no.	**Model group \ Fleet**	Hake Longline	Tuna Longline	Shark Longline	Prawn	Squid Jig	SC Rock Lobster	Beach Seine & Gill Net	Handline	Incidental mortality
7	Anchovy									
8	Sardine									
9	Redeye									
10	Other small pelagic fish									
11	Chub mackerel									
12	Juvenile horse mackerel									
13	Adult horse mackerel									
14	Mesopelagic fish									
15	Snoek	0.0000291								
16	Other large pelagic fish	0.0000498	0.0083364	0.0000189	0.0000097		0.0000109	0.0000918		
17	Cephalopods	0.0000054	0.0000273	0.0000000	0.0000529	0.0079091	0.0000320			
18	Small *M. capensis*									
19	Large *M. capensis*	0.0262966							0.0035227	
20	Small *M. paradoxus*									
21	Large *M. paradoxus*	0.0166739								
22	Pelagic-feeding demersal fish	0.0000918			0.0000038		0.0000001			
23	Benthic-feeding demersal fish	0.0015740	0.0002913	0.0000021	0.0000051		0.0000016			
24	Pelagic-feeding chondrichthyans	0.0000231	0.0006221	0.0023981			0.0000097			
25	Benthic-feeding chondrichthyans			0.0000393				0.0000455		
26	Apex chondrichthyans									
27	Seals									0.003

Appendix Table 7.4: Discard amounts calculated for model groups[1] used in the 2004-2008 southern Benguela ecosystem trophic model. Discard proportions were sourced from Somhlaba *et al.* (2006)[a], Walmsley *et al.* (2007b)[b] and Petersen *et al.* (2009)[c].

Model Group	**Discard Proportion**	**Catch ($t.km^{-2}.yr^{-1}$)**	**Discards ($t.km^{-2}.yr^{-1}$)**
Anchovy[a]	0.1000	1.0242	0.1024
Sardine[a]	0.2000	0.9711	0.1942
Chub mackerel[b]	0.0008	0.0020	0.0000
Horse mackerel[b]	0.0009	0.1480	0.0001
Snoek[b]	0.0000	0.0420	0.0000
Other large pelagic fish[b]			0.0000
Kob	0.0002	0.0020	0.0000
Cephalopods[b]	0.0026	0.0410	0.0001
Hake[b]			
Small *M. capensis*_overall	0.0846	0.0001	0.0000
Small *M. paradoxus*_overall	0.1252	0.0452	0.0056
Pelagic-feeding demersal fish (total)[b,2]			0.0000
Cape John Dory	0.0013	0.0044	0.0000
Benthic-feeding demersal fish (total)[b,3]			0.0001
Jacopever	0.0042	0.0045	0.0000
Kingklip	0.0001	0.0142	0.0000
Monkfish	0.0018	0.0332	0.0001
Cape gurnard	0.0007	0.0014	0.0000
Agulhas sole	0.0002	0.0015	0.0000
Panga	0.0001	0.0004	0.0000
Pelagic-feeding chondrichthyans (total)[c,4]			0.0006
Short-finned mako shark	0.0400	0.0008	0.0000
Blue shark	0.2290	0.0023	0.0005

1 Walmsley *et al.* (2007b) also lists discards for benthic-feeding chondrichthyans, i.e. dogfish (19%), blancmange skate (0.02%), slimeskate (0.01%), yellowspotted catshark (0.04%) and spiny dogsharks (0.07%). However, no landings were recorded from which to calculate discards for the period of interest in this study.

2 Walmsley *et al.* (2007b) also lists discards for buttersnoek/ribbonfish in this category (0.43%). However, no landings were recorded from which to calculate discards for the period of interest in this study.

3 Walmsley *et al.* (2007b) also lists discards for lesser gurnard (0.21%), large-scaled rattail (0.57%) and smooth-scaled rattail/purple grenadier (0.37%) in this category. However, no landings were recorded from which to calculate discards for the period of interest in this study.

4 Walmsley *et al.* (2007b) also lists discards for biscuit skate in this category (0.07%). However, no landings were recorded from which to calculate discards for the period of interest in this study.

Appendix Table 7.5: Diet data adopted for the current 2004-2008 period (04-08) in the southern Benguela ecosystem trophic model. The dietary proportions used for the current period are compared to those in the 1980s, i.e. the 1980s dietary proportion was the same (=), higher (↑) or lower (↓) than the current period. Diets which were altered for the Snoek and Cephalopod model groups during the diet test are also shown (04-08 diet test). Diet data were sourced from Shannon *et al.* (2003) and modified where necessary to better reflect prey availability in the period 2004-2008. Gelatinous zoopl. = Gelatinous zooplankton; Other small pelagics = Other small pelagic fish; Juvenile horse mack. = Juvenile horse mackerel; Adult horse mack. = Adult horse mackerel; Mesopelagics = Mesopelagic fish; Other large pelagics = Other large pelagic fish; Pelagic demersals = Pelagic-feeding demersal fish; Benthic demersals = Benthic-feeding demersal fish; Pelagic chond. = Pelagic-feeding chondrichthyans; Benthic chond. = Benthic-feeding chondrichthyans; Apex chond. = Apex chondrichthyans.

Prey \ Predator	Phytoplankton		Benthic producers		Microzooplankton		Mesozooplankton	
	1980	04-08	1980	04-08	1980	04-08	1980	04-08
Phytoplankton					=	0.400	=	0.500
Benthic producers								
Microzooplankton					=	0.200	=	0.500
Mesozooplankton								
Macrozooplankton								
Gelatinous zoopl.								
Anchovy								
Sardine								
Redeye								
Other small pelagics								
Chub mackerel								
Juvenile horse mack.								
Adult horse mack.								
Mesopelagics								
Snoek								
Other large pelagics								
Cephalopods								
Small *M. capensis*								
Large *M. capensis*								
Small *M. paradoxus*								
Large *M. paradoxus*								
Pelagic demersals								
Benthic demersals								
Pelagic chond.								
Benthic chond.								
Apex chond.								
Seals								
Cetaceans								
Seabirds								
Meiobenthos								
Macrobenthos								
Detritus					=	0.400		
Import								

Appendix Table 7.5 continued...

Prey \ Predator	Macrozooplankton		Gelatinous zoopl.		Anchovy		Sardine	
	1980	04-08	1980	04-08	1980	04-08	1980	04-08
Phytoplankton	=	0.600			=	0.050	=	0.320
Benthic producers								
Microzooplankton					=	0.040	=	0.320
Mesozooplankton	=	0.400	=	0.640	=	0.570	=	0.290
Macrozooplankton			=	0.120	=	0.340	=	0.070
Gelatinous zoopl.			=	0.040				
Anchovy								
Sardine								
Redeye								
Other small pelagics								
Chub mackerel								
Juvenile horse mack.								
Adult horse mack.								
Mesopelagics								
Snoek								
Other large pelagics								
Cephalopods								
Small *M. capensis*								
Large *M. capensis*								
Small *M. paradoxus*								
Large *M. paradoxus*								
Pelagic demersals								
Benthic demersals								
Pelagic chond.								
Benthic chond.								
Apex chond.								
Seals								
Cetaceans								
Seabirds								
Meiobenthos								
Macrobenthos								
Detritus			=	0.200				
Import								

Appendix Table 7.5 continued...

Prey \ Predator	Redeye		Other small pelagics		Chub mackerel		Juvenile horse mack.	
	1980	04-08	1980	04-08	1980	04-08	1980	04-08
Phytoplankton								
Benthic producers								
Microzooplankton								
Mesozooplankton	=	0.600	=	0.810	=	0.010	=	0.750
Macrozooplankton	=	0.400	=	0.160	=	0.800	=	0.250
Gelatinous zoopl.			=	0.030				
Anchovy					=	0.019		
Sardine								
Redeye					↓	0.011		
Other small pelagics								
Chub mackerel								
Juvenile horse mack.								
Adult horse mack.								
Mesopelagics					=	0.160		
Snoek								
Other large pelagics								
Cephalopods								
Small *M. capensis*								
Large *M. capensis*								
Small *M. paradoxus*								
Large *M. paradoxus*								
Pelagic demersals								
Benthic demersals								
Pelagic chond.								
Benthic chond.								
Apex chond.								
Seals								
Cetaceans								
Seabirds								
Meiobenthos								
Macrobenthos								
Detritus								
Import								

Appendix Table 7.5 continued...

Prey \ Predator	Adult horse mack.		Mesopelagics		Snoek			Other large pelagics	
	1980	04-08	1980	04-08	1980	04-08	04-08 diet test	1980	04-08
Phytoplankton									
Benthic producers									
Microzooplankton									
Mesozooplankton	=	0.390	=	0.400					
Macrozooplankton	=	0.520	=	0.600	=	0.170	0.170	=	0.080
Gelatinous zoopl.									
Anchovy	↓	0.044			↑	0.278	0.324	↑	0.210
Sardine	↓	0.021			↓	0.131	0.152	↑	0.099
Redeye	↓	0.025			↓	0.161	0.189	↓	0.122
Other small pelagics					=	0.000	0.000	=	0.030
Chub mackerel					=	0.000	0.000	=	0.030
Juvenile horse mack.					=	0.010	0.010	=	0.050
Adult horse mack.					=	0.000	0.000		
Mesopelagics					=	0.050	0.050	=	0.020
Snoek					=	0.000	0.000		
Other large pelagics								↓	0.010
Cephalopods					=	0.010	0.010	=	0.140
Small *M. capensis*					=	0.020	0.010	=	0.010
Large *M. capensis*									
Small *M. paradoxus*					=	0.060	0.030	=	0.030
Large *M. paradoxus*									
Pelagic demersals					=	0.110	0.055	=	0.090
Benthic demersals									
Pelagic chond.									
Benthic chond.									
Apex chond.									
Seals									
Cetaceans									
Seabirds									
Meiobenthos									
Macrobenthos								=	0.030
Detritus									
Import								=	0.050

Appendix Table 7.5 continued...

Prey \ Predator	Cephalopods			Small *M. capensis*		Large *M. capensis*		Small *M. paradoxus*	
	1980	04-08	04-08 diet test	1980	04-08	1980	04-08	1980	04-08
Phytoplankton									
Benthic producers									
Microzooplankton									
Mesozooplankton									
Macrozooplankton	=	0.270	0.270	=	0.720	=	0.100	=	0.780
Gelatinous zoopl.									
Anchovy	↑	0.049	0.141	↓	0.034	↑	0.107	↓	0.034
Sardine	↓	0.023	0.067	↓	0.016	↓	0.050	↓	0.016
Redeye	↑	0.028	0.082	↑	0.020	↑	0.062	↑	0.020
Other small pelagics						=	0.010	↑	0.000
Chub mackerel						=	0.020		
Juvenile horse mack.						=	0.030		
Adult horse mack.						=	0.160		
Mesopelagics	=	0.100	0.100	=	0.080	=	0.100	=	0.080
Snoek						↑	0.000		
Other large pelagics									
Cephalopods	=	0.050	0.050	=	0.050	=	0.050	=	0.010
Small *M. capensis*	=	0.020	0.020			↑	0.110		
Large *M. capensis*						↓	0.040		
Small *M. paradoxus*	=	0.080	0.080	=	0.020	=	0.150		
Large *M. paradoxus*									
Pelagic demersals				=	0.050	↑	0.005	=	0.050
Benthic demersals				=	0.010	↑	0.005	=	0.010
Pelagic chond.									
Benthic chond.									
Apex chond.									
Seals									
Cetaceans									
Seabirds									
Meiobenthos									
Macrobenthos	=	0.380	0.190						
Detritus									
Import									

Appendix Table 7.5 continued...

Prey \ Predator	Large *M. paradoxus*		Pelagic demersals		Benthic demersals		Pelagic chond.	
	1980	04-08	1980	04-08	1980	04-08	1980	04-08
Phytoplankton								
Benthic producers								
Microzooplankton								
Mesozooplankton			=	0.010	=	0.010		
Macrozooplankton	=	0.210	=	0.650	=	0.050		
Gelatinous zoopl.								
Anchovy	↑	0.005	↓	0.056	↓	0.025	↓	0.039
Sardine	↓	0.002	↓	0.026			↓	0.018
Redeye	↓	0.003	↑	0.032	↑	0.015	↑	0.023
Other small pelagics	=	0.020					=	0.020
Chub mackerel							=	0.010
Juvenile horse mack.								
Adult horse mack.							=	0.090
Mesopelagics	=	0.360	=	0.150	=	0.050	=	0.250
Snoek	↓	0.010					=	0.010
Other large pelagics							=	0.010
Cephalopods	=	0.100	=	0.020	=	0.020	=	0.200
Small *M. capensis*			↑	0.000	↑	0.000		
Large *M. capensis*					↑	0.000	=	0.040
Small *M. paradoxus*	=	0.150	=	0.020	↑	0.000		
Large *M. paradoxus*	=	0.020			↑	0.000	=	0.050
Pelagic demersals	=	0.030	↑	0.028	=	0.020	↑	0.045
Benthic demersals	=	0.090	↑	0.008	=	0.020	↑	0.095
Pelagic chond.							=	0.100
Benthic chond.					=	0.010		
Apex chond.								
Seals								
Cetaceans								
Seabirds								
Meiobenthos								
Macrobenthos					=	0.780		
Detritus								
Import								

Appendix Table 7.5 continued...

Prey \ Predator	Benthic chond.		Apex chond.		Seals		Cetaceans	
	1980	04-08	1980	04-08	1980	04-08	1980	04-08
Phytoplankton								
Benthic producers								
Microzooplankton								
Mesozooplankton							=	0.030
Macrozooplankton							=	0.040
Gelatinous zoopl.								
Anchovy					↑	0.138	↑	0.195
Sardine					↓	0.065	↓	0.092
Redeye					↓	0.080	↓	0.113
Other small pelagics					↑	0.000	=	0.020
Chub mackerel					=	0.010		
Juvenile horse mack.					=	0.010		
Adult horse mack.	=	0.010	=	0.030	=	0.020	=	0.270
Mesopelagics	=	0.010			=	0.010	=	0.040
Snoek			=	0.070	=	0.020		
Other large pelagics			=	0.010	↓	0.001		
Cephalopods	=	0.070			=	0.230	=	0.160
Small *M. capensis*					=	0.100	=	0.010
Large *M. capensis*	=	0.010			=	0.020	↑	0.005
Small *M. paradoxus*					=	0.100	=	0.020
Large *M. paradoxus*					=	0.020	↑	0.005
Pelagic demersals	=	0.050	↑	0.005	↑	0.028		
Benthic demersals	=	0.200	↑	0.005	↑	0.077		
Pelagic chond.			=	0.100				
Benthic chond.	=	0.050	=	0.430				
Apex chond.								
Seals			=	0.200				
Cetaceans			=	0.150				
Seabirds								
Meiobenthos								
Macrobenthos	=	0.600			=	0.070		
Detritus								
Import								

Appendix Table 7.5 continued...

Prey \ Predator	Seabirds		Meiobenthos		Macrobenthos	
	1980	04-08	1980	04-08	1980	04-08
Phytoplankton						
Benthic producers			=	0.050	=	0.05
Microzooplankton						
Mesozooplankton	↑	0.009				
Macrozooplankton	↑	0.096				
Gelatinous zoopl.						
Anchovy	↑	0.306				
Sardine	↓	0.144				
Redeye	↑	0.019				
Other small pelagics	=	0.060				
Chub mackerel	=	0.004				
Juvenile horse mack.	↑	0.008				
Adult horse mack.						
Mesopelagics	↓	0.103				
Snoek	↑	0.002				
Other large pelagics						
Cephalopods	↑	0.065				
Small *M. capensis*	=	0.040				
Large *M. capensis*						
Small *M. paradoxus*	=	0.131				
Large *M. paradoxus*						
Pelagic demersals	↑	0.007				
Benthic demersals						
Pelagic chond.						
Benthic chond.						
Apex chond.						
Seals	=	0.004				
Cetaceans						
Seabirds	=	0.002				
Meiobenthos					=	0.080
Macrobenthos					=	0.070
Detritus			=	0.950	=	0.800
Import						

Appendix Table 7.6: Trophic indicator values calculated for the southern Benguela ecosystem over the time periods 1900, 1960, 1980 and 2004-2008. The percentage (%) change* in an indicator value from the pristine (1900) to the current (2004-2008) period is also included, with a plus (+) indicating an increase and a minus (-) a decrease. Total Fin Fish = Pelagic-caught & Demersal-caught Fish; Pelagic-caught Fish (PEL) = anchovy, sardine, redeye (ASR), other small pelagic fish, juvenile horse mackerel, mesopelagic fish, chub mackerel, all large pelagic fish (snoek & other large pelagic fish); Demersal-caught Fish (DEM) = all hake (small & large *M. capensis*, small & large *M. paradoxus*), pelagic- & benthic-feeding demersal fish, adult horse mackerel; Small Fish (SMF) = ASR, other small pelagic fish, juvenile horse mackerel, small hake; Large Fish (LAF) = large hake, all large pelagic fish; Planktivorous Fish (PLA) = ASR, other small pelagic fish, all horse mackerel, mesopelagic fish, small hake; Piscivorous Fish (PIS) = chub mackerel, large hake, all large pelagic fish, pelagic- & benthic-feeding demersal fish; Prop. of pred. fish = Proportion of predatory fish; Pelagic Fish Predators (PFP) = seabirds, seals, cetaceans, all large pelagic fish, large hake, chub mackerel; Chondrichthyans = apex, pelagic- & benthic-feeding chondrichthyans; Total Fishery = fin fish, cephalopods & chondrichthyans caught.

	Trophic Indicator	**1900**	**1960**	**1980**	**2004-2008**	**% change**
Biomass (B) ($t.km^{-2}$)	Total System B (excl. detritus)	219.6	182.7	221.3	269.3	+10
	Total Fin Fish B	41.4	34.9	33.6	47.1	+6
	Total PEL B	26.8	25.6	21.2	33.9	+12
	Total DEM B	14.6	9.3	12.4	13.2	-5
	Total SMF B	18.1	19.5	14.2	26.6	+19
	Total LAF B	4.7	2.7	1.9	2.0	-40
	Total PLA B	30.6	29.2	24.5	36.8	+9
	Total PIS B	10.7	5.7	9.1	10.3	-2
	B PEL/DEM	1.83	2.74	1.71	2.57	+17
	B SMF/LAF	3.88	7.19	7.57	13.35	+55
	B PLA/PIS	2.86	5.08	2.68	3.57	+11
	Prop. of pred. fish	0.25	0.16	0.26	0.21	-9
	Total PFP B	5.2	5.0	2.4	2.4	-38
	Total Chondrichthyan B	1.3	0.6	1.5	1.4	+6

* The % change for catch-based indicators is calculated from the first harvest period modelled (1960) to the current period (2004-2008).

Appendix Table 7.6 continued...

	Trophic Indicator	1900	1960	1980	2004-2008	% change
Production (P) (t.km^{-2}.yr^{-1})	Total System P	138115.5	13325.7	16235.5	20118.1	+18
	Total Fin Fish P	50.9	42.9	39.4	55.6	+4
	Total PEL P	34.0	30.6	25.0	40.3	+8
	Total DEM P	16.9	12.3	14.4	15.3	-5
	Total SMF P	27.5	26.5	18.8	33.8	+10
	Total LAF P	3.7	2.1	1.4	1.5	-42
	Total PLA P	43.0	38.7	30.8	45.8	+3
	Total PIS P	7.9	4.2	8.6	9.8	+10
	P PEL/DEM	2.00	2.49	1.74	2.63	+14
	P SMF/LAF	7.50	12.75	13.56	22.86	+51
	P PLA/PIS	5.42	9.15	3.58	4.69	-7
	Total PFP P	3.9	2.6	1.8	1.8	-38
Consumption (Q) (t.km^{-2}.yr^{-1})	Q by PEL Predators	343.6	309.3	252.4	408.6	+9
	Q by DEM Predators	102.9	77.2	88.4	90.5	-6
	Q of PEL Prey	32.2	28.8	22.5	27.1	-9
	Q of DEM Prey	13.7	11.0	13.0	13.5	-1
	Q by PLA Predators	402.5	362.0	294.7	447.4	+5
	Q by PIS Predators	43.9	24.6	46.1	51.7	+8
	Q of PLA Prey	40.8	36.6	27.8	32.3	-12
	Q of PIS Prey	5.1	3.2	7.7	8.4	+24
	Q by PEL Predators/DEM Predators	3.34	4.01	2.85	4.52	+15
	Q of PEL Prey/DEM Prey	2.36	2.62	1.72	2.00	-8
	Q by PLA Predators/PIS Predators	9.16	14.73	6.39	8.65	-3
	Q of PLA Prey/PIS Prey	8.01	11.41	3.60	3.84	-35
Catch (Y) (t.km^{-2}.yr^{-1})	Total System Y	0.0	3.0	3.0	3.5	*+8
	Total Fin Fish Y	0.0	2.6	3.0	3.5	*+12
	Total PEL Y	0.0	1.6	2.1	2.6	*+25
	Total DEM Y	0	1.2	0.9	0.9	*-14
	Total SMF Y	0	1.5	2.1	2.6	*+27
	Total LAF Y	0.0	0.8	0.6	0.7	*-8
	Total PLA Y	0	1.8	2.3	2.7	*+21
	Total PIS Y	0.0	1.0	0.7	0.8	*-12
	Y PEL/DEM	0	1.31	2.34	2.92	*+38
	Y SMF/LAF	0	1.84	3.66	3.78	*+34
	Y PLA/PIS	0	1.78	3.15	3.51	*+33
	Total Chondrichthyan Y	0	0.00	0.01	0.01	*+80

* The % change for catch-based indicators is calculated from the first harvest period modelled (1960) to the current period (2004-2008).

Appendix Table 7.6 continued...

	Trophic Indicator	1900	1960	1980	2004-2008	% change
Trophic Level (TL)	Mean TL of the Y	4.5	3.6	3.7	3.6	-12
	System TL	3.8	3.7	3.7	3.6	-2
	PEL TL	3.6	3.5	3.6	3.5	-2
	DEM TL	4.0	4.0	3.9	3.8	-3
	PIS TL	4.1	4.1	3.9	3.8	-3
	PLA TL	3.7	3.5	3.6	3.5	-2
	PFP TL	4.6	4.4	4.5	4.5	-1
Turnover Rate (P/B) (yr^{-1})	Total Primary P/Total B	54.47	64.87	54.12	52.77	-2
	Total Fin Fish P/Total Fin Fish B	1.23	1.23	1.17	1.18	-2
	Total PEL P/Total PEL B	1.27	1.20	1.18	1.19	-3
	Total DEM P/Total DEM B	1.16	1.32	1.16	1.16	0
	Total SMF P/ Total SMF B	1.51	1.36	1.32	1.27	-9
	Total LAF P/ Total LAF B	0.78	0.76	0.74	0.74	-3
	Total PLA P/ Total PLA B	1.40	1.33	1.26	1.24	-6
	Total PIS P/Total PIS B	0.74	0.74	0.94	0.95	+12
Catch: Production (Y/P)	Total Fishery Y/Total Fishery P	0.00	0.06	0.07	0.06	*-5
	Total Fin Fish Y/Total Fin Fish P	0.00	0.06	0.08	0.06	*-1
	PEL Y/PEL P	0.00	0.05	0.08	0.06	*+12
	DEM Y/DEM P	0	0.10	0.06	0.06	*-25
	SMF Y/SMF P	0	0.06	0.11	0.08	*+16
	LAF Y/LAF P	0.00	0.38	0.41	0.46	*+9
	PLA Y/PLA P	0	0.04	0.07	0.06	*+13
	PIS Y/PIS P	0.00	0.23	0.08	0.08	*-49
Catch: Biomass (Y/B) (yr^{-1})	Total Fishery Y/Total Fishery B	0.00	0.07	0.08	0.07	*-3
	Total Fin Fish Y/Total Fin Fish B	0.00	0.08	0.09	0.07	*-3
	PEL Y/PEL B	0.00	0.06	0.10	0.08	*+11
	DEM Y/DEM B	0	0.13	0.07	0.07	*-31
	SMF Y/SMF B	0	0.08	0.15	0.10	*+12
	LAF Y/LAF B	0.00	0.30	0.30	0.34	*+7
	PLA Y/PLA B	0	0.06	0.09	0.07	*+10
	PIS Y/PIS B	0.00	0.17	0.08	0.08	*-39
System Indices	Finn's mean path length	2.5	2.4	3.2	3.4	+14
	System Y/System B (excl. detritus) (yr^{-1})	0.00	0.02	0.01	0.01	*-11
	Prop. of r-strategists (B/P) (yr)	0.02	0.02	0.02	0.02	+2

* The % change for catch-based indicators is calculated from the first harvest period modelled (1960) to the current period (2004-2008).

Appendix 7.7: Pelagic-caught fish (PEL) community decision tree source code for the Windows Expert (WinExp) expert system.

Trophic model-generated indicators of the southern Benguela ecosystem for communicating with fisheries managers

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Pelagic-caught fish (PEL) Community Decision Tree
An expert system intended for use by fisheries managers and stakeholders to assess the trend displayed by the Pelagic-caught fish (PEL) community within the southern Benguela ecosystem between two time periods. Fish included in the PEL community are anchovy, sardine, redeye, other small pelagic fish, juvenile horse mackerel, chub mackerel, mesopelagic fish, all large pelagic fish (snoek and other large pelagic fish), and are caught within the pelagic fishery (purse-seine, line-fishery, long line and other fishing sectors). There are three PEL community decisions available: 1 – Improving, 2 – Not Improving or 3 – Deteriorating. The decisions are based on two community indicators: PEL biomass and PEL Y/PEL B (catch per biomass). The indicators are examined to determine whether they display one of three trends: Increase, Same or Decrease. Indicator trends are verified using a 5% limit, i.e. <5% change between the two time periods is classified as the same, whereas a ≥5% change between two time periods is classified as an increasing/decreasing trend.
The PEL Community decision tree is the first step in the 3-step process towards assessing the overall trend of the southern Benguela ecosystem. The decision tree assesses the PEL community in terms of the bigger picture, i.e. overall functioning of the community and is intended as a complement to the single species assessments conducted.

Questions:
Question 1: What trend does PEL B display?
Explanation: Biomass (B) is a reflection of the resource potential of the Pelagic-caught fish (PEL) community within the ecosystem. The higher the biomass, the bigger the buffer the community will be afforded in times of adverse conditions (environmental or other).
Answers: 1- Increasing 2- Same 3- Decreasing

Question 2: What trend does PEL Y/PEL B display?
Explanation: Catch per biomass (Y/B) is a reflection of the fishing pressure on the Pelagic-caught fish (PEL) community within the ecosystem. A sustainable fishing pressure is one which can be maintained by the community.
Answers: 1- Increasing 2- Same 3- Decreasing

Rules:
Rule 1: q1a1 and q2a1
Decision: 2
Explanation: The Pelagic-caught fish (PEL) community can sustain the current fishing pressure. Be aware of possible changing environmental conditions or fishing practices that could negatively affect the PEL community.

Rule 2: q1a1 and (q2a2 or q2a3)
Decision: 1
Explanation: The Pelagic-caught fish (PEL) community biomass is increasing and the PEL community can sustain the current fishing pressure. Be aware of possible changing environmental conditions or fishing practices that could negatively affect the PEL community.

Rule 3: q1a2 and (q2a1 or q2a2 or q2a3)
Decision: 2
Explanation: The Pelagic-caught fish (PEL) community can sustain the current fishing pressure. Be aware of possible changing environmental conditions or fishing practices that could negatively affect the PEL community.

Rule 4: q1a3 and (q2a1 or q2a2)
Decision: 3
Explanation: The current fishing pressure is too high to be sustained by the Pelagic-caught fish (PEL) community.

Rule 5: q1a3 and q2a3
Decision: 2
Explanation: The Pelagic-caught fish (PEL) community can sustain the current fishing pressure. Be aware of possible changing environmental conditions or fishing practices that could negatively affect the PEL community.

Appendix 7.8: Demersal-caught fish (DEM) community decision tree source code for the Windows Expert (WinExp) expert system.

Trophic model-generated indicators of the southern Benguela ecosystem for communicating with fisheries managers

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Demersal-caught fish (DEM) Community Decision Tree

An expert system intended for use by fisheries managers and stakeholders to assess the trend displayed by the Demersal-caught fish (DEM) community within the southern Benguela ecosystem between two time periods. Fish included in the DEM community are adult horse mackerel, all hake (small & large *M. capensis*, small & large *M. paradoxus*), pelagic- and benthic-feeding demersal fish, and are caught within the demersal fishery (midwater trawl, demersal trawl, long line and other fishing sectors). Although midwater trawl is a pelagic fishing gear, it has been included in the demersal fishery classification because it targets adult horse mackerel, which are also caught within the demersal trawl fishery.

There are three DEM community decisions available: 1 – Improving, 2 – Not Improving or 3 – Deteriorating. The decisions are based on two community indicators: DEM biomass and DEM Y/DEM B (catch per biomass). The indicators are examined to determine whether they display one of three trends: Increase, Same or Decrease. Indicator trends are verified using a 5% limit, i.e. <5% change between the two time periods is classified as the same, whereas a ≥5% change between two time periods is classified as an increasing/decreasing trend.

The DEM Community decision tree is the second step in the 3-step process towards assessing the overall trend of the southern Benguela ecosystem. The decision tree assesses the DEM community in terms of the bigger picture, i.e. overall functioning of the community and is intended as a complement to the single species assessments conducted.

<ins>Questions:</ins>

Question 1: What trend does DEM B display?

Explanation: Biomass (B) is a reflection of the resource potential of the Demersal-caught fish (DEM) community within the ecosystem. The higher the biomass, the bigger the buffer the community will be afforded in times of adverse conditions (environmental or other).

Answers: 1- Increasing 2- Same 3- Decreasing

Question 2: What trend does DEM Y/DEM B display?

Explanation: Catch per biomass (Y/B) is a reflection of the fishing pressure on the Demersal-caught fish (DEM) community within the ecosystem. A sustainable fishing pressure is one which can be maintained by the community.

Answers: 1- Increasing 2- Same 3- Decreasing

Rules:
Rule 1: q1a1 and q2a1
Decision: 2
Explanation: The Demersal-caught fish (DEM) community can sustain the current fishing pressure. Be aware of possible changing environmental conditions or fishing practices that could negatively affect the DEM community.

Rule 2: q1a1 and (q2a2 or q2a3)
Decision: 1
Explanation: The Demersal-caught fish (DEM) community biomass is increasing and the DEM community can sustain the current fishing pressure. Be aware of possible changing environmental conditions or fishing practices that could negatively affect the DEM community.

Rule 3: q1a2 and (q2a1 or q2a2 or q2a3)
Decision: 2
Explanation: The Demersal-caught fish (DEM) community can sustain the current fishing pressure. Be aware of possible changing environmental conditions or fishing practices that could negatively affect the DEM community.

Rule 4: q1a3 and (q2a1 or q2a2)
Decision: 3
Explanation: The current fishing pressure is too high to be sustained by the Demersal-caught fish (DEM) community.

Rule 5: q1a3 and q2a3
Decision: 2
Explanation: The Demersal-caught fish (DEM) community can sustain the current fishing pressure. Be aware of possible changing environmental conditions or fishing practices that could negatively affect the DEM community.

Appendix 7.9: Southern Benguela ecosystem decision tree source code for the Windows Expert (WinExp) expert system.

Trophic model-generated indicators of the southern Benguela ecosystem for communicating with fisheries managers

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Southern Benguela Ecosystem Decision Tree

An expert system intended for use by fisheries managers and stakeholders to determine the overall trend displayed by the southern Benguela ecosystem between two time periods. The southern Benguela ecosystem decision tree is the final step in the 3-step process, which first involved an assessment of the Pelagic-caught fish (PEL) community using the PEL community decision tree (step 1), and an assessment of the Demersal-caught fish (DEM) community using the DEM community decision tree (step 2).

There are four ecosystem decisions available: 1 – Improving, 2 – Not Improving, 3 – Deteriorating or 4 – Can’t Say. The decisions are based upon the PEL and DEM community assessments (Improving, Not Improving or Deteriorating) and a combination of five indicators. The indicators are:

Indicator 1: Proportion of predatory fish (Prop. of pred. fish)
- captures biomass trends regarding predatory fish within the ecosystem

Indicator 2: DEM Trophic Level (TL)
- clarifies trophic positioning of the DEM community

Indicator 3: Biomass ratio of small: large fish (B SMF/LAF)
- captures biomass trends regarding size structure of the fish community within the ecosystem
- small fish = anchovy, sardine, redeye, other small pelagic fish, juvenile horse mackerel, small hake (*M. capensis* and *M. paradoxus*)
- large fish = all large pelagic fish (snoek and other large pelagic fish), large hake (*M. capensis* and *M. paradoxus*)

Indicator 4: Pelagic Predator Fish Biomass (PFP B)
- captures biomass trends regarding pelagic fish predators

Indicator 5: System Trophic Level (TL)
- captures possible "fishing down the food web" effects

The indicators and motivation for their use are explained in further detail within Chapter 3: Trophic Model-Generated Indicators of the Southern Benguela Ecosystem of the thesis.

The indicators are examined to determine whether they display one of three trends: Increase, Same or Decrease. Indicator trends are verified using a 5% limit, i.e. <5% change between the two time periods is classified as the same, whereas a ≥5% change between two time periods is classified as an increasing/decreasing trend.

The decision tree assesses the southern Benguela ecosystem from a system perspective, i.e. overall functioning of the ecosystem and is intended as a complement to the single species assessments conducted.

<u>Questions:</u>
Question 1: What trend does the PEL community display?
Explanation: The Pelagic-caught fish (PEL) community is an important component of the southern Benguela ecosystem. An optimally functioning ecosystem has all components in good, working order.
Answers: 1- Improving 2- Not Improving 3- Deteriorating

Question 2: What trend does the DEM community display?
Explanation: The Demersal-caught fish (DEM) community is an important component of the southern Benguela ecosystem. An optimally functioning ecosystem has all components in good, working order.
Answers: 1- Improving 2- Not Improving 3- Deteriorating

Question 3: What trend does Prop. of pred. fish display?
Explanation: The proportion of predatory fish (Prop. of pred. fish) indicator is a measure of whether predatory fish are being sustained within the southern Benguela ecosystem. More predatory fish is indicative of an optimally functioning ecosystem.
Answers: 1- Increasing 2- Same 3- Decreasing

Question 4: What trend does DEM TL display?
Explanation: Demersal-caught fish (DEM) Trophic Level (TL) describes the trophic position of the DEM community within the southern Benguela ecosystem. Changes in the TL may be attributed to fishing pressures acting upon the DEM community within the ecosystem, i.e. a decrease could be a result of more intense fishing of the larger demersal fish.
Answers: 1- Increasing 2- Same 3- Decreasing

Question 5: What trend does B SMF/LAF display?
Explanation: The biomass ratio of small: large fish (B SMF/LAF) provides information about the size structure of the fish community within the southern Benguela ecosystem. More large fish is indicative of an optimally functioning ecosystem, whereas more small fish is indicative of either removal of the large fish through fishing (bad for ecosystem functioning) or good recruitment (good for ecosystem functioning on the condition that the recruits will grow into adults).
Answers: 1- Increasing 2- Same 3- Decreasing

Question 6: What trend does PFP B display?
Explanation: Pelagic fish predator biomass (PFP B) captures information about the top pelagic fish predators within the southern Benguela ecosystem. An optimally functioning ecosystem contains representatives at all levels of the food web, i.e. producers, consumers, secondary consumers and top predators.
Answers: 1- Increasing 2- Same 3- Decreasing

Question 7: What trend does System TL display?
Explanation: System trophic level (TL) collectively describes the trophic position of all fish, cephalopods and mammals within the southern Benguela ecosystem food web. Changes in the TL may be attributed to external pressures acting upon the ecosystem food web, in particular fishing down the food web.
Answers: 1- Increasing 2- Same 3- Decreasing

<u>Rules:</u>
Rule 1: q1a1 and q2a1
Decision: 1
Explanation: The Pelagic-caught fish (PEL) and Demersal-caught fish (DEM) communities within the ecosystem are both improving. The overall conclusion reached is that the southern Benguela ecosystem is Improving.

Rule 2: q1a1 and q2a2 and q3a1 and q4a1
Decision: 1
Explanation: The Pelagic-caught fish (PEL) community is improving, whilst the Demersal-caught fish (DEM) community is not improving. A detailed examination of the fish community was conducted using the indicators, Proportion of predatory fish (Prop. of pred. fish) and DEM Trophic Level (TL).
Both Prop. of pred. fish and DEM TL displayed increasing trends, indicating that there are more predatory fish within the ecosystem and they are not negatively affected by fishing.
The overall conclusion reached is that the southern Benguela ecosystem is Improving.
Be aware of possible changing environmental conditions or fishing practices that could negatively affect the fish community and ecosystem.

Rule 3: q1a1 and q2a2 and q3a1 and q4a2
Decision: 4
Explanation: The Pelagic-caught fish (PEL) community is improving, whilst the Demersal-caught fish (DEM) community is not improving. A detailed examination of the fish community was conducted using the indicators, Proportion of predatory fish (Prop. of pred. fish) and DEM Trophic Level (TL).
Prop. of pred. fish was increasing, indicating more predatory fish within the ecosystem, but DEM TL was the same, indicating that fishing is likely to be acting upon the ecosystem, negatively affecting the DEM community.
However, the net effect within the ecosystem cannot be clarified, i.e. cannot decide between an Improving or Not Improving trend. The components within the DEM community require further examination.

Rule 4: q1a1 and q2a2 and ((q3a1 and q4a3) or (q3a2 and q4a3))
Decision: 2
Explanation: The Pelagic-caught fish (PEL) community is improving, whilst the Demersal-caught fish (DEM) community is not improving. A detailed examination of the fish community was conducted using the indicators, Proportion of predatory fish (Prop. of pred. fish) and DEM Trophic Level (TL).
Prop. of pred. fish was increasing/the same indicating more/presence of predatory fish within the ecosystem, but DEM TL was decreasing indicating that the fishing pressures acting upon the ecosystem are negatively affecting the DEM community.
The overall conclusion reached is that the southern Benguela ecosystem is Not Improving.
Be aware of possible changing environmental conditions or fishing practices that could negatively affect the fish community and ecosystem.

Rule 5: q1a1 and q2a2 and q3a2 and (q4a1 or q4a2)
Decision: 4
Explanation: The Pelagic-caught fish (PEL) community is improving, whilst the Demersal-caught fish (DEM) community is not improving. A detailed examination of the fish community was conducted using the indicators, Proportion of predatory fish (Prop. of pred. fish) and DEM Trophic Level (TL).
Prop. of pred. fish was the same, indicating predatory fish are present within the ecosystem.
DEM TL was increasing/the same, indicating that fishing is unlikely to be negatively affecting the DEM community.
The additional indicators examined do not clarify between a Not Improving or Deteriorating ecosystem trend. The components within the DEM community require further examination.

Rule 6: q1a1 and q2a2 and q3a3 and (q4a1 or q4a2)
Decision: 2
Explanation: The Pelagic-caught fish (PEL) community is improving, whilst the Demersal-caught fish (DEM) community is not improving. A detailed examination of the fish community was conducted using the indicators, Proportion of predatory fish (Prop. of pred. fish) and DEM Trophic Level (TL).
Prop. of pred. fish was decreasing, indicating fewer predatory fish within the ecosystem, but DEM TL was increasing/the same indicating that the pressures acting upon the ecosystem, i.e. fishing, are not negatively affecting the DEM community.
The overall conclusion reached is that the southern Benguela ecosystem is Not Improving.
Be aware of possible changing environmental conditions or fishing practices that could negatively affect the fish community and ecosystem.

Rule 7: q1a1 and q2a2 and q3a3 and q4a3
Decision: 3
Explanation: The Pelagic-caught fish (PEL) community is improving, whilst the Demersal-caught fish (DEM) community is not improving. A detailed examination of the fish community was conducted using the indicators, Proportion of predatory fish (Prop. of pred. fish) and DEM Trophic Level (TL).
Both Prop. of pred. fish and DEM TL displayed decreasing trends, indicating that there are fewer predatory fish within the ecosystem and within the DEM community.
The overall conclusion reached is that the southern Benguela ecosystem is Deteriorating.

Rule 8: q1a1 and q2a3 and ((q3a1 and q4a1) or (q3a2 and q4a1))
Decision: 2
Explanation: The Pelagic-caught fish (PEL) community is improving, whilst the Demersal-caught fish (DEM) community is deteriorating. A detailed examination of the fish community was conducted using the indicators, Proportion of predatory fish (Prop. of pred. fish) and DEM Trophic Level (TL).
Both Prop. of pred. fish and DEM TL displayed increasing trends, indicating that there are more predatory fish within the ecosystem and they are not negatively affected by ecosystem pressures, i.e. fishing.
<u>OR</u>
Prop. of pred. fish was the same and DEM TL increased, indicating that there are predatory fish within the ecosystem and they are not negatively affected by ecosystem pressures, i.e. fishing.
However, in both cases, the DEM community is still not in good shape.
The overall conclusion reached is that the southern Benguela ecosystem is Not Improving.
Be aware of possible changing environmental conditions or fishing practices that could negatively affect the fish community and ecosystem.

Rule 9: q1a1 and q2a3 and q3a1 and q4a2
Decision: 4
Explanation: The Pelagic-caught fish (PEL) community is improving, whilst the Demersal-caught fish (DEM) community is deteriorating. A detailed examination of the fish community was conducted using the indicators, Proportion of predatory fish (Prop. of pred. fish) and DEM Trophic Level (TL).
Prop. of pred. fish was increasing indicating more predatory fish within the ecosystem. However, DEM TL was the same, indicating that fishing is likely to be acting upon the ecosystem, negatively affecting the DEM community.
The net effect within the ecosystem cannot be clarified, i.e. cannot decide between a Not Improving or Deteriorating trend. Components within the DEM community require further examination.

Rule 10: q1a1 and q2a3 and ((q3a1 and q4a3) or (q3a2 and q4a3))
Decision: 3
Explanation: The Pelagic-caught fish (PEL) community is improving, whilst the Demersal-caught fish (DEM) community is deteriorating. A detailed examination of the fish community was conducted using the indicators, Proportion of predatory fish (Prop. of pred. fish) and DEM Trophic Level (TL).
Prop. of pred. fish was increasing, indicating more predatory fish within the ecosystem, but DEM TL was decreasing, indicating that fishing is negatively affecting the DEM community.
<u>OR</u>
Prop. of pred. fish was the same, indicating the presence of predatory fish within the ecosystem. However, DEM TL was decreasing, indicating that fishing is acting upon the ecosystem, negatively affecting the DEM community.
In both cases, the DEM community is in bad shape.
The overall conclusion reached is that the southern Benguela ecosystem is Deteriorating.

Rule 11: q1a1 and q2a3 and q3a2 and q4a2
Decision: 4
Explanation: The Pelagic-caught fish (PEL) community is improving, whilst the Demersal-caught fish (DEM) community is deteriorating. A detailed examination of the fish community was conducted using the indicators, Proportion of predatory fish (Prop. of pred. fish) and DEM Trophic Level (TL).
Both Prop. of pred. fish and DEM TL was the same, indicating the presence of predatory fish within the ecosystem and that fishing is likely to be acting upon the ecosystem, negatively affecting the DEM community.
However, no ecosystem trend is apparent from the additional indicators examined, so no clarification can be made between the Not Improving or Deteriorating ecosystem trends. A detailed examination of the components within the DEM community will be required.

Rule 12: q1a1 and q2a3 and q3a3
Decision: 3
Explanation: The Pelagic-caught fish (PEL) community is improving, whilst the Demersal-caught fish (DEM) community is deteriorating. A detailed examination of the fish community was conducted using the indicator Proportion of predatory fish (Prop. of pred. fish).
Prop. of pred. fish was decreasing, indicating that there are fewer predatory fish within the ecosystem.
The overall conclusion reached is that the southern Benguela ecosystem is Deteriorating.
Be aware of possible changing environmental conditions or fishing practices that could negatively affect the fish community and ecosystem.

Rule 13: q1a2 and q2a1 and q5a1 and (q6a1 or q6a2)
Decision: 2
Explanation: The Pelagic-caught fish (PEL) community is not improving whilst the Demersal-caught fish (DEM) community is improving. A detailed examination of the fish community was conducted using the indicators, Biomass ratio of small: large fish (B SMF/LAF) and Pelagic Fish Predator Biomass (PFP B).
B SMF/LAF was increasing, indicating good recruitment of small fish within the ecosystem.
PFP B was increasing/the same, indicating that there are more/sufficient large pelagic fish predators within the ecosystem.
The overall conclusion reached is that the southern Benguela ecosystem is Not Improving.
Be aware of possible changing environmental conditions or fishing practices that could negatively affect the fish community and ecosystem.

Rule 14: q1a2 and q2a1 and q5a1 and q6a3
Decision: 3
Explanation: The Pelagic-caught fish (PEL) community is not improving whilst the Demersal-caught fish (DEM) community is improving. A detailed examination of the fish community was conducted using the indicators, Biomass ratio of small: large fish (B SMF/LAF) and Pelagic Fish Predator Biomass (PFP B).
B SMF/LAF was increasing, indicating the presence of more small fish within the ecosystem, but PFP B was decreasing, indicating that the ecosystem is lacking large pelagic fish predators.
The overall conclusion reached is that the southern Benguela ecosystem is Deteriorating.

Rule 15: q1a2 and q2a1 and (q5a2 or q5a3)
Decision: 2
Explanation: The Pelagic-caught fish (PEL) community is not improving whilst the Demersal-caught fish (DEM) community is improving. A detailed examination of the size structure of the fish communities was conducted using the indicator Biomass ratio of small: large fish (B SMF/LAF).
B SMF/LAF was the same/decreasing indicating that although the PEL community is not in good shape, the overall size structure of fish within the ecosystem is reasonable, i.e. sufficient large fish to ensure an optimally functioning ecosystem.
The overall conclusion reached is that the southern Benguela ecosystem is Not Improving.
Be aware of possible changing environmental conditions or fishing practices that could negatively affect the fish community and ecosystem.

Rule 16: q1a2 and q2a2
Decision: 2
Explanation: The Pelagic-caught fish (PEL) and Demersal-caught fish (DEM) communities within the ecosystem are both not improving. The overall conclusion reached is that the southern Benguela ecosystem is Not Improving.
Be aware of possible changing environmental conditions or fishing practices that could negatively affect the fish community and ecosystem.

Rule 17: q1a2 and q2a3 and ((q3a1 and q6a1) or (q3a2 and q6a1))
Decision: 2
Explanation: The Pelagic-caught fish (PEL) community is not improving, whilst the Demersal-caught fish (DEM) community is deteriorating. A detailed examination of the fish community was conducted using the indicators, Proportion of predatory fish (Prop. of pred. fish) and Pelagic Fish Predator Biomass (PFP B).
Prop. of pred. fish was increasing/the same and PFP B was increasing, indicating that there are more large pelagic and more/some demersal predatory fish within the ecosystem.
The overall conclusion reached is that the southern Benguela ecosystem is Not Improving.
Be aware of possible changing environmental conditions or fishing practices that could negatively affect the fish community and ecosystem.

Rule 18: q1a2 and q2a3 and q3a1 and q6a2
Decision: 4
Explanation: The Pelagic-caught fish (PEL) community is not improving, whilst the Demersal-caught fish (DEM) community is deteriorating. A detailed examination of the fish community was conducted using a combination of the indicators, Proportion of predatory fish (Prop. of pred. fish) and Pelagic Fish Predator Biomass (PFP B).
Prop. of pred. fish was increasing, indicating more predatory fish within the ecosystem, and PFP B was the same, indicating the presence of pelagic predators within the ecosystem.
The net effect within the ecosystem cannot be clarified, i.e. cannot decide between a Not Improving or Deteriorating trend. Components within the fish community require further examination.

Rule 19: q1a2 and q2a3 and ((q3a1 and q6a3) or (q3a2 and q6a3))
Decision: 3
Explanation: The Pelagic-caught fish (PEL) community is not improving, whilst the Demersal-caught fish (DEM) community is deteriorating. A detailed examination of the fish community was conducted using a combination of the indicators, Proportion of predatory fish (Prop. of pred. fish) and Pelagic Fish Predator Biomass (PFP B).
Prop. of pred. fish was increasing/the same, indicating more/presence of predatory fish within the ecosystem. However, PFP B was decreasing, indicating that although there are predatory fish within the ecosystem, the system falls short on pelagic fish predators.
The overall conclusion reached is that the southern Benguela ecosystem is Deteriorating.

Rule 20: q1a2 and q2a3 and q3a2 and q6a2
Decision: 4
Explanation: The Pelagic-caught fish (PEL) community is not improving, whilst the Demersal-caught fish (DEM) community is deteriorating. A detailed examination of the fish community was conducted using a combination of the indicators, Proportion of predatory fish (Prop. of pred. fish) and Pelagic Fish Predator Biomass (PFP B).
Both Prop. of pred. fish and PFP B was the same, indicating the presence of predatory fish, both pelagic and demersal.
However, no ecosystem trend is apparent from the additional indicators examined, so no clarification can be made between the Not Improving or Deteriorating ecosystem trends. Components within the fish community require further examination.

Rule 21: q1a2 and q2a3 and q3a3
Decision: 3
Explanation: The Pelagic-caught fish (PEL) community is not improving, whilst the Demersal-caught fish (DEM) community is deteriorating. A detailed examination of the fish community was conducted using the indicator Proportion of predatory fish (Prop. of pred. fish).
Prop. of pred. fish was decreasing, indicating that there are fewer predatory fish within the ecosystem.
The overall conclusion reached is that the southern Benguela ecosystem is Deteriorating.

Rule 22: q1a3 and q2a1 and q5a1 and q7a1
Decision: 4
Explanation: The Pelagic-caught fish (PEL) community is deteriorating, whilst the Demersal-caught fish (DEM) community is improving. A detailed examination of the fish community was conducted using the indicators, Biomass ratio of small: large fish (B SMF/LAF) and System Trophic level (TL).
B SMF/LAF was increasing indicating that there are fewer large fish within the ecosystem. System TL was increasing, indicating that fishing down of the food web is not occurring. These trends are contradictory since large fish would occupy a high TL within the food web and therefore, their absence should lower the TL of the System.
The overall conclusion reached is that we Can't Say what trend the southern Benguela ecosystem is displaying, but it is definitely not an Improving trend.

Rule 23: q1a3 and q2a1 and q5a1 and q7a2
Decision: 2
Explanation: The Pelagic-caught fish (PEL) community is deteriorating, whilst the Demersal-caught fish (DEM) community is improving. A detailed examination of the fish community was conducted using the indicators, Biomass ratio of small: large fish (B SMF/LAF) and System Trophic level (TL).
B SMF/LAF was increasing and System TL was the same, indicating that there are fewer large fish within the ecosystem and that fishing down of the pelagic food web may be occurring.
The overall conclusion reached is that the southern Benguela ecosystem is Not Improving. Be aware of possible changing environmental conditions or fishing practices that could negatively affect the fish community and ecosystem.

Rule 24: q1a3 and q2a1 and q5a1 and q7a3
Decision: 3
Explanation: The Pelagic-caught fish (PEL) community is deteriorating, whilst the Demersal-caught fish (DEM) community is improving. A detailed examination of the fish community was conducted using the indicators, Biomass ratio of small: large fish (B SMF/LAF) and System Trophic level (TL).
B SMF/LAF was increasing and System TL was decreasing, indicating that there are fewer large fish within the ecosystem and fishing down of the pelagic food web is occurring.
The overall conclusion reached is that the southern Benguela ecosystem is Deteriorating.

Rule 25: q1a3 and q2a1 and (q5a2 or q5a3)
Decision: 2
Explanation: The Pelagic-caught fish (PEL) community is deteriorating, whilst the Demersal-caught fish (DEM) community is improving. A detailed examination of the size structure of the fish community was conducted using the indicator Biomass ratio of small: large fish (B SMF/LAF).
B SMF/LAF was the same/decreasing, indicating that the size structure of the fish community is not getting worse (large fish are present), but the PEL community is still not in good shape. The overall conclusion reached is that the southern Benguela ecosystem is Not Improving. Be aware of possible changing environmental conditions or fishing practices that could negatively affect the fish community and ecosystem.

Rule 26: q1a3 and q2a2 and (q5a1 or q5a2)
Decision: 3
Explanation: The Pelagic-caught fish (PEL) community is deteriorating, whilst the Demersal-caught fish (DEM) community is not improving. A detailed examination of the fish community was conducted using the indicator Biomass ratio of small: large fish (B SMF/LAF).
B SMF/LAF was increasing/the same, indicating that the size structure of the fish community within the ecosystem is skewed towards small fish. However, the PEL community is deteriorating, indicating that the small fish present cannot be small pelagic fish (anchovy, sardine or redeye). Thus, the only small fish occurring in the system is hake, indicating that they are not growing into adults, which is bad for the ecosystem.
The overall conclusion reached is that the southern Benguela ecosystem is Deteriorating.

Rule 27: q1a3 and q2a2 and q5a3 and (q4a1 or q4a2)
Decision: 4
Explanation: The Pelagic-caught fish (PEL) community is deteriorating, whilst the Demersal-caught fish (DEM) community is not improving. A detailed examination of the fish community was conducted using the indicators, Biomass ratio of small: large fish (B SMF/LAF) and DEM Trophic level (TL).
B SMF/LAF was decreasing and DEM TL was increasing/the same, indicating that more large fish are present within the ecosystem and that the larger demersal fish do not seem to be negatively affected by fishing.
However, the net effect within the ecosystem cannot be clarified, i.e. cannot decide between a Not Improving or Deteriorating trend. Components within the PEL community require further examination.

Rule 28: q1a3 and q2a2 and q5a3 and q4a3
Decision: 3
Explanation: The Pelagic-caught fish (PEL) community is deteriorating, whilst the Demersal-caught fish (DEM) community is not improving. A detailed examination of the fish community was conducted using the indicators, Biomass ratio of small: large fish (B SMF/LAF) and DEM Trophic level (TL).
Both B SMF/LAF and DEM TL were decreasing, indicating that although there are large fish within the ecosystem, fishing down of the demersal food web is occurring.
The overall conclusion reached is that the southern Benguela ecosystem is Deteriorating.

Rule 29: q1a3 and q2a3
Decision: 3
Explanation: The Pelagic-caught fish (PEL) and Demersal-caught fish (DEM) communities within the ecosystem are both deteriorating. The overall conclusion reached is that the southern Benguela ecosystem is Deteriorating.