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Review and update of harvest strategy settings for the Commonwealth Small Pelagic Fishery

Single species and ecosystem considerations

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January 2015

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In submitting this report, the researcher has agreed to FRDC publishing this material in its edited form.

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Executive Summary

This study undertook ecosystem and population modelling to evaluate and provide advice on the reference points (e.g. biomass depletion levels) and settings (e.g. exploitation rates) for the four main target species in the harvest strategy of the Commonwealth Small Pelagic Fishery (SPF) – Jack Mackerel, *Trachurus declivis*, Redbait *Emmelichthys nitidus*, Blue Mackerel *Scomber australasicus* and Australian Sardine *Sardinops sagax*. The project was developed at the request of the Resource Assessment Group for the SPF (SPFRAG). The focus was to improve the harvest strategy for the fishery to make it fully compliant with the Commonwealth Harvest Strategy Policy (HSP).

The study used a new variant of the Atlantis ecosystem model (Atlantis-SPF). Findings on the effects of fishing the four SPF target species on other parts of the food chain are clear. Both singly and in combination, depleting these target species has only minor impacts on other parts of the ecosystem. Unlike some other regions which show higher levels of dependence on similar species, such as in Peru and the Benguela systems (Smith *et al.*, 2011), the food web in southern and eastern Australia does not appear to be highly dependent on SPF target species. None of the key higher trophic level predators in SE Australia, such as seals, penguins and tunas, has a high dietary dependence on these species. Studies using other ecosystem models such as Ecosim in the same region have reached similar conclusions (Goldsworthy *et al.*, 2013; Bulman *et al.*, 2011).

The findings have implications for the target and limit reference points that should be selected for the main commercial species in the SPF. Equilibrium B_{MSY} for these species ranged from about 30 to 35% of unfished levels. However, these levels are uncertain and it may be more appropriate to use the default values from the HSP with B_{MSY} set at B_{40} (40% of unfished levels) and the default B_{MEY} set at 1.2 times this level, close to B_{50}. This study suggests that the target reference point for these SPF target species should be set at B_{50} and the limit reference point at B_{20}, in line with the HSP default settings. The results presented in this report, combined with evidence from other studies, suggest that these levels are safe from an ecosystem perspective and provide reasonable levels of yield relative to MSY.

Population modelling suggests that target exploitation rates (ERs) for the SPF should be species-specific and possibly even stock-specific. The current average Tier 1 harvest rate of 15% appears to be too high for eastern Redbait. Taking account of some of the sensitivity scenarios, it may also be too high for western Redbait and Jack Mackerel.

Our results help inform the choice of suitable ERs for each of the species and stocks. For Tier 1, the analyses focus on achieving the reference points recommended by the ecosystem modelling, that it is to achieve a median depletion of 0.5 or B_{50}, while maintaining less than a 10% chance of falling below the suggested limit reference point of B_{20}. The base case exploitation rates that achieve this target, assuming surveys every five years, are as follows:

- Eastern Redbait 9%
- Western Redbait 10%
- Jack Mackerel 12%
- Eastern Blue Mackerel 23%
- Western Blue Mackerel 23%
- Eastern Sardine 33%
- Western Sardine 33%

In the current harvest strategy Tier 2 rates are set at half the Tier 1 rate. We assumed that the Tier 2 rate would only be applied after 5 years of exploitation at Tier 1, and that no further surveys would take place. It is generally not safe to apply Tier 2 for long periods of time unchecked. Particularly for the shorter lived species (Blue Mackerel and Sardine), this can result in unacceptable probabilities of depletion in quite short periods of time (5 or 6 years), while the period is on the order of 20 years for the other two species. An alternative approach would be make the Tier 2 rate more precautionary (i.e. less than half the Tier 1 rate) and/or reduce the period over which it is applied (e.g. not more than 5 years).

Introduction

Background

The Commonwealth Small Pelagic Fishery (SPF), managed by the Australian Fisheries Management Authority (AFMA), is a purse-seine and mid-water trawl fishery extending from southern Queensland to southern Western Australia (see Ward *et al*.. 2012b for details). The target species are Jack Mackerel, *Trachurus declivis*, Redbait *Emmelichthys nitidus*, Blue Mackerel *Scomber australasicus* and Australian Sardine *Sardinops sagax* (off parts of the East Coast only). Yellowtail Scad, *Trachurus novaezelandiae*, is taken as by-product.

The SPF is managed by a combination of input and output controls that include limited entry, zoning, mesh size restrictions and total allowable catches (TAC). A new Management Plan was implemented in 2009 that established Eastern and Western management sub-areas (zones, hereafter east and west) rather than the previous four (AFMA 2009a) and introduced some new controls such as Individual Transferable Quotas (ITQs).

There is a tiered Harvest Strategy (AFMA 2009b) with prescribed levels of research required for each Tier (ABARE 2009, AFMA 2009b). Recommended Biological Catches (RBCs) are determined by the Small Pelagic Fishery Resource Assessment Group (SPFRAG).

Tier 1: RBCs for each Tier 1 species in each zone are set at 10-20% (average 15% over five years) of the median spawning biomass estimated using the Daily Egg Production Method (DEPM). The exploitation rate applied each season is determined by the SPFRAG based on the time period since the last DEPM (as outlined in the HS) and annual assessments of catch/effort data and size/age structure of catches.

Tier 2: Maximum RBCs for each Tier 2 species in each zone are specified based, where possible, on up to 7.5% of the median spawning biomass estimate. RBCs are determined by the SPFRAG on the basis of old (>5 years) DEPM estimates and annual assessments of catch/effort data and size/age structure of catches.

Tier 3: Maximum RBCs for Tier 3 species in each zone may not exceed 500 t. RBCs are determined by SPFRAG on the basis of catch and effort data.

This project was developed at the request from the SPFRAG. The focus is to improve the harvest strategy for the fishery to make it fully compliant with the Commonwealth Harvest Strategy Policy. The current harvest strategy was fully implemented in 2009 but since then several significant events have occurred, including several publications in the international literature questioning the appropriateness of "standard" single species target reference points for low trophic level species (Smith *et al.,* 2011; Pikitch *et al.*, 2012), and the adoption of more conservative reference points for key low trophic level species by the Marine Stewardship Council (MSC). In addition, a review of the harvest rate settings in the harvest strategy undertaken during the public scrutiny on the fishery during the "super trawler" issue revealed that the same maximum harvest rate was being applied to species of very different productivities. For both these reasons, the RAG considered that it was time to review and, if necessary, update the key harvest strategy settings (biological reference points and maximum harvest rates) for the fishery.

Need

The SPF has been the focus of considerable stakeholder scrutiny in 2012. Part of this focus has been on the harvest strategy, which has been in place since 2009. Two questions have arisen about the current harvest strategy: 1) What reference points for exploitation rates are appropriate for the species exploited in this fishery, taking into account their ecological role in the food chain? 2) Is the maximum exploitation rate specified in the strategy appropriate for all the target species, given their different productivities, life histories and trophic importance? Questions have also been raised about the possibility and impacts of localised depletion in this fishery, but these will not be dealt with in this proposal.

There was an urgent need to review and if necessary update the harvest strategy settings for the SPF. Specifically, there was a need to answer the two questions outlined above, both of which involve settings in the current harvest strategy. One concerned appropriate choice of target (and limit) reference points, while the other concerned selecting individual harvest rates for each of the target species in the fishery, appropriate to its life history and productivity. Notwithstanding that the vessel which caused the high level of scrutiny on the fishery has departed Australian waters, answering the two questions was fundamental to proper implementation of the Commonwealth Harvest Strategy Policy for this fishery. The need for a review of the harvest strategy settings had been flagged by SPF RAG ahead of the controversy with the "super trawler" and is addressed in this report.

Objectives

1. Provide advice on best practice reference points for the four main target species in the SPF

2. Provide advice on suitable exploitation rates to achieve management targets for the four main target species in the SPF

Methods

This project used a different type of mathematical model to address each of its two objectives. Objective 1 was addressed using an Atlantis ecosystem model developed for the project, and objective 2 was addressed using a population dynamics and management strategy evaluation model also developed for this project.

Objective 1: Provide advice on best practice reference points for the four main target species in the SPF

Modern fisheries management is based around the concept of using technical reference points (calculated or quantified on the basis of biological or economic characteristics of the fishery) to provide insight into the performance of the fishery with respect to conceptual criteria that reflect the management objective for the fishery (Caddy and Mahon 1995). Quantitative assessments can be used to explore whether management regulations may meet these criteria.

With the shift to ecosystem based management, ecosystem considerations have come to increasing prominence – e.g. the recommendations of the Marine Stewardship Council (http://www.msc.org/) and environmental NGOs (e.g. Pew; Cury et al., 2011; Pikitch *et al.*, 2014) regarding considerations around the sustainable exploitation of forage fish and predator-prey implications. Consequently the FAO recommends the use of ecosystem models as best practice when considering these broader criteria (FAO

2008). In this study the Atlantis ecosystem modelling framework was used as a testbed to look at potential ecosystem effects of the harvest strategy settings for the Commonwealth Small Pelagic Fishery.

Atlantis Model Development

Atlantis SE, originally developed for the exploration of alternative management options for the Southern and Eastern Scalefish and Shark Fishery (SESSF), was used as the basis for a model of the main planktivore groups targeted by the Small Pelagics Fishery (SPF) and the ecosystem of which they are a part. Of the many Atlantis models that have been developed for south eastern Australia (Fulton *et al.* 2007, Savina *et al.* 2008, Johnson *et al.* 2011, Fulton and Johnson 2012), Atlantis SE was judged the most appropriate in terms of its spatial and taxonomic coverage and because of the past attention put into fitting this model to historical datasets. Atlantis-SE is one of the most sophisticated and well understood ecosystem models globally.

The version of Atlantis-SE updated for use in the South-Eastern Australia Program (SEAP), which considered fisheries and aquaculture options under climate change, was used as a basis for Atlantis-SPF. The new model Atlantis-SPF was further modified and tailored to consider SPF questions by:

i. splitting out the various planktivorous groups targeted by the SPF;
ii. adding additional predators that are of specific conservation concern and are known (or thought) to be dependent on forage fish (e.g. the Little Penguin *Eudyptula minor*);
iii. refining the representation of taxonomic groups that were present in the existing model as “background players”, but would be a focus of particular attention for this study; e.g. Redbait, *Emmelichthys nitidus*, and the functional group representing tunas and billfish (parameterised to represent Southern Bluefin Tuna *Thunnus maccoyii* in the south and *Thunnus*, *Makaira*, *Tetrapturus* and *Xiphias* species along the eastern seaboard); and
iv. implementing an additional means of representing fishing pressure in Atlantis-SPF. The model can either use the full socioeconomically-driven representation of the fishery used in Atlantis-SE or this can be replaced with a directly imposed fishing mortality (F) to allow for more direct control of alternative fishing pressures.

Atlantis-SPF Spatial Domain

The spatial domain of Atlantis-SPF is the same as that of Atlantis-SE (**Error! Reference source not found.** 1), which was based on physical and ecological properties and distributions of the water bodies and geomorphology of the area (summarised in IMCRA 1998, Butler *et al.* 2001, Lyne and Hayes 2005 and Fulton *et al.* 2007). Vertically the model covers depths down to 1800m.

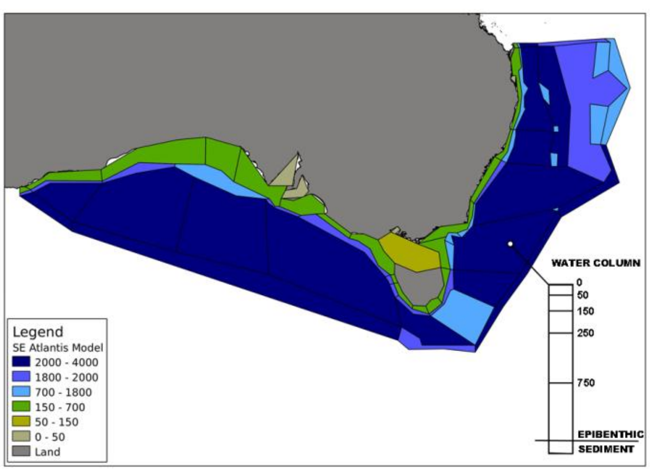


Figure 1: Map of the model domain for Atlantis-SPF.

Physical properties

The same physical forcing as used for Atlantis SE is used to set the physical environment of Atlantis-SPF. Vertical and horizontal exchanges between boxes, as well as temperature and salinity, were taken from the data-assimilated version of global ocean model OFAM (Oke *et al.*. 2005). The hydrodynamic data base used is available at http://www.bom.gov.au/bluelink/ and the data assimilated hindcast runs of that model known as SPINUP6 from http://www.marine.csiro.au/ofam1/.

Trophic Structure

Biological Groups

The biological components of the Atlantis-SPF model span the entire foodweb (Table 1). In the main they are the same as for Atlantis-SE with parameter values updated to reflect the state of the system in 2005. The resolution of the pelagic groups has been greatly expanded. The main sources of information used to parameterise these groups were Greely *et al.* (1999), Reid *et al.* (2002), Jackson and Pecl (2003), Pecl and Moltschaniwskyj (2006), Woehler *et al.* (2006), Stevenson & Woehler (2007), Kirkwood and O'Connor (2010), Raymond *et al.* (2010), Bulman *et al.* (2011), McCutcheon *et al.* (2011), Vertigan & Woehler (2012a,b), Ward *et al.* (2012a, b), Goldsworthy *et al.* (2013) and Woehler (unpublished, who supplied unpublished surveys of Little Penguins currently being run in Tasmania). Estimates of abundance for Little Penguin colonies from across south eastern Australia were also obtained from the OSRA (Oil Spill Response Atlas) database.

A single set of biological parameters is used across the model domain, unless the group is defined as having multiple stocks – in which case fecundity, background mortality and diet connection strength can vary among stocks. The groups in Atlantis-SPF have the same stock structure as in Atlantis-SE. Of the groups added or modified when creating Atlantis SPF, the Anchovy, Redbait and seabirds are all assumed to constitute a single stock spanning the area. Similarly, both forms of mesopelagics are assumed to have only one stock; note the migratory vs non-migratory classification of species in these groups refers to the daily vertical migration behaviour shown by some species not geographic migration relevant to stock mixing. As there is no information available to suggest multiple geographic stocks the two mesopelagics functional groups are both assumed to have a single reproductive stock in the modelled region. In contrast, the model assumes there are three mackerel stocks (Figure 2), two Sardine stocks (east and west of Tasmania), and two tuna stocks (one representing *Thunnus maccoyii* in the south and the other representing the aggregate of *Thunnus*, *Makaira*, *Tetrapturus* and *Xiphias* along the eastern seaboard). The Little Penguin are assumed to have a reproductively-isolated stock in each box along the coastline of the model (representing the small foraging and dispersal extent of each colony), this structure sees this functional group have 20 stocks in the model in total.

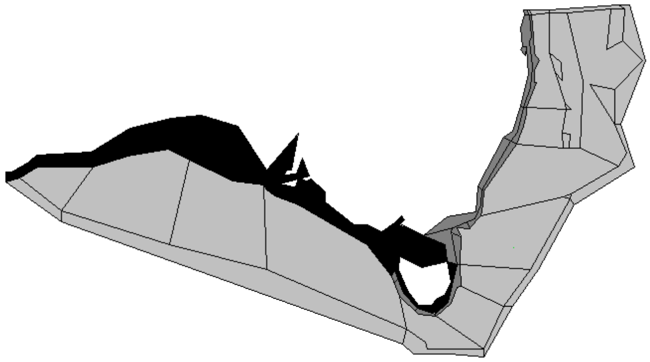


Figure 2: Stock structure of the mackerel groups (both jack and Blue Mackerel) in Atlantis-SPF. Each shade of grey represents the extent of each stock (one on the shelf in Bass Strait and west, one along the eastern shelf, and one off shore).

Table 1: Trophic groups included in Atlantis-SPF. Groups in **bold** were added or modified when creating Atlantis-SPF and are not present to the same resolution in Atlantis-SE.

Model Component	Group Composition
Pelagic invertebrates	
Large phytoplankton	Diatoms
Small phytoplankton	Picophytoplankton
Microzooplankton	Heterotrophic flagellates and other small zooplankton
Zooplankton	Copepods and other mesozooplankton
Carnivorous zooplankton	Krill and chaetognaths
Gelatinous zooplankton	Salps (pryosomes), coelenterates
Pelagic bacteria	Pelagic attached and free-living bacteria
Cephalopods (Squid)	*Sepioteuthis australis*, *Notodarus gouldi*
Benthic invertebrates	
Sediment bacteria	Aerobic and anaerobic bacteria
Meiobenthos	Meiobenthos
Carnivorous infauna	Polychaetes and other benthic carnivores
Deposit feeders	Holothurians, echinoderms, burrowing bivalves
Deep water filter feeders	Sponges, corals, crinoids, bivalves
Other shallow water filter feeders	Mussels, oysters, sponges, corals
Scallops	*Pecten fumatus*
Herbivorous benthic grazers	Urchins, *Haliotis laevigata*, *Haliotis rubra*, gastropods
Deep water macrozoobenthos	Crustacea, asteroids, molluscs
Shallow water macrozoobenthos	Stomatopods, octopus, seastar, gastropod, and non-commercial crustaceans
Rock lobster	*Jasus edwardsii*, *Jasus verreauxi*
Macroalgae	Kelp
Seagrass	Seagrass
Prawns	*Haliporoides sibogae*

Model Component	Group Composition
Giant crab	*Pseudocarcinus gigas*
Fin-fish	
Sardine	***Sardinops*, sprat**
Anchovy	***Engraulis***
Redbait	**Emmelichthyidae (*Emmelichthys nitidus*)**
Blue Mackerel	***Scomber australisicus***
Jack Mackerel	***Trachurus declivis***
Migratory mesopelagics	**Myctophids**
Non-migratory mesopelagics	**Sternophychids, cyclothene (lightfish)**
School whiting	*Sillago*
Shallow water piscivores	*Arripis*, *Thyrsites atu*, *Seriola*, leatherjackets
Blue warehou	*Seriolella brama*
Spotted warehou	*Seriolella punctata*
Tuna and billfish	***Thunnus*, *Makaira*, *Tetrapturus*, *Xiphias***
Gemfish	*Rexea solandri*
Shallow water demersal fish	Flounder, *Pagrus auratus*, Labridae, *Chelidonichthys kumu*, *Pterygotrigla*, *Sillaginoides punctata*, *Zeus faber*
Flathead	*Neoplatycephalus richardsoni*, *Platycephalus*
Redfish	*Centroberyx*
Morwong	*Nemadactylus*
Pink ling	*Genypterus blacodes*
Blue grenadier	*Macruronus novaezelandiae*
Blue-eye trevalla	*Hyperoglyphe Antarctica*
Ribaldo	*Mora moro*
Orange roughy	*Hoplostethus atlanticus*
Dories and oreos	Oreosomatidae, Macrouridae, *Zenopsis*
Cardinalfish	Cardinalfish
Sharks	
Gummy shark	*Mustelus antarcticus*
School shark	*Galeorhinus galeus*
Demersal sharks	*Heterodontus portusjacksoni*, Scyliorhinidae, Orectolobidae
Pelagic sharks	*Prionace glauca*, *Isurus oxyrunchus*, *Carcharodon carcharias*, *Carcharhinus*
Dogfish	Squalidae
Gulper sharks	*Centrophorus*
Skates and rays	Rajidae, Dasyatidae
Top predators	
Flying seabirds	**Albatross, shearwater, gulls, terns, gannets**
Penguins	***Eudyptula minor***
Pinnipeds (Seals)	*Arctocephalus pusillus doriferus*, *Arctocephalus forsteri*
Sea lion	*Neophoca cinerea*
Dolphins and small whales	Delphinidae
Toothed whales (Orca)	*Orcinus orca*
Baleen whales	*Megaptera novaeangliae*, *Balaenoptera*, *Eubalaena australis*

Model Component	Group Composition
Abiotic model components	
Dissolved Inorganic Nitrogen (DIN)	Ammonia, nitrate
Discards	Carrion and discards from fishing vessels (including whole fish discarded if over quota as well as the waste of fish processed at sea)
Labile detritus	Decomposing material that breaks down on the order of a week
Refractory detritus	Decomposing material that breaks down on the order of a year

Trophic Connections

The diet connections between the biological groups in the model identify multiple potential pathways through the foodweb. They are parameterised as the maximum potential availability of each prey to each potential predator. The realised rate of predation is then conditioned on level of contact (spatial overlap within a box), the state of any relevant habitat (if a habitat-associated group) and gape limitation (i.e. size of the mouth versus size of the prey given the feeding mode of the predator).

The base connection matrix used was taken from the parameterisations used for the SEAP project, updated based on O'Sullivan and Cullen (1983), Wingham (1985), Skira (1986), Gales *et al.* (1993), Gales and Pemberton (1994), Uchikawa *et al.* (2002), Hume *et al.* (2004), and Kowalczyk *et al.* (2013). The original Atlantis-SE parameterisations were initially drawn from an extensive list of publications (see Fulton *et al.* 2007, Fulton and Johnson 2012) and then filtered such that only the parameterisations leading to biomass trajectories consistent with observations were retained. This suite of parameterisations captures uncertainty around productivity and the degree of diet specialisation. In moving to Atlantis-SPF however, only one parameterisation leads to plausible estimates of the number of penguins (all other parameterisations lead to the extinction of the group and so are inappropriate).

The realised diet in any one location in the model at any one time is determined by these potential trophic connections and the biomass of species at that location, their relative sizes (the model uses gap limitation to determine if a predator can successfully take the prey). This means there can be significant variation in realised diet between locations and time periods depending on the associated species and size composition. However, a sense of the degree of maximum potential strength of trophic connection across the model domain is given in Figure 3, which shows the potential availability of prey to predators given average size-at-age.

Movement

Seasonal shifts in distributions are the simplest representation of movement in Atlantis, but many of the pelagic groups that are the focus of Atlantis-SPF are assumed to use forage and density-dependent movement. This uses the concept of ideal free distributions to represent how forage fish follow a combination of favourable forage (e.g. plankton) fields and environmental conditions rather than have time-invariant distributions.

Model Calibration

The model was calibrated to existing biological and catch data simultaneously for each group and all spatial areas. These time series are constructed from available observational data (detailed in Fulton *et al.* 2007 and the sources listed above for the biological groups) or reported fisheries statistics. For groups where no time series data are available (e.g. meiobenthos), biological parameters are calibrated to achieve a stable ecosystem within the range of biomass values reported for these groups in the literature.

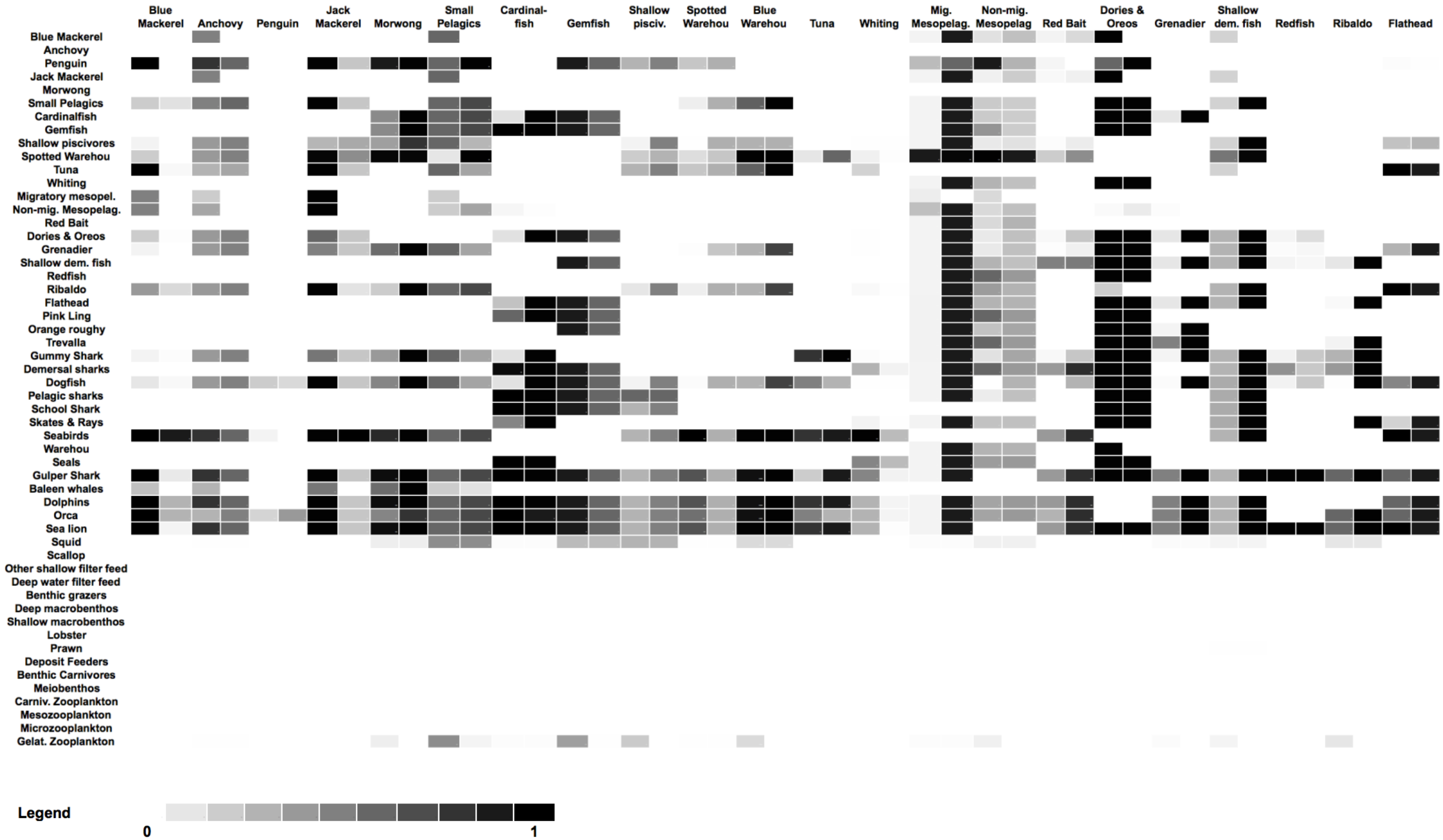
The tuning method used is a modified form of pattern-oriented modelling (Fulton *et al.* 2007, Kramer-Schadt *et al.* 2007). Knowledge of the most sensitive parameters (from previous sensitivity and factor analyses by Pantus and Dennison (2005) and Fulton *et al.* (2007)) is used to determine the parameters on which to focus during the calibration process. These parameters (starting with the most uncertain for the current model implementation) are adjusted according to the following criteria:

(i) simultaneous minimisation of the deviation of model-based estimates (of biomass values, age structure and realised diet composition) from observed time series across all groups in all spatial boxes, subject to the constraint that the shapes of the time series of biomass must reflect the observed time series in the majority of boxes (this is because it is possible for a flat line to have a smaller deviation than a curve with the correct shape that has a small phase shift relative to the observations);

(ii) observed catches must be sustained without driving any model group to extinction; and

rate parameters are not to be moved beyond reported bounds (from a meta-analysis of the literature) without expert advice from researchers active in the region and unless those values were of uncertain veracity for the system (e.g. a tropical value had been used in a temperate system initially) and the group itself is poorly constrained (i.e. the most uncertain parameters of the most uncertain groups are modified before those of more well-specified groups or solidly founded parameters; thus at one extreme the gravity term will never be changed through to the other extreme where the diet parameters for infaunal worms may see significant modification, for example).

An example time series showing how interannual variability in the biomass of forage species is being captured in Atlantis-SPF is given in Figure 4. This figure demonstrates how interannual variability in environmental conditions and ecosystem state manifests itself in the relative biomass of Sardine. This is a model trajectory and not fit to any observed timeseries. However, it does show that the tarjectories in the model do show the same kinds of interannual variation seen in reality and so the model is a fair test of potential stresses in the system related to such highly variable stock levels. Example spatial distributions for the focus groups in Atlantis-SPF are given in Figure 5, these represent single snapshots in time and vary through the course of the simulation (and within a simulated year) and between simulations as conditions change and the species move in response.


Blue Mackerel
Anchovy
Penguin
Jack Mackerel
Morwong
Small Pelagics
Cardinal-fish
Gemfish
Shallow pisciv.
Spotted Warehou
Blue Warehou
Tuna
Whiting
Mig. Mesopelag.
Non-mig. Mesopelag
Red Bait
Dories & Oreos
Grenadier
Shallow dem. fish
Redfish
Ribaldo
Flathead
Blue Mackerel
Anchovy
Penguin
Jack Mackerel
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School Shark
Skates & Rays
Seabirds
Warehou
Seals
Gulper Shark
Baleen whales
Dolphins
Orca
Sea lion
Squid
Scallop
Other shallow filter feed
Deep water filter feed
Benthic grazers
Deep macrobenthos
Shallow macrobenthos
Lobster
Prawn
Deposit Feeders
Benthic Carnivores
Meiobenthos
Carniv. Zooplankton
Mesozooplankton
Microzooplankton
Gelat. Zooplankton
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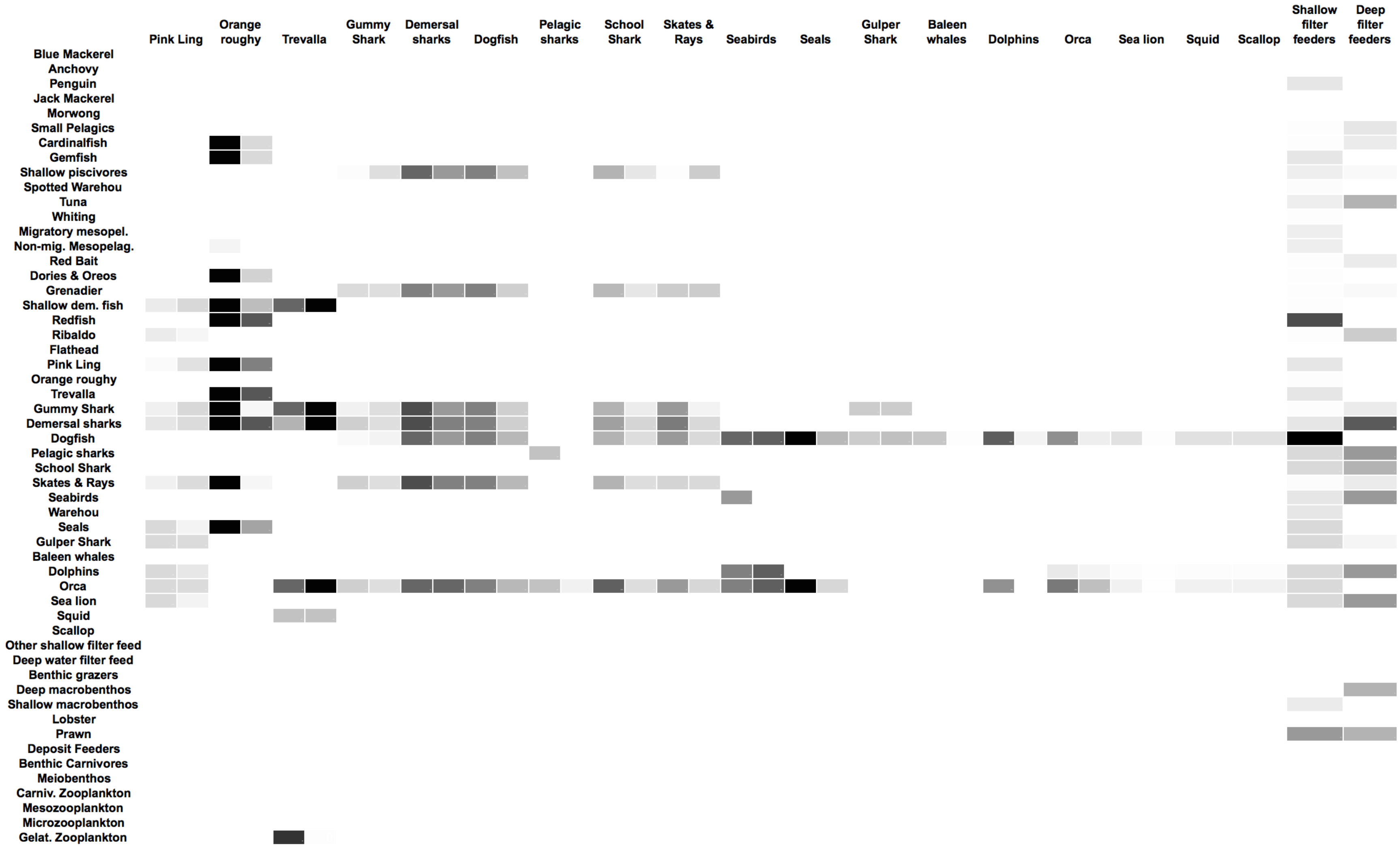
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Pelagic sharks
School Shark
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Skates & Rays
Seabirds
Warehou
Seals
Gulper Shark
Baleen whales
Dolphins
Orca
Sea lion
Squid
Scallop
Other shallow filter feed
Deep water filter feed
Benthic grazers
Deep macrobenthos
Shallow macrobenthos
Lobster
Prawn
Deposit Feeders
Benthic Carnivores
Meiobenthos
Carniv. Zooplankton
Mesozooplankton
Microzooplankton
Gelat. Zooplankton

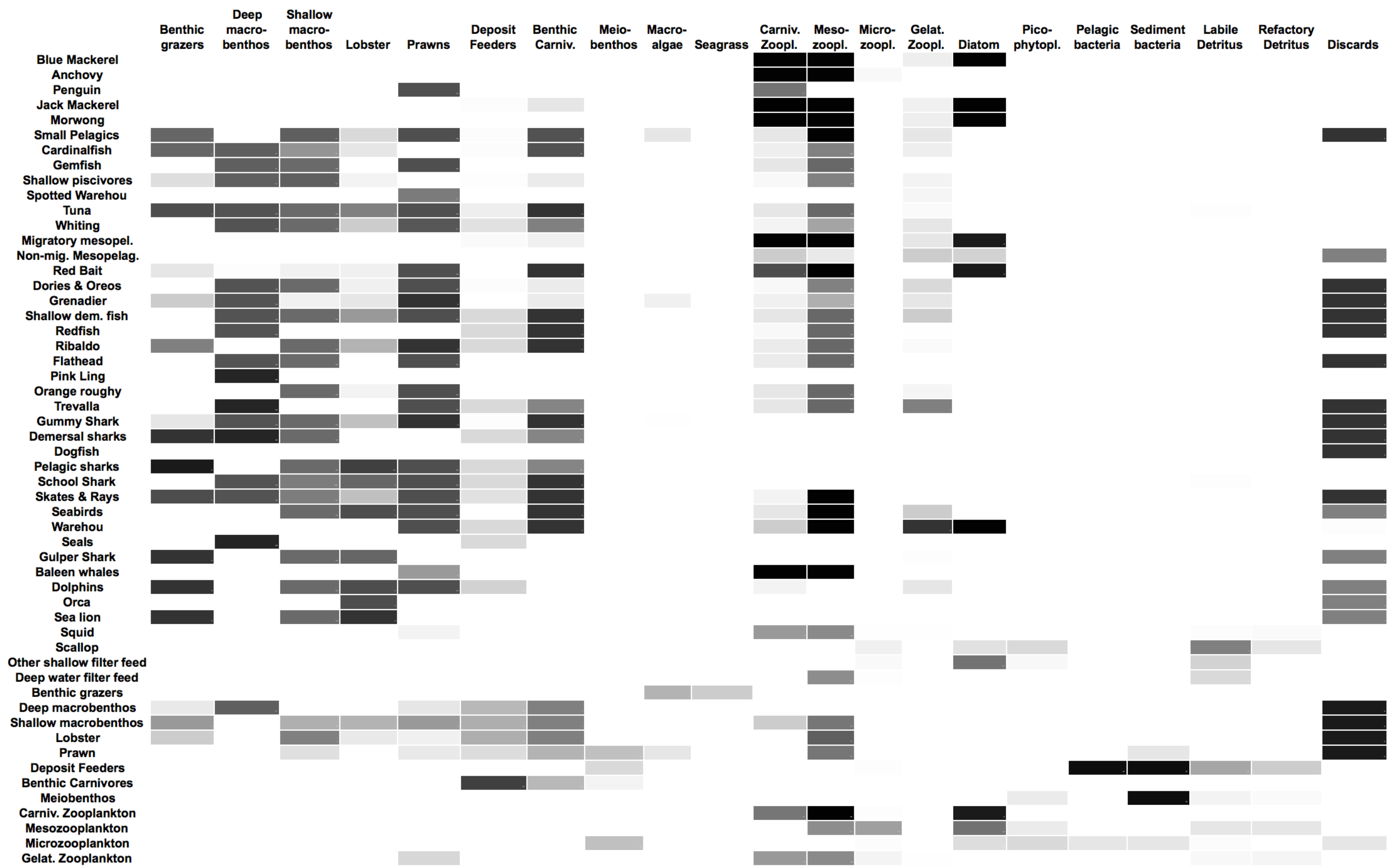


Figure 3: Potential relative maximum availability accounting for gape limitation (based on average size-at-age). The prey are the columns and predators are the rows. Juvenile prey are shown in the left half of each column and adult prey in the right (for ease of reading the figure juvenile and adult predators are not distinguished, only the largest possible connection per predator is shown).

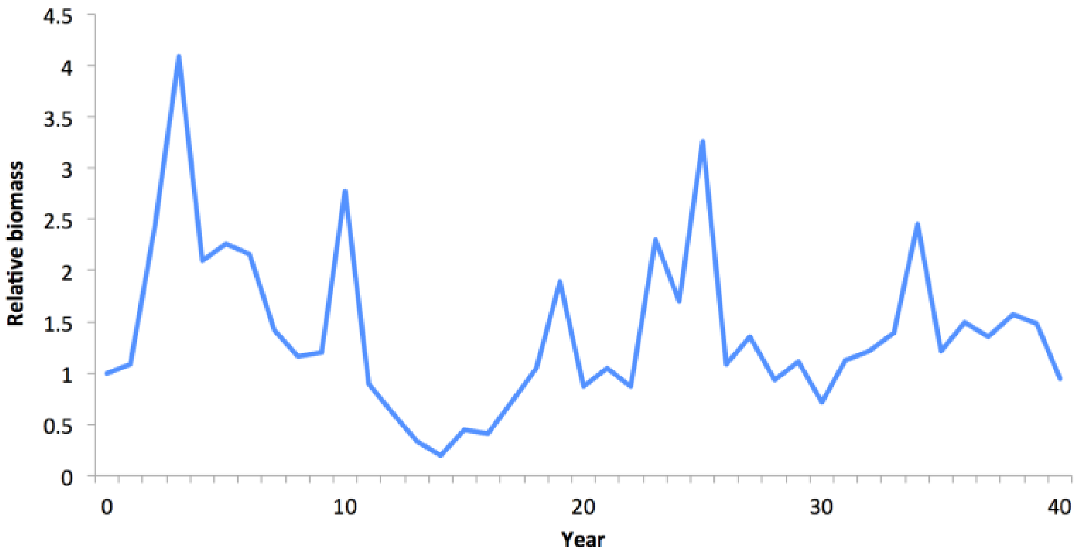


Figure 4: A representative relative biomass trajectory for the Sardine group, showing the level of variability that the model can capture for these forage groups (driven by recruitment, the physical environment and predator-prey interactions).

Fisheries Structure

As mentioned above, fisheries can be represented in two ways in Atlantis-SPF. The model can either use the full socioeconomically-driven representation of the fishery used in Atlantis-SE (detailed in Fulton *et al.* 2007) or this can be replaced with a fishing mortality (F) based method. The latter allows more direct exploration of the effects of fishing in the SPF given the set of management regulations and F-based harvest control rules used in that fishery. The starting Fs used in this case are set based on the biomass levels used to initialise the model (based on estimates for 2004) and observed catches taken in the year equivalent to the first year of the model simulation period (i.e. 2005).

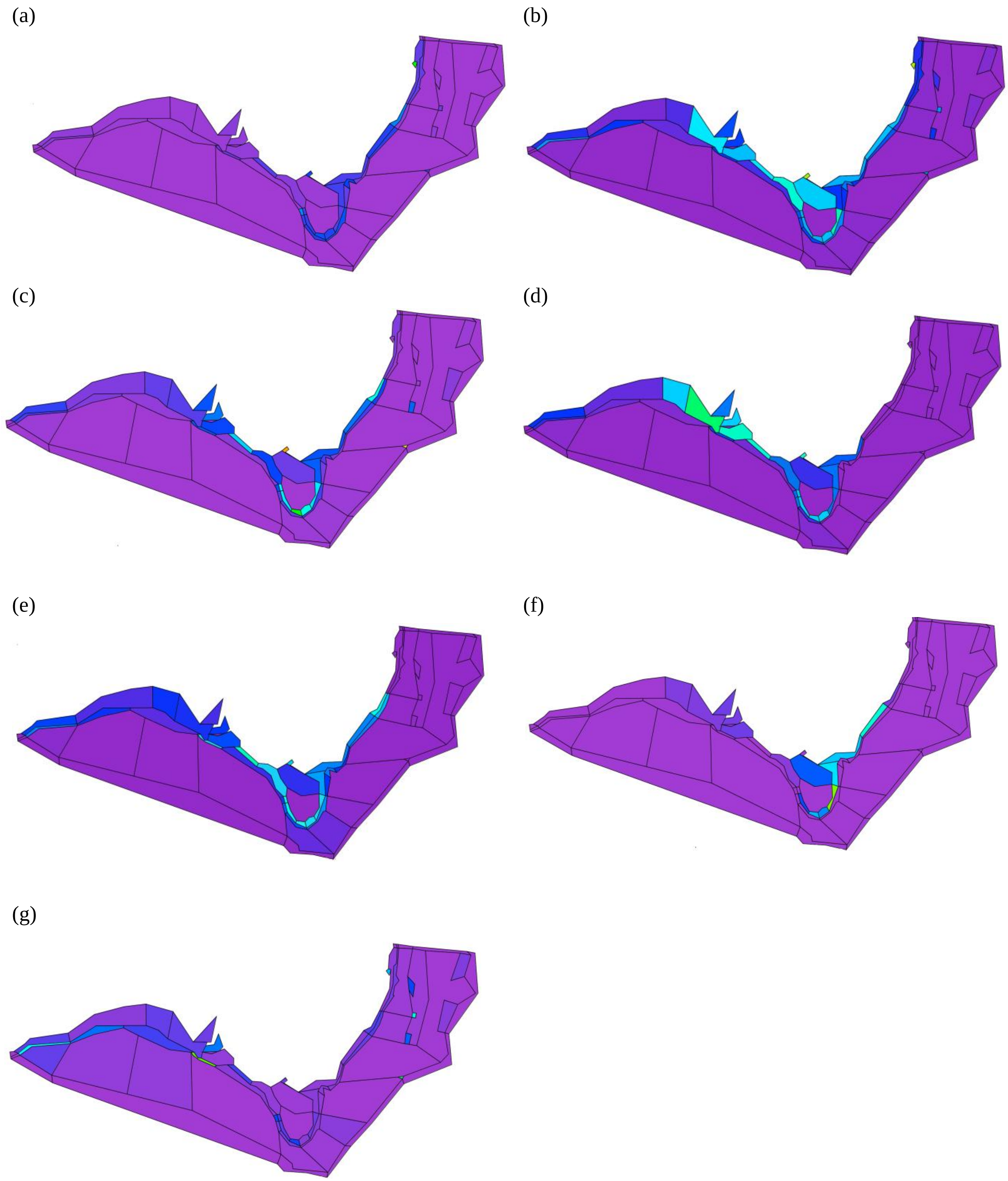


Figure 5: Example spatial distributions of biomasses for Atlantis-SPF groups (a) Jack Mackerel, (b) Blue Mackerel, (c) anchovy, (d) Sardine, (e) Redbait, (f) Little Penguin and (g) tuna and billfish. These are snapshots, as the distributions shift through time (between seasons) as conditions change – 3D time series of biomass (as well as size-at-age and catch) are associated with each of these distributions. For clarity, the individual keys are omitted, but each plot shows the biomass distribution with the purple colour at one extreme indicating zero (or very small) biomasses through to red showing the highest densities.

Objective 2: Provide advice on suitable exploitation rates to achieve management targets for the four main target species in the SPF

A conventional single species population model was used to test suitable harvest strategies to address objective 2.

MODEL SPECIFICATIONS

The model was adapted to each of the four quota species prescribed under the Small Pelagic Fishery (SPF) management plan. The four species are:

- Jack Mackerel (*Trachurus declivis*),
- Blue Mackerel (*Scomber australasicus*),
- Redbait (*Emmelichthys nitidus*), and
- Australian Sardine (*Sardinops sagax*).

The same model structure was used in all four cases, with different Parameterisation for each species.

Basic dynamics

The operating model is age-structured, and recruitment is driven by spawning biomass. The basic population dynamics are governed by the equation:

$$N_{y+1,a} = \begin{cases} R_{y+1} & \text{if } a = 0 \\ N_{y,a-1}e^{-M_y - S_{y,a-1}F_y} & \text{if } 1 \le a < x \\ N_{y,x-1}e^{-M_y - S_{y,x-1}F_y} + N_{y,x}e^{-M_y - S_{y,x}F_y} & \text{if } a = x \end{cases} \tag{1}$$

where $N_{y,a}$ is the number of animals of age *a* at the start of year *y*, M_y is the rate of natural mortality in year *y*, $S_{y,a}$ is the selectivity of the fishery on animals of age *a* during year *y*, F_y is the fully-selected fishing mortality during year *y*, and *x* is the maximum (plus-group) age. The final term R_y represents recruitment, which is governed by a Beverton-Holt stock-recruitment relationship with autocorrelated deviations, Parameterised in terms of steepness and R_0.

$$R_y = \frac{4hR_0 SSB_y / SSB_0}{(1-h) + (5h-1)SSB_y / SSB_0} e^{\varepsilon_y - \sigma_R^2/2} \tag{2a}$$

with devations given by $\varepsilon_y = \rho_R \varepsilon_{y-1} + \sqrt{1-\rho_R^2}\eta_y$ (2b)

and the stochastic component given by $\eta_y \sim N(0;\sigma_R^2)$; (2c)

where Equation 2a is the stock-recruitment relationship, SSB_y is spawning stock biomass in year *y*, *h* is the steepness of the stock-recruitment relationship, SSB_0 is the unexploited spawning stock biomass, R_0 is the recruitment corresponding to SSB_0, σ_R^2 is the extent of variation about the stock-recruitment relationship due to un-modelled white-noise processes, and ρ_R determines the extent of auto-correlation in the deviations about the stock-recruitment due to red noise processes.

The catch during (future) year *y* is determined using the equation:

$$C_y = \sum_{a=0}^{x} \tfrac{w_{y,a+1/2} S_{y,a} F_y}{M_y + S_{y,a} F_y} N_{y,a} (1 - e^{-M_y - S_{y,a} F_y}) \tag{3}$$

where $w_{y,a+1/2}$ is weight-at-age in the middle of year *y*.

The length-at-age relationship was based on the Von Bertalanffy growth model, as defined in the equation:

$$L_a = L_\infty \left(1 - \exp\left(-K * \left(a - t_0\right)\right)\right) \tag{4}$$

where L_a is length-at-age, L_∞ is asymptotic length, *K* is the rate of growth and t_0 is the theoretical age at length zero.

The weight-at-length relationship was determined by the equation:

$$w = \Omega_1 * L^{\Omega_2} \tag{5}$$

where *w* is weight, *L* is length, and Ω_1 and Ω_2 are parameters.

Maturity-at- length was determined by the equation:

$$mat = \frac{1}{1 + \exp\left(\Omega_3 + \Omega_4 * L\right)} \tag{6}$$

where *mat* is the proportion mature, *L* is length, and Ω_3 and Ω_4 are parameters.

Control rules

Australian SPF Harvest Strategy (HS) sets Recommended Biological Catch (RBC) and exploitation rate for each species based on a tiered approach. Three tiers are defined as a function of data availability.

Tier 1, option 1

Tier 1 RBCs are set based on biomass estimates from both catch data and fishery-independent DEPM surveys. The maximum RBC for a given year is given by

$$RBC_y = S\hat{S}B_{y-n} \times HR_n \tag{7}$$

where $S\hat{S}B_{y-n}$ is the estimate of SSB derived from the last DEPM survey, *n* is the age of the DEPM survey in years, and HR_n is the maximum harvest rate (HR) for a DEPM survey of age *n*. HR varies as a linear function of *n*: $HR_n = -\varphi n + \gamma$ where φ and γ are control parameters.

Tier 1, option 2

RBC for a given year can be set up to $\eta \cdot S\hat{S}B_{y-n}$ where η is a control parameter, as long as *n* is less than 5 years. If *n* is larger than 5 years, RBC defaults to tier 2.

Tier 2

Tier 2 involves the setting of RBCs based on an annual assessment of fishery catch and effort data, as well as annual information on the age structure of the catch. This process has no explicit quantitative rule, so it is not evaluated here. However, a maximum RBC can be set for each of the four SPF species, based on a fraction of the last estimated stock biomass. The fraction is generally half that of the exploitation rate used for Tier 1.

Performance measures

Seven performance measures were used to evaluate the performance of the different control rules and the impact of the sensitivity analyses on performance. Depletion and catch were estimated from the last 5 years of 50-year long simulations, with 1000 iterations. Probabilities of biomass falling below a given threshold were calculated using the whole (50-year) time series.

- Average depletion (“Mean Dep.”)
- Average catch relative to catch at E_{MSY} (“Mean catch”)
- Probability of biomass falling below 60% of B_0. (“P Dep. 0.60”)
- Probability of biomass falling below 50% of B_0. (“P Dep. 0.50”)
- Probability of biomass falling below 40% of B_0. (“P Dep. 0.40”)
- Probability of biomass falling below 30% of B_0. (“P Dep. 0.30”)
- Probability of biomass falling below 20% of B_0. (“P Dep. 0.20”)

SCENARIOS FOR THE MANAGEMENT STRATEGY EVALUATION

Table 2 describes the management scenarios considered. In all base scenarios, the DEPM survey is assumed to have a CV of 0.3 and to provide an unbiased estimate of spawning biomass. Scenario 3 is taken as the “base-case”, with DEPM surveys every 5 years and a constant exploitation rate at 15% (i.e. φ=0 and γ=0.15). The remaining scenarios differ from the base case as follows:

- Scenario 1: No exploitation.
- Scenario 2: DEPM surveys every 2 years. Exploitation rate constant at 20%.
- Scenario 4: Only one DEPM survey in the first year. Exploitation rate constant at 7.5%.
- Scenario 5: DEPM surveys every 10 years. Exploitation rate constant at 15% for five years after the survey, and 7.5% in subsequent years.
- Scenario 6: DEPM surveys every 5 years. Exploitation rate decreases linearly with survey age from 20% to a minimum of 7.5%.
- Scenario 7: Same as scenario 6, but DEPM surveys every ten years.
- Scenario 8: DEPM surveys every 2 years. Exploitation rate constant at a level that results in 75% depletion (i.e. 75% of unexploited biomass).
- Scenario 9: Same as scenario 8, but with DEPM surveys every 5 years.
- Scenario 10: Same as scenario 8, but with DEPM surveys every 10 years.

Table 3 describes the sensitivity scenarios identified as critical. These scenarios evaluate four key factors: survey uncertainty, survey bias, steepness and selectivity. Again, taking scenario 3 as base, the sensitivity scenarios differ as follows:

- Scenario S1: DEPM survey CV is 0.5.
- Scenario S2: DEPM survey positive bias of 50%.
- Scenario S3: DEPM survey negative bias of -50%.
- Scenario S4: DEPM survey positive bias of 25%.
- Scenario S5: DEPM survey negative bias of -25%.
- Scenario S6: High steepness.
- Scenario S7: Low steepness.
- Scenario S8: Selectivity curve shifted right by one year.
- Scenario S9: Selectivity curve shifted left by one year.

Table 2: Base scenarios for the management strategy evaluation. Scenario 3 is the base for these analyses**.**

Scenario	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
HR	0.0	0.2	**0.15**	0.075	.15-.075	Tiers	Tiers	Depl=0.75	Depl=0.75	Depl=0.75
DEPM CV	**-**	0.3	**0.3**	0.3	0.3	0.3	0.3	0.3	0.3	0.3
DEPM bias	-	0.0	**0.0**	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DEPM freq	-	2	**5**	only one	10	5	10	2	5	10
Steepness	base	base	**base**	base	base	base	base	base	base	base
Selectivity	base	base	**base**	base	base	base	base	base	base	base

Table 3: Sensitivity scenarios for the management strategy evaluation

Scenario	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**
HR	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
DEPM CV	0.5	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
DEPM bias	0	0.5	-0.5	0.25	-0.25	0.0	0.0	0.0	0.0
DEPM freq	5	5	5	5	5	5	5	5	5
Steepness	base	base	base	base	base	high	low	base	base
Selectivity	base	base	base	base	base	base	base	+1 year	-1 year

Results of the management strategy evaluation are presented by species and stock. All species use the operating model described above. For each species, the Parameterisation of the model is described first, followed by the identification of reference points and a profile of exploitation rate vs. depletion, and finally the results for all the management scenarios.

To identify reference points, the model was run using a constant harvest rate (on estimated biomass, i.e. SSB) between 0 and 1, at steps of 0.025 to set the TAC. For each exploitation rate, 1000 50-year projections were run to guarantee that equilibrium was reached. Initial conditions were set to unexploited, equilibrium biomass. Only recruitment uncertainty was used ($\sigma_R = 0.6$); no assessment or implementation uncertainty was included.

Results

Objective 1

Simulation experiments

Achieving the "best fit" parameterisation discussed here was considerably more difficult than anticipated due to the lack of detailed data for some of the new groups, specifically Little Penguins (where only patchy and gross trajectories per colony were available for fitting). Moreover, it was quite difficult to find a parameterisation that saw Little Penguins maintained in the model domain. The short foraging range of this species, and the reproductive isolation of each colony, meant that unless the potential availability of prey was high and prey breadth broad it was difficult to keep the species sufficiently provisioned across the year. In addition on land mortalities are high so additional at sea mortality (e.g. due to starvation) typically lead to rapid and catastrophic outcomes under parameterisations that were more specialist. Ultimately, the key advance was to allow for strong differential in background (i.e. on land) mortality rates, which varied by three orders of magnitude from more remote locations in the west of the model domain (where mortality was quite low) and the boxes representing the south east coast of Tasmania (where land-based mortality was relatively high).

The stable "best fit" parameterisation is used as the basis of the following simulation experiments. This parameterisation did have high potential availability of SPF species to predators and as such has the potential to reflect the effects of depletion of SPF species (i.e. was aimed at trying to allow for effects of polygon-level depletion to be manifest).

Effects of variation in the exploitation rate of individual SPF species/groups

Yield curves

The calibrated Atlantis-SPF representation was used to explore the relationship between catch and exploitation rate for each SPF species/group. Catch achieved in the long-term (50 years from 2005) at base levels of exploitation were calculated by running the model forward under current TAC levels. To fill out the yield curves, the base exploitation rates for each species/group separately were multiplied by scaling factors that best allowed characterisation of the full yield curves (e.g. 0, 0.25, 0.5, 1, 5, 25, 50). While F can differ among stocks of the same species, this was only applied where the current TACs as a percentage of the stock's biomass implied different starting Fs on different stocks.

For three of the species (Figure 6a,b,d) the shape of the yield curve was clear form the points (or easily determined by joining points using a smoother). For sardine however (Figure 6c) nonlinear dynamical responses mean that no such simple curve was possible. Equilibrium yield curves calculated for individual species based on knowledge of biological parameters and fishery selectivity alone have a simple shape. Yield curves from a complex model such as Atlantis may also have a simple shape (as for Jack Mackerel and Redbait, Figure 6a,d), but may also exhibit more complex and unpredictable characteristics (as for Blue Mackerel and Sardine, Figure 6b,c). In contrast to single species models, these more complex relationships can arise in an ecosystem model such as Atlantis due to a range of trophic interactions leading to changes in prey distribution, predator switching, and resulting changes in growth and mortality. Note that a relative biomass of 1 corresponds to zero fishing of the species concerned and base levels of fishing mortality for the remaining species.

System-wide effects

The objective was to investigate the impact on all functional groups included in the Atlantis-SPF system due to variation in the exploitation rate of small pelagic species/groups one at a time. To achieve this, F scalar values were selected that achieved final depletion of the SPF target species in 2025 close to 0.1, 0.5 and 0.8 of unfished levels for the calibrated base case (Table 4). When changing the F value for a species/group, the F values for the other small pelagic species were kept at base levels (scalar of 1.0). For comparative purposes, relative recruited adult biomass levels for all groups were compared with the case for no small pelagic fishing (*F*=0) for all small pelagics, Figures 7 and 8. The results are presented based on the 6-year averages at the end of a 50-year projection.

As each of the depletion scenarios were compared with the *F*=0 case, any patterns that were common across scenarios are mainly due to base fishing of all fishable small pelagics (e.g. the decline of blue warehou, Figure 7a). It is only of interest to examine differences in the observed patterns caused by change in the exploitation level of the individual small pelagic species. Large changes among the small pelagic groups were not generally observed, except in isolated instances such as for Sardine when the exploitation level for Jack Mackerel was changed (Figure 7a). The effect on the biomass of all other modelled groups was less than 20% except for discards (which grow in all cases as the *F*=0 has no discards, whereas any $F > 0$ case will have some level of associated discarding across all the fished species). The results suggest that if a single small pelagic species is heavily exploited, the effect on species other than small pelagic species (and especially any effects on predators) is minimal.

Nonlinear responses across food pathways can mean that simple extrapolations of effects at one level of depletion to another are not possible (or at least not straightforward). This is the case for the depletion of Jack Mackerel and the implications for Sardines, Blue Mackerel and red bait is a case in point. Presenting the many different model outputs required to tease apart these effects would be overwhelming here, but spatiotemporal analyses of age specific diet composition and predation pressure were used to explore what was driving nonlinear responses. It was found, for example, that the predation pressure exerted on Sardine by gelatinous zooplankton is lower at low levels of Jack Mackerel depletion than at higher levels, as the predation pressure on very small mackerel is partially switched to Sardine when those mackerel are no longer there. However, the reverse pattern is true for predation by squid (due to shifts in relative size-at-age of the Sardine). Similarly, predation pressure by tunas, dories and oreos do not shift in the same way for red bait – with pressure by dories and oreos and larger tuna on large age classes of red bait increasing with Jack Mackerel depletion, but the predation pressure by small tuna on the smallest age classes decreasing (due to both shifts in relative prey biomass across many prey species but also relative size-at-age). Even more predatory groups are involved for Blue Mackerel with different predators and different sizes of those predators responding in different ways – across tuna, dories and oreos, flathead, flying seabirds and penguins.

Picophytoplankton, prawn, scallop, warehou and school shark are the other groups most affected by high exploitation of small pelagic groups. Sometimes picophytoplankton, other times scallops, warehou and school shark were negatively affected with high exploitation of small pelagic species, while sometimes picophytoplankton, prawns and scallop were positively affected, though still by small relative amounts. This pattern of results reflects the many ways in which there can be a redirection of trophic pathways – either through competition, consumption trophic cascades (e.g. where the zooplankton released from predation by the depletion of the small pelagic groups causes a cascade through the plankton, microbial web and their predators such as filter feeders), prey shifts or a shifting emphasis of sub-webs. Shifts in other species (e.g. school shark) can reflect where shifts in their competitors or predators (e.g. large pelagic sharks) are responding to a change in the small pelagic groups via a shift in absolute abundance or prey targeting. This is the case for school shark where the large sharks redistribute predation pressure as small pelagic groups drop from their diet. Even relatively small shifts in their major predators can be expressed as noticeable shifts in the stock's abundance for species as sensitive to shifting mortality structure as school shark.

The fact that the outcome of these shifts is small in terms of biomass changes (all less than 20% and most at undetectable levels) suggests that because of prey switching (see further exploration of this below), increased exploitation on small pelagic groups individually has minimal impact on other groups in the system.

Discards of SPF species were affected by the exploitation rate of the species - increasing with the level of exploitation. The increase in the discards saw the detritus groups grow in turn and under the highest levels of exploitation there was a small resulting shift in emphasis on the detritus based contributions to the overall food web structure. In addition, when either of the mackerels were under heavily exploitation then discards of the other mackerel species increased by as much as 30%, while the discards of other fished shelf species declined (typically not by much however, though it was dependent on the exact exploitation rate and functional group in question).

Table 4: Scalars applied to the base exploitation rate in the calibrated base model to test the system-wide effects of exploitation rates that achieve adult available biomass depletion levels of 0.8, 0.5 and 0.1 for SPF groups.

F scalar	SPF group	Target biomass depletion
0.5	Jack Mackerel	0.8
1	Jack Mackerel	0.5
10	Jack Mackerel	0.1
0.5	Sardine	0.8
5	Sardine	0.5
50	Sardine	0.1
0.25	Blue Mackerel	0.8
0.5	Blue Mackerel	0.5
5	Blue Mackerel	0.1
0.25	Redbait	0.8
0.5	Redbait	0.5
2	Redbait	0.1

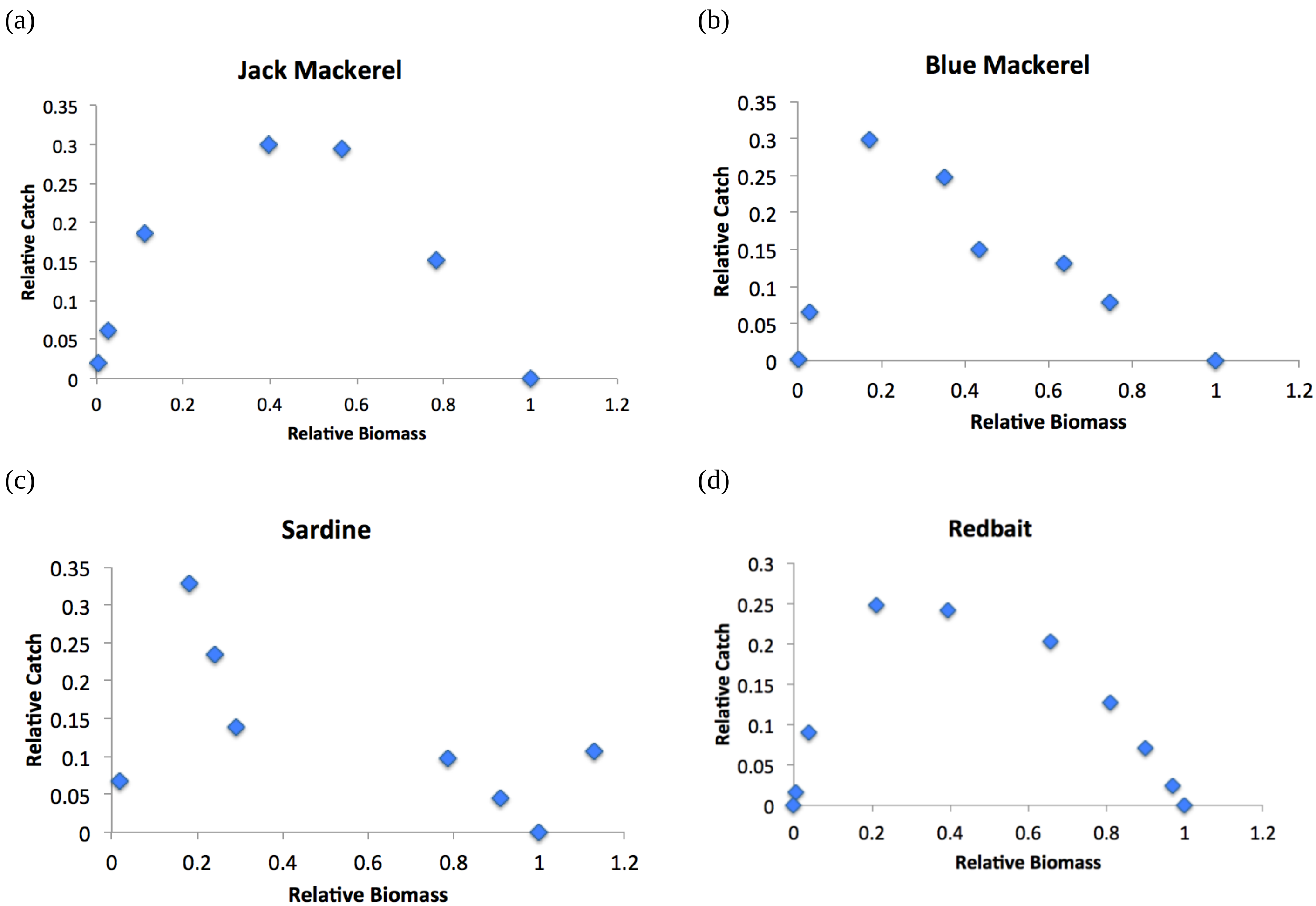
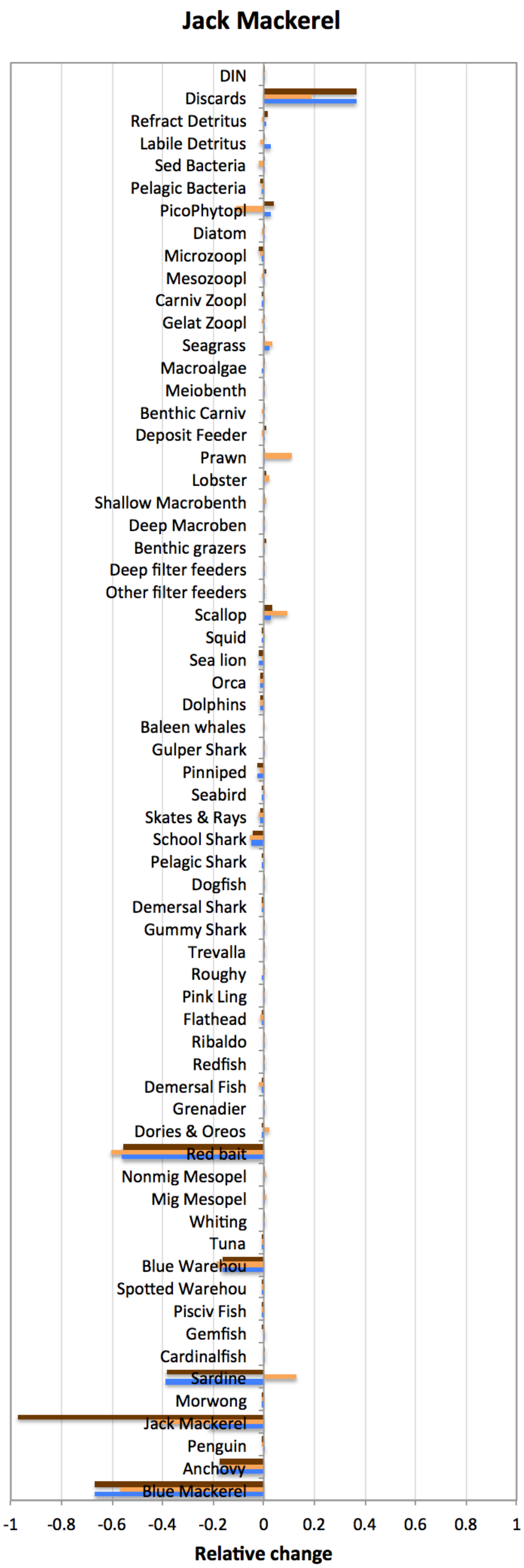


Figure 6: Relative catch and relative biomass achieved from the base Atlantis-SPF model when the base relative exploitation rate is adjusted for each individual species/group separately (by multiplying by scaling factors of 0, 0.25, 0.5, 1, 5, 25, 50) to produce a range of relative equilibrium biomass levels from about 0 to 1.0 (and thus suggest the form of yield curves) - for (a) Jack Mackerel, (b) Blue Mackerel, (c) Sardine, (d) Redbait.

(a)



(b)

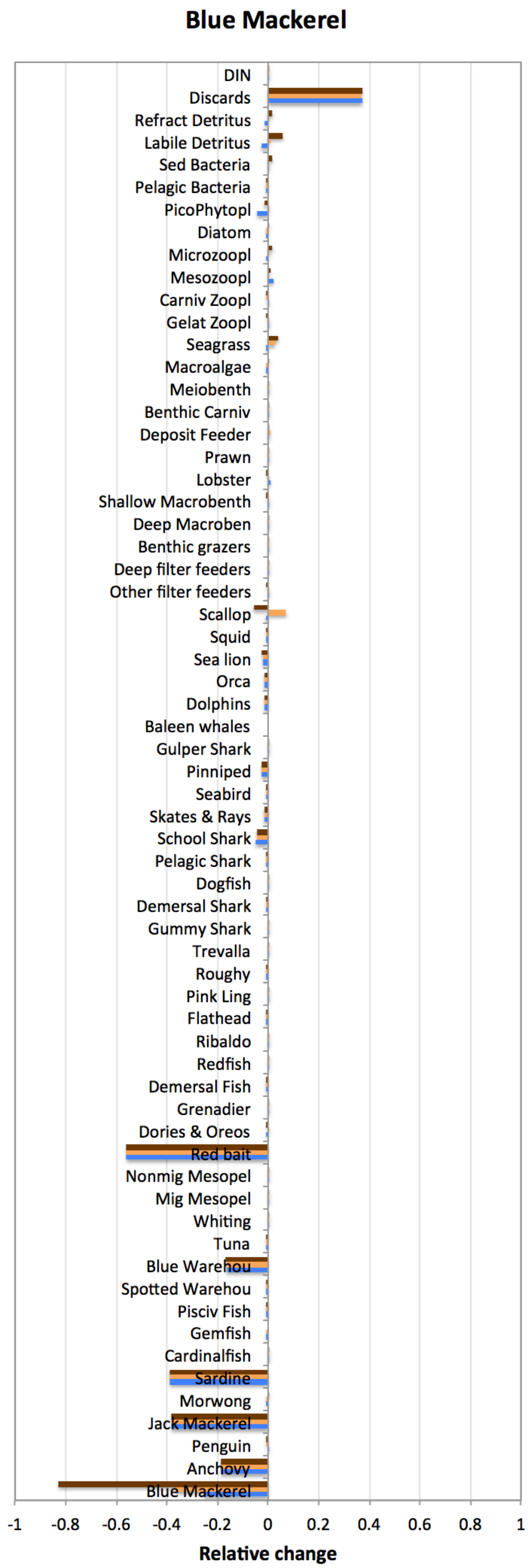


Figure 7: Relative effects of depletion of (a) Jack Mackerel and (b) Blue Mackerel. Brown is depletion to 10% of B_0, orange is 50% depletion and blue is depletion to 80% of B_0.

(a) (b)

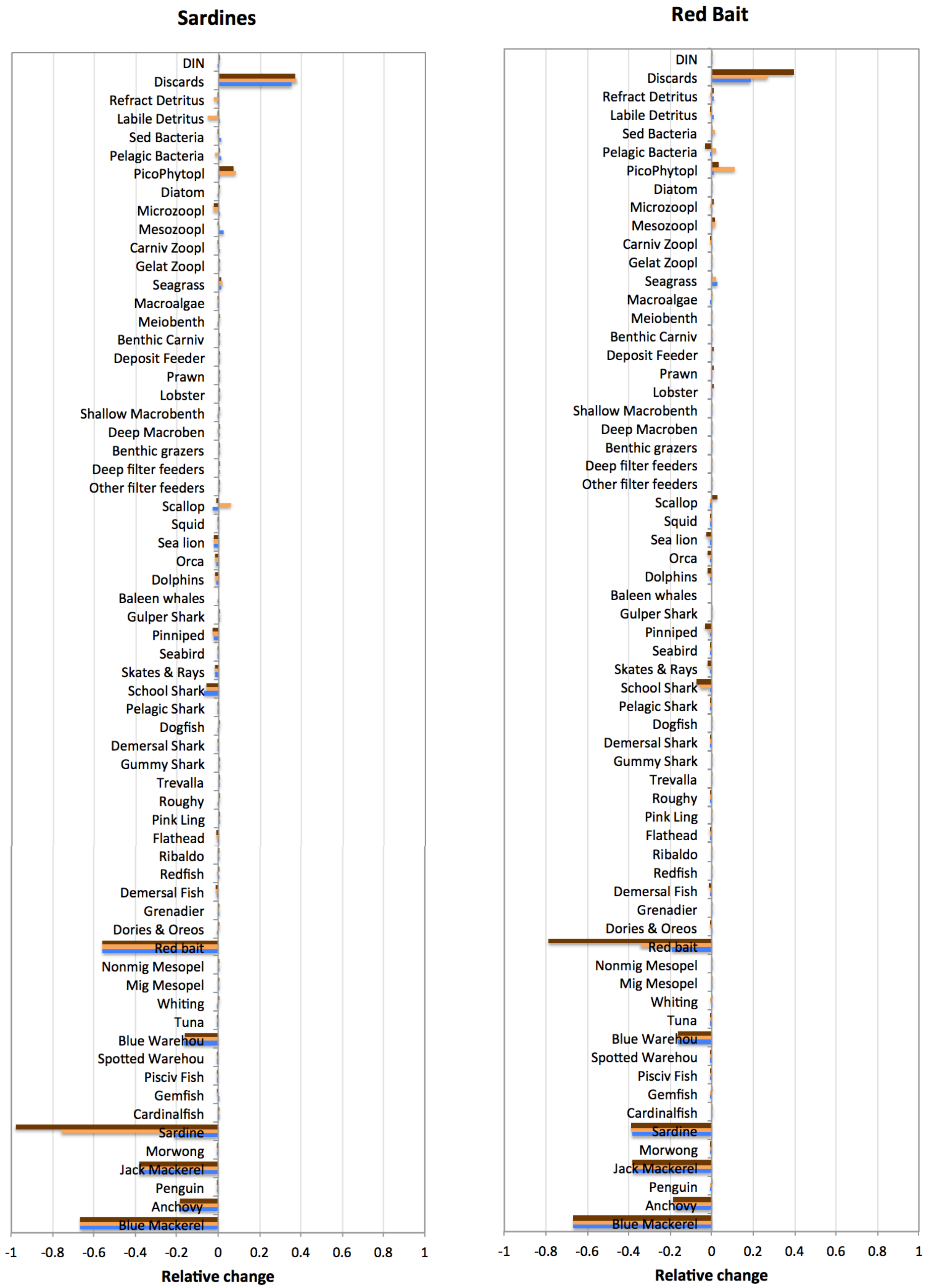


Figure 8: Relative effects of depletion of (a) Sardine and (b) red bait. Brown is depletion to 10% of B0, orange is 50% depletion and blue is depletion to 80% of B0.

Effects of variation in the exploitation rate of all SPF species/groups simultaneously

System-wide effects

The question arose about the effect of depletion of all small pelagics simultaneously as it became clear that wider effects of depletion of individual small pelagic species for the calibrated Atlantis-SPF scenario were minimal. We already know that lower levels of exploitation on all small pelagics (including the current *F* scenario) have minimal broad system impacts, so this investigation was limited to an examination of very high exploitation of all fishable small pelagics. Such a scenario would not occur within any current management framework as it would violate all rules for setting sustainable catch limits. However, the purpose is to investigate theoretically which (particularly predator) groups would be most affected by a reduced abundance of all fishable small pelagic groups.

Current exploitation of small pelagic species was multiplied by scaling factors of 1, 5 and 50 and the effect of those exploitation rates on 6 year average relative biomass of all modelled groups was examined at the end of a 20 year projection period (Figure 9). Levels of exploitation that greatly reduce the available biomass of all fishable small pelagic species still have minimal impact on the broader system, showing only a minor decrease in school shark biomass (less than 20%) and an expected increase in fishery discards of up to 25% (reflecting comparison with the no-fishing scenario).

The ability of predators of small pelagics to switch to alternative prey under the high *F* scenario can be examined by examining changes in diet proportions of all prey when compared to the no fishing zero *F* scenario (Table 5) . Predators are ordered from left to right according to the composition of their diet being fishable small pelagic species when there is no fishing. More than 20% of the diet of certain age classes of toothed whales and sea lions and pinnipeds may be composed of fishable small pelagics, but they compose less than 10% of the diet of all of the other predators in Table 5. Other predators not shown have very small proportions of their diet being fishable small pelagics under no fishing. This is consistent with the data used to calibrate the model.

As anchovy is not a commercially fished species, the small changes in their abundance are due to indirect trophic effects from fishing the commercial small pelagic species as the current F's on anchovy are very low. This means that some species such as toothed whales, sea lions, pinnipeds and Penguin can increase their preference for anchovy. Sea lions and pinnipeds also show a switch towards scallop and shallow macrobenthos. Tuna may switch to large zooplankton (i.e. krill), pelagic shark to shallow macrobenthos and shallow piscivorous fish to other filter feeders, benthic grazers and shallow macrobenthos.

It is notable that no small pelagic predator changes diet preference for Jack Mackerel or Blue Mackerel under this extreme scenario. This is because even under a zero fishing scenario, there are no predators that have these species as a large component of their diet (consistent with the diet data used to construct and calibrate the model), which of course would remain unchanged should the abundance of those prey species reduce. However, even though these prey species form a small proportion of any predator's diet, the total consumption of them from all sources is still sufficient to produce an average annual natural mortality for Blue Mackerel of 0.28 and Jack Mackerel 0.19 under zero fishing (other small pelagics were Sardines 0.58, anchovy 0.65 and Redbait 0.32).

The change in discards is no linear, seeing a much greater step up under a five-fold increase in F then if F is increased fifty-fold. The make-up is also very different. When *F* has increased five-fold the discards of Blue Mackerel and Sardine increase by 2.5x or more, though the discards of red bait only increases by roughly 20% and the discards of Jack Mackerel hold relatively steady. This reflects the differential overall pressure on the SPF species as *F* increases, with Jack Mackerel showing the least evidence of pressure until the *F* multiplier grows substantially (when all are heavily depleted). Once *F* has increased by fifty-fold there is little standing biomass of any of the main SPF target species and the discards in that case reflect other fished species (e.g. SESSF species) or species that could be incidentally taken by SPF, such as anchovy.

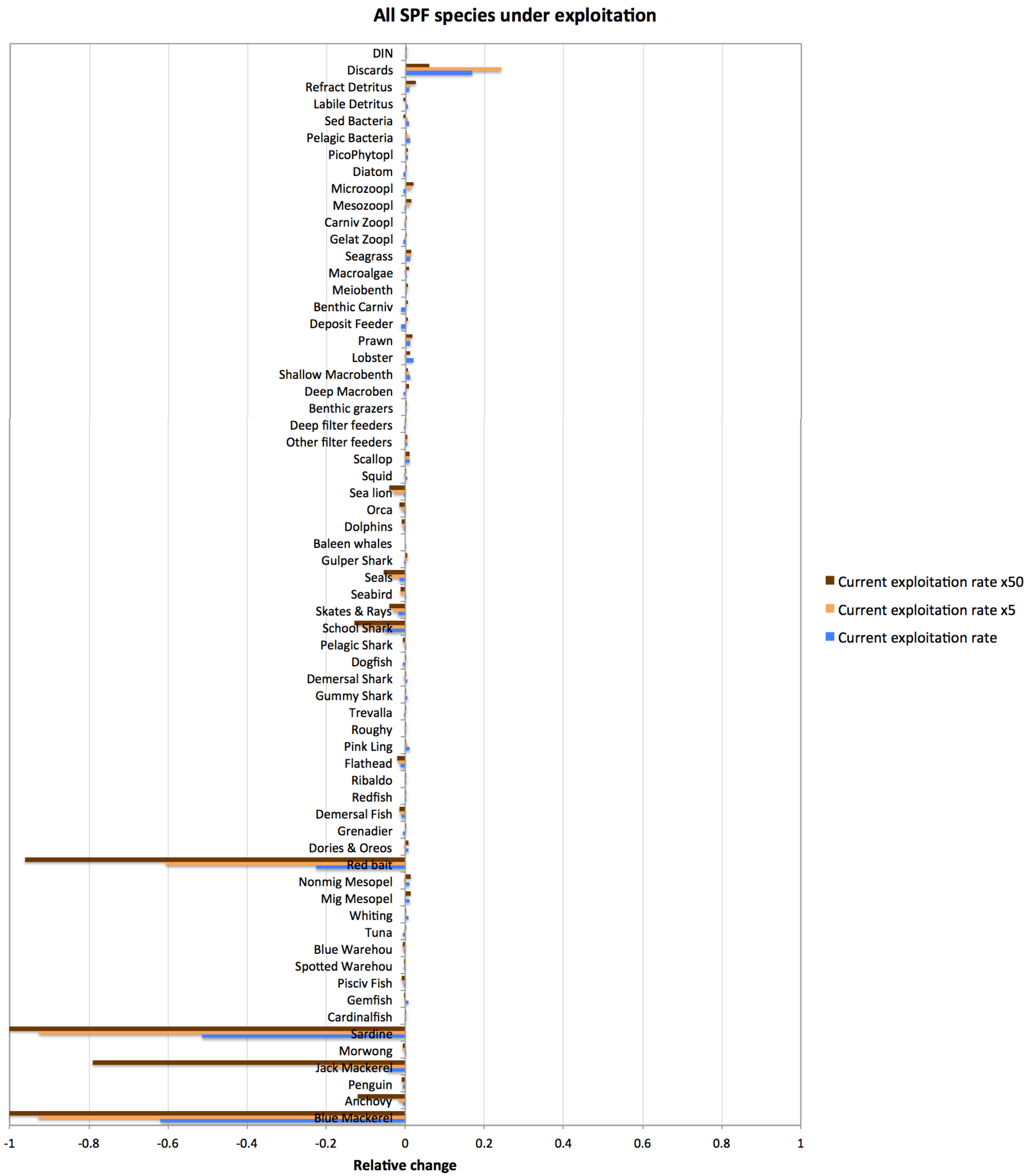


Figure 9: Relative effects on the biomass of all groups in the base Atlantis-SPF of an extreme increase in the exploitation rate of all small pelagic species/groups – current exploitation multiplied by a factors of 1, 5 and 50 (20 year projection).

Table 5: Indicative prey switching of major predators of small pelagics when all small pelagics are subjected to an extreme level of fishing mortality (current F x 50) compared to no fishing (F=0). A '+' indicates switching to a species under high F, and '-' is away from, with the number of symbols indicating the relative strength of that switching compared to that seen in other groups.

	Predator						
Prey	Toothed whale	Sea lion	Seal	Penguin	Tuna	Pelagic shark	Shallow piscivorous fish
Blue Mackerel							
Anchovy	++	+	+	+			
Jack Mackerel							
Sardine		-		-			
Shallow water piscivores	--	-	--		-		-
Migratory mesopelagics		--	-	-			-
Non-migratory mesopelagics	+						
Redbait	+	--	-				
Dories and oreos		-					
Shallow water demersal fish		-	-				
Scallops		++	++				
Other shallow water filter feeders							++
Benthic grazer		--	--			--	++
Lobster	-						
Shallow macrobenthos		++	++		+	++	++
Carnivorous zooplankton				--	--		--
Gelatinous zooplankton			-		-	--	--
Zooplankton					++		+

Objective 2: Provide advice on suitable exploitation rates to achieve management targets for the four main target species in the SPF

Evaluation of harvest strategies for the small pelagic fishery

Stage 1

The first set of evaluations examines the application of the current harvest strategy settings for the SPF, including various scenarios and sensitivity tests.

Results of the management strategy evaluation are presented by species. All species use the operating model described above. For each species, the Parameterisation of the operating model is described first, followed by the identification of reference points and a profile of exploitation rate vs. depletion, and finally the results for all the management scenarios. In the following, probabilities of depletion are expressed as percentages. For example, “P Dep. 0.5” is the probability (as a % of runs) that the stock is below B_{50} (half of the unfished biomass) at the end of the simulation period. Unfished biomass is defined as the mean equilibrium biomass of a population simulated with no fishing and only recruitment uncertainty.

1. REDBAIT (*Emmelichthys nitidus*)

Parameterisation

Data for Redbait (*Emmelichthys nitidus*) were derived from Ward *et al.*. (2012), Neira *et al.*. (2008) and Giannini *et al.*. (2010). Two stocks (east and west) were Parameterised separately. The value for steepness used was 0.74 (Giannini *et al.*. 2010). Natural mortality was set at $0.26yr^{-1}$. Annex 1 shows the numerical values used for all parameters. Figure 10 shows the length-at-age and weight-at-age relationships. Table 6 gives the parameters used for these relationships.

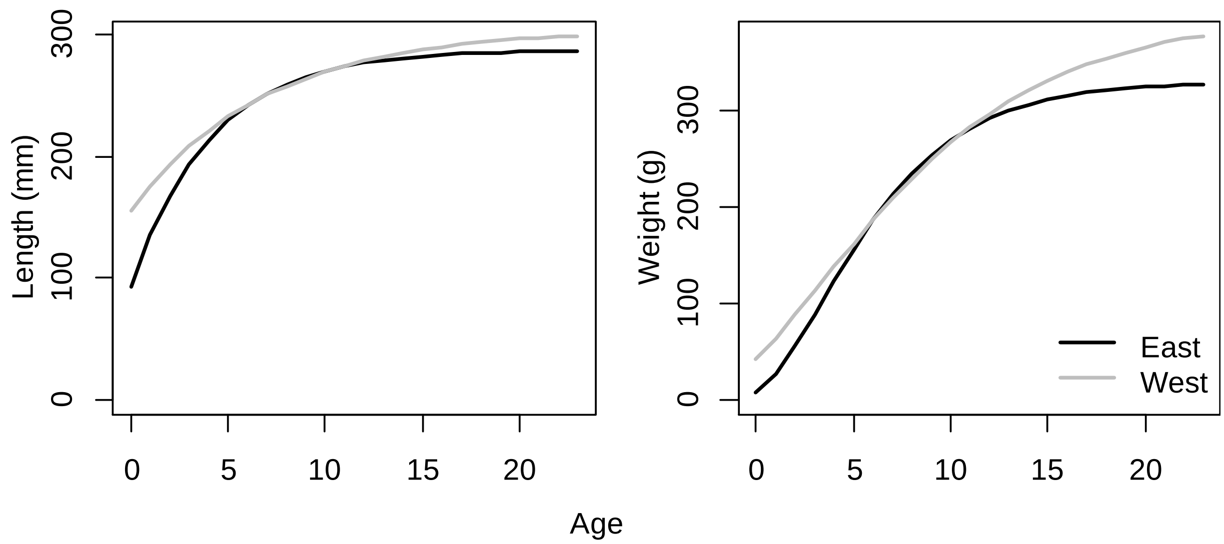


Figure 10: Length- and weight-at-age for Redbait

Selectivity was derived using a catch curve from catches reported in Ward *et al.*. (2012). A catch curve (i.e. a linear model) was fit to the log of sampled fish-by-age, for those ages above the age at which the catch is highest. Selectivity for ages above this age was assumed to be 1, while for those ages below it was defined as the ratio between the catch curve and the log of sampled fish-by-age. Maturity was taken from Neira *et al.*. (2008) and parameters are shown in Table 6. The catch curve and the selectivity and maturity ogives are shown in Figure 11 for the eastern stock and Figure 12 for the western stock.

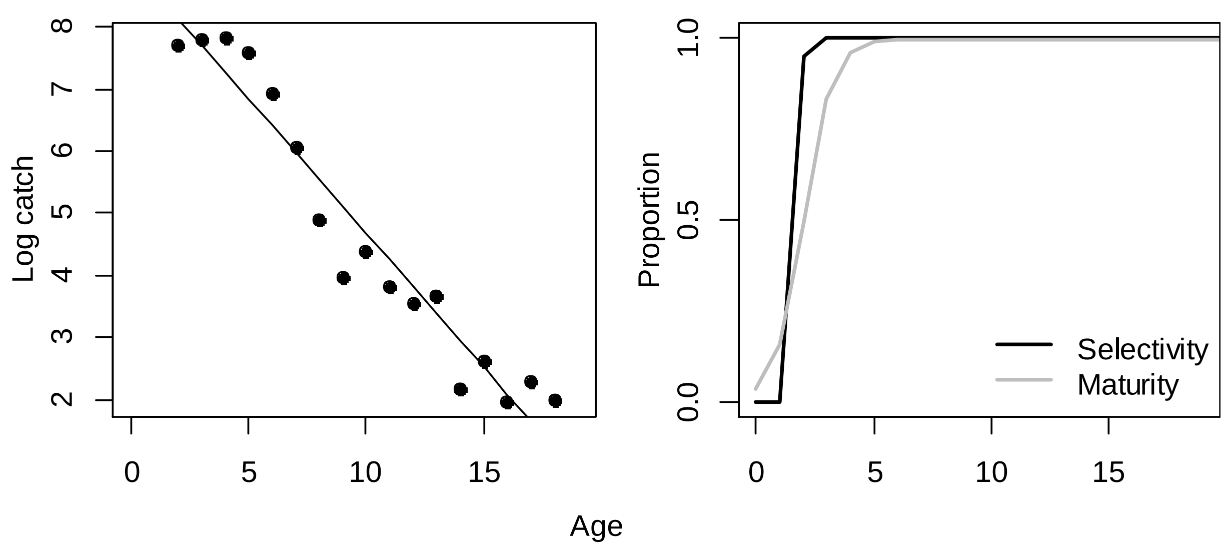


Figure 11: Catch curve and selectivity and maturity ogives for the eastern Redbait stock.

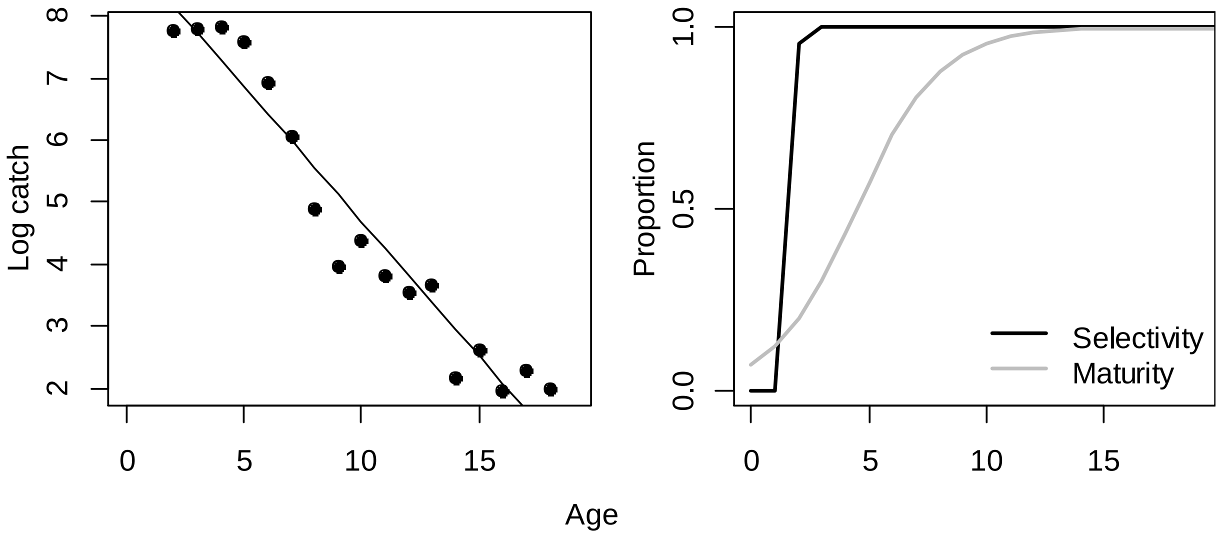


Figure 12: Catch curve and selectivity and maturity ogives for the western Redbait stock.

Table 6: Growth and maturity parameters for Redbait

Parameter	East	West
L_∞ (mm)	288.0	305.2
K (yr^{-1})	0.24	0.14
t_0 (yr)	-1.61	-4.94
Ω_1	2.0E-6	2.0E-6
Ω_2	3.342	3.342
Ω_3*	3.24	2.50
Ω_4* (yr^{-1})	-1.62	-0.56

*For Redbait, maturity is Parameterised in terms of age. It also uses equation (4), but uses age instead of length (*L*).

Identification of reference points

Profiles of exploitation rate vs. depletion and exploitation rate vs. relative catch are shown in Figure 13. Reference points are shown in Table 7.

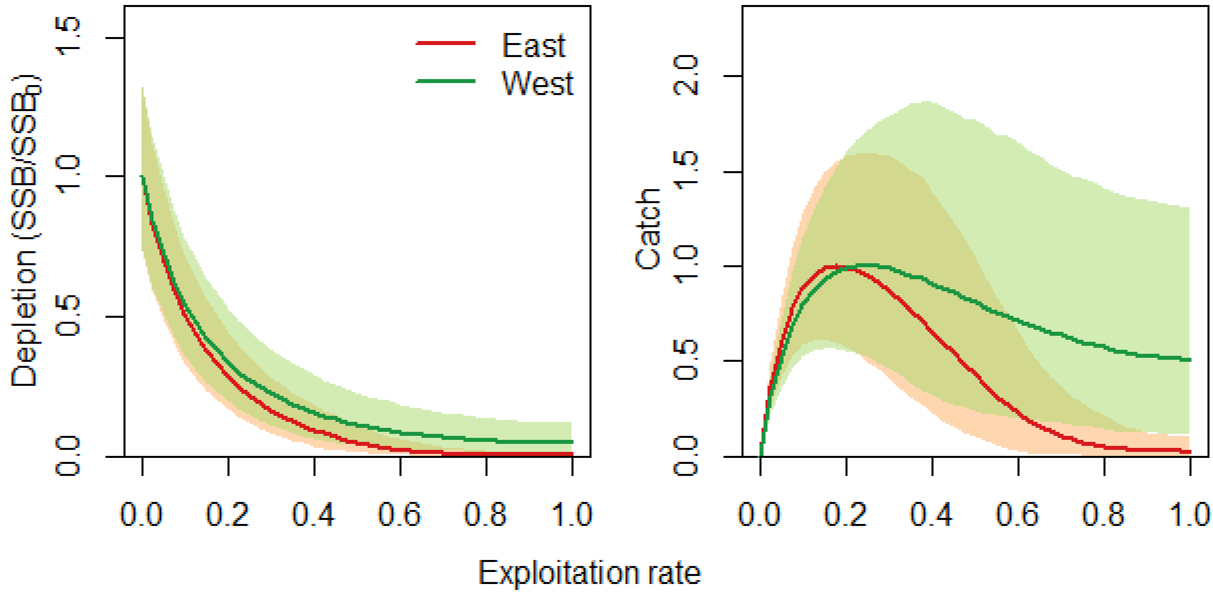


Figure 13: Profiles of exploitation rate vs. depletion and relative catch for Redbait. Shaded regions show the 95% simulation interval. Solid lines are means.

Table 7: Exploitation rate reference points for Redbait. Values are the exploitation rates necessary to achieve a given objective. E_{MSY} is the exploitation rate that maximizes expected catch.

Objective	East	West
E_{MSY}*	0.175	0.250
Depl = 0.9	0.015	0.016
Depl = 0.8	0.031	0.034
Depl = 0.75	0.040	0.044
Depl = 0.7	0.050	0.055
Depl = 0.6	0.073	0.082
Depl = 0.5	0.102	0.116
Depl = 0.4	0.140	0.162

*Depletion levels for E_{MSY} are 0.33 and 0.27 for east and west respectively.

MSE, base cases

Results for the base cases are shown in Table 8 for the eastern stock and Table 9 for the western stock. See the methods section under objective 2 for description of the scenarios. Results for the eastern stock show that the base case harvest strategy (Tier 1 with a constant exploitation rate of 15% and surveys every five years) results in catches close to MSY and an average depletion of 0.39, but a reasonably high probability of depleting the stock below B_{20} (9%), The Tier 2 strategy (constant exploitation rate of 7.5% but no assessment, Scenario 4) results in poor performance with a high probability of depleting the stock. Reducing the frequency of DEPM surveys to every 10 years (Scenario 5) also results in high probability of depletion, even though the second five years apply a Tier 2 exploitation rate. For the western stock, the average stock sizes are higher and the probabilities of depletion correspondingly lower. Only scenario 2 (constant exploitation rate of 20%) leads to unacceptable probabilities (defined in the harvest strategy policy as greater than a 10% chance) of the stock being reduced below B_{20}. These differences between the eastern and western stocks are consistent with the results shown in Figure 13 and Table 7 which shows the western stock to be somewhat more productive.

Table 8: MSE results for Redbait, east stock.

Scenario	1	2	3	4	5	6	7	8	9	10
Index										
Mean Dep.	1	0.3	**0.39**	0.20	0.37	0.40	0.47	0.75	0.76	0.76
Mean Catch	0.00	0.99	**0.96**	0.64	0.90	0.94	0.60	0.52	0.52	0.52
P Dep. 0.60	0.00	100	**95.32**	95.60	93.34	94.60	82.61	20.75	21.50	23.59
P Dep. 0.50	0.00	97.99	**87.09**	90.55	84.33	85.02	65.49	3.94	5.50	6.83
P Dep. 0.40	0.00	91.53	**67.05**	84.13	66.84	63.93	41.21	0.00	0.00	1.07
P Dep. 0.30	0.00	67.94	**33.82**	72.78	42.67	31.01	19.89	0.00	0.00	0.00
P Dep. 0.20	0.00	22.12	**9.30**	60.60	21.73	8.10	8.14	0.00	0.00	0.00

Table 9: MSE results for Redbait, west stock.

Scenario	1	2	3	4	5	6	7	8	9	10
Index										
Mean Dep.	1	0.38	**0.46**	0.69	0.45	0.47	0.54	0.77	0.77	0.77
Mean Catch	0.00	0.98	**0.92**	0.61	0.86	0.89	0.55	0.48	0.48	0.48
P Dep. 0.60	1.13	98.67	**93.29**	51.42	91.01	92.55	80.36	28.08	28.88	30.09
P Dep. 0.50	0.00	95.12	**82.45**	25.12	78.83	80.33	61.41	6.91	8.29	9.67
P Dep. 0.40	0.00	84.06	**57.61**	7.62	58.25	54.52	36.15	0.00	0.00	1.82
P Dep. 0.30	0.00	51.06	**25.49**	1.17	33.19	23.45	15.33	0.00	0.00	0.00
P Dep. 0.20	0.00	11.97	**5.72**	0.00	14.3	5.11	5.51	0.00	0.00	0.00

MSE, sensitivity cases

Results for the sensitivity cases are shown in Table 10 for the eastern stock and Table 11 for the western stock. See the methods section for objective 2 for description of the scenarios. Several of these scenarios are problematic for the eastern stock. For example, the probability that the stock will be depleted below B_{20} is greater than 10% (the default value in the Commonwealth harvest strategy policy - HSP) for S1 (DEPM survey CV increased from 0.3 to 0.5), S2 (the DEPM survey has a positive bias of 50%), S4 (the DEPM survey has a positive bias of 25%), S7 (the stock has lower steepness – is less productive – than anticipated) and S9 (the true selectivity curve is shifted to the left by one year, resulting in a higher exploitation rate than anticipated). For the western stock, scenarios S1, S2 and S7 also breach the HSP risk criterion, though only by a small margin.

Table 10: MSE sensitivity results for Redbait, east stock.

Scenario	3	S1	S2	S3	S4	S5	S6	S7	S8	S9
Index										
Mean Dep.	**0.39**	0.38	0.34	0.44	0.36	0.41	0.46	0.29	0.43	0.34
Mean Catch	**0.96**	0.92	0.96	0.94	0.97	0.96	1.14	0.71	1.06	0.84
P Dep. 0.60	**95.32**	93.03	97.41	91.95	96.51	93.73	89.78	100	92.98	97.37
P Dep. 0.50	**87.09**	83.35	92.66	78.58	90.17	83.32	74.20	96.93	81.09	92.48
P Dep. 0.40	**67.05**	63.94	79.49	51.73	73.63	59.66	46.58	89.19	55.46	78.89
P Dep. 0.30	**33.82**	37.82	50.61	20.32	42.30	27.03	18.72	67.95	24.11	49.47
P Dep. 0.20	**9.30**	*17.13*	*18.16*	3.94	*13.63*	6.00	4.07	*29.45*	4.92	*18.03*

Table 11: MSE sensitivity scenarios for Redbait, west stock.

Scenario	3	S1	S2	S3	S4	S5	S6	S7	S8	S9
Index										
Mean Dep.	**0.46**	0.46	0.42	0.5	0.44	0.48	0.51	0.38	0.48	0.44
Mean Catch	**0.92**	0.89	0.95	0.88	0.93	0.90	1.02	0.76	0.95	0.87
P Dep. 0.60	**93.29**	90.49	95.91	89.56	94.71	91.74	89.03	97.36	91.92	94.73
P Dep. 0.50	**82.45**	78.45	88.98	73.27	86.15	78.27	72.21	92.26	78.81	86.04
P Dep. 0.40	**57.61**	55.23	70.48	44.15	64.60	50.69	43.46	77.69	51.81	64.32
P Dep. 0.30	**25.49**	28.70	38.92	15.69	31.76	19.73	16.18	46.36	20.62	31.85
P Dep. 0.20	**5.72**	*10.80*	*11.48*	2.58	8.23	3.66	3.23	*13.95*	3.94	8.39

2. JACK MACKEREL (*Trachurus declivis*)

Parameterisation

Data for Jack Mackerel (*Trachurus declivis*) were taken from Ward *et al.*. (2012b) and Giannini *et al.*. (2010). No information was available for the western stock, so the following information corresponds to the eastern stock. The value for steepness used was 0.75 (Giannini *et al.*. 2010). Natural mortality was set at 0.26yr^{-1}. Annex 1 shows the numerical values used for all parameters. Figure 14 shows the length-at-age and weight-at-age relationships. Table 12 gives the parameters used for these relationships.

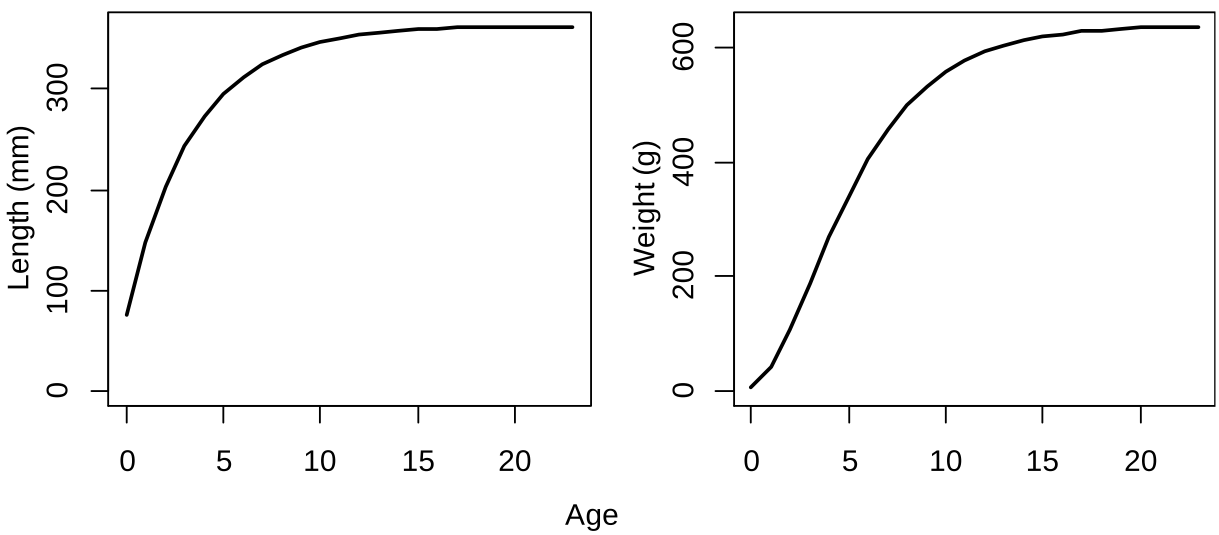


Figure 14: Length- and weight-at-age for Jack Mackerel.

Selectivity was derived using a catch curve from catches reported in Ward *et al.*. (2012b). A catch curve (i.e. a linear model) was fit to the log of sampled fish-by-age, for those ages above the age at which the catch is highest. Selectivity for ages above this age was assumed to be 1, while for those ages below it was defined as the ratio between the catch curve and the log of sampled fish-by-age. Maturity was taken from Ward *et al.*. (2012b) and parameters are shown in Table 12. The catch curve and the selectivity and maturity ogives are shown in Figure 15.

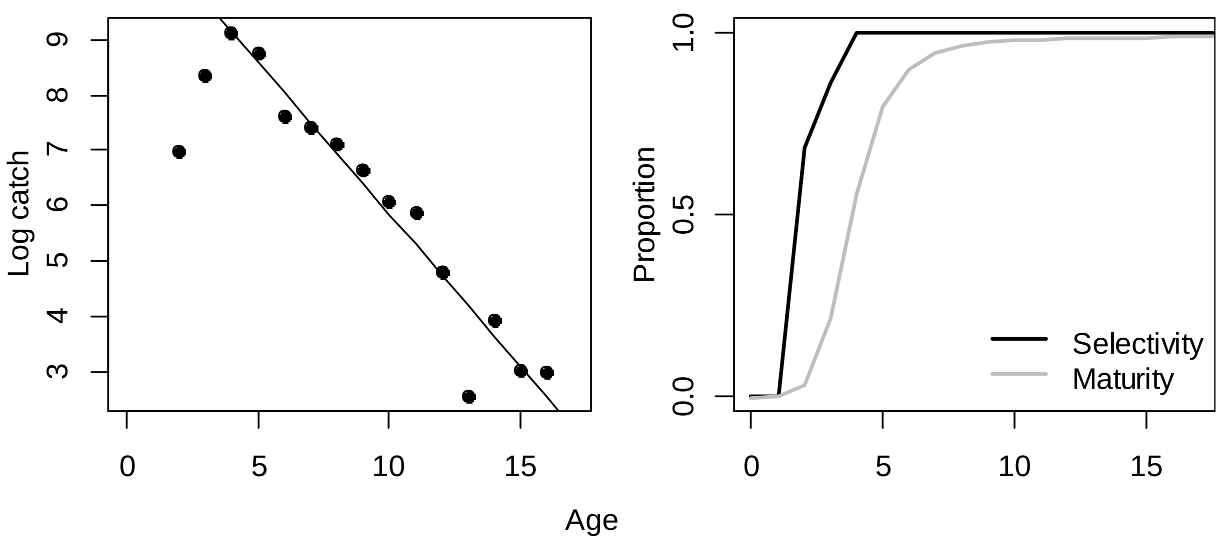


Figure 15: Catch curve and selectivity and maturity ogives for Jack Mackerel.

Table 12: Growth and maturity parameters for Jack Mackerel

Parameter	
L_∞ (mm)	362.8
K (yr^{-1})	0.29
t_0 (yr)	-0.81
Ω_1	9.4E-6
Ω_2	3.060
Ω_3	13.4
Ω_4 (mm^{-1})	-0.05

Identification of reference points

Profiles of exploitation rate vs. depletion and exploitation rate vs. relative catch are shown in Figure 16. Reference points are shown in Table 13.

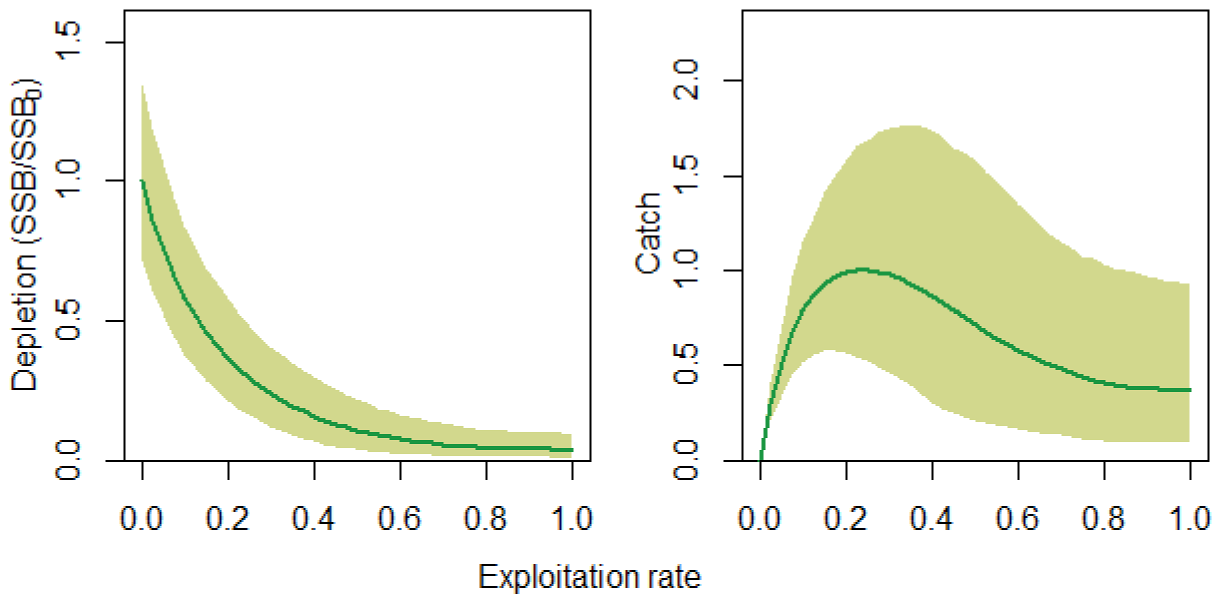


Figure 16: Profiles of exploitation rate vs. depletion and relative catch for Jack Mackerel. Shaded region shows the 95% simulation interval. Solid lines are means.

Table 13: Reference points for Jack Mackerel. Values are the exploitation rates necessary to achieve a given objective. E_{MSY} is the exploitation rate that maximizes expected catch.

Objective	Exploitation rate
E_{MSY}*	0.225
Depl = 0.9	0.018
Depl = 0.8	0.039
Depl = 0.75	0.050
Depl = 0.7	0.064
Depl = 0.6	0.093
Depl = 0.5	0.131
Depl = 0.4	0.179

*Depletion level for E_{MSY} is 0.33.

MSE, base cases

Results for the base cases are shown in Table 14. See the methods section under objective 2 for description of the scenarios. The base case scenario (constant exploitation rate of 15% and DEPM surveys every 5 years) results in an average depletion of 0.47 and a probability of being below B_{20} of less than 10%. The only scenario that breaches the HSP risk criterion is scenario 5 (DEPM surveys every 10 years).

Table 14: MSE results for Jack Mackerel.

Scenario	1	2	3	4	5	6	7	8	9	10
Index										
Mean Dep.	1	0.38	**0.47**	0.63	0.45	0.48	0.54	0.76	0.76	0.76
Mean Catch	0.00	0.98	**0.91**	0.72	0.87	0.88	0.54	0.51	0.5	0.51
P Dep. 0.60	1.10	96.82	**87.22**	57.42	84.19	85.36	70.82	22.42	23.38	25.66
P Dep. 0.50	0.00	90.52	**70.39**	33.53	68.51	68.17	50.50	5.29	6.98	8.98
P Dep. 0.40	0.00	72.60	**43.47**	14.12	48.88	40.56	28.91	0.00	0.00	1.89
P Dep. 0.30	0.00	36.83	**17.72**	4.02	28.60	16.47	13.13	0.00	0.00	0.00
P Dep. 0.20	0.00	6.13	**3.97**	0.00	*14.05*	3.66	5.51	0.00	0.00	0.00

MSE, sensitivity cases

Results for the sensitivity cases are shown in Table 15. See the methods section under objective 2 for description of the scenarios. None of these scenarios results in breaching the HSP risk criterion at B_{20}, although S7 (low productivity) comes close.

Table 15: MSE sensitivity results for Jack Mackerel.

Scenario	3	S1	S2	S3	S4	S5	S6	S7	S8	S9
Index										
Mean Dep.	0.47	0.47	0.42	0.52	0.45	0.49	0.52	0.39	0.51	0.42
Mean Catch	0.91	0.88	0.94	0.87	0.93	0.89	1.01	0.76	0.99	0.80
P Dep. 0.60	87.22	83.52	91.83	80.38	89.89	84.00	79.04	94.10	81.76	92.16
P Dep. 0.50	70.39	67.18	79.98	58.96	75.39	65.03	57.53	85.05	61.23	80.91
P Dep. 0.40	43.47	43.34	56.80	30.70	50.01	36.82	30.95	65.17	33.44	57.80
P Dep. 0.30	17.72	22.05	27.80	9.85	22.29	13.64	10.82	33.33	11.42	28.55
P Dep. 0.20	3.97	8.84	8.35	1.99	5.77	2.79	2.62	9.42	2.08	8.73

3. BLUE MACKEREL (*Scomber australasicus*)

Parameterisation

Data for Blue Mackerel (*Scomber australasicus*) were derived from Ward *et al.*. (2012b), Ward and Rogers (2007) and Giannini *et al.*. (2010). Two stocks (east and west) were Parameterised separately. The value for steepness used was 0.59 (Giannini *et al.*. 2010). Natural mortality was set at $0.62 yr^{-1}$. Annex 1 shows the numerical values used for all parameters. Figure 17 shows the length-at-age and weight-at-age relationships. Table 16 gives the parameters used for these relationships.

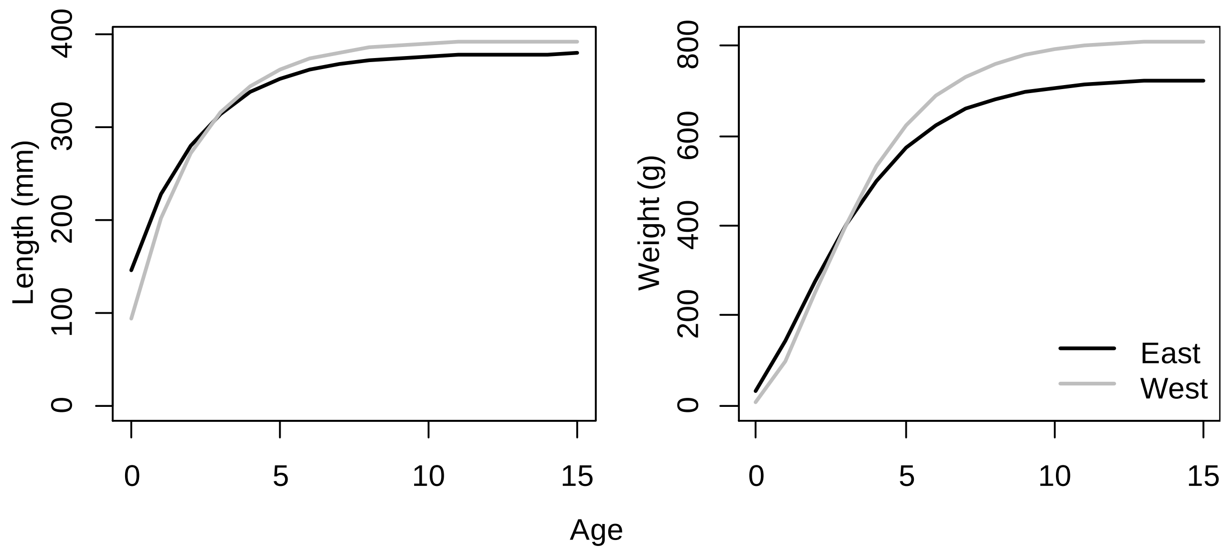


Figure 17: Length- and weight-at-age for Blue Mackerel

Selectivity was derived using a catch curve from catches reported in Ward *et al.*. (2012b). A catch curve (i.e. a linear model) was fit to the log of sampled fish-by-age, for those ages above the age at which the catch is highest. Selectivity for ages above this age was assumed to be 1, while for those ages below it was defined as the ratio between the catch curve and the log of sampled fish-by-age. No catch-at-age data was available for the eastern stock, so selectivity was assumed to be similar for both stocks.

Maturity was taken from Ward and Rogers (2007) and parameters are shown in Table 13. The catch curve and the selectivity and maturity ogives are shown in Figure 18 for the eastern stock and Figure 19 for the western stock.

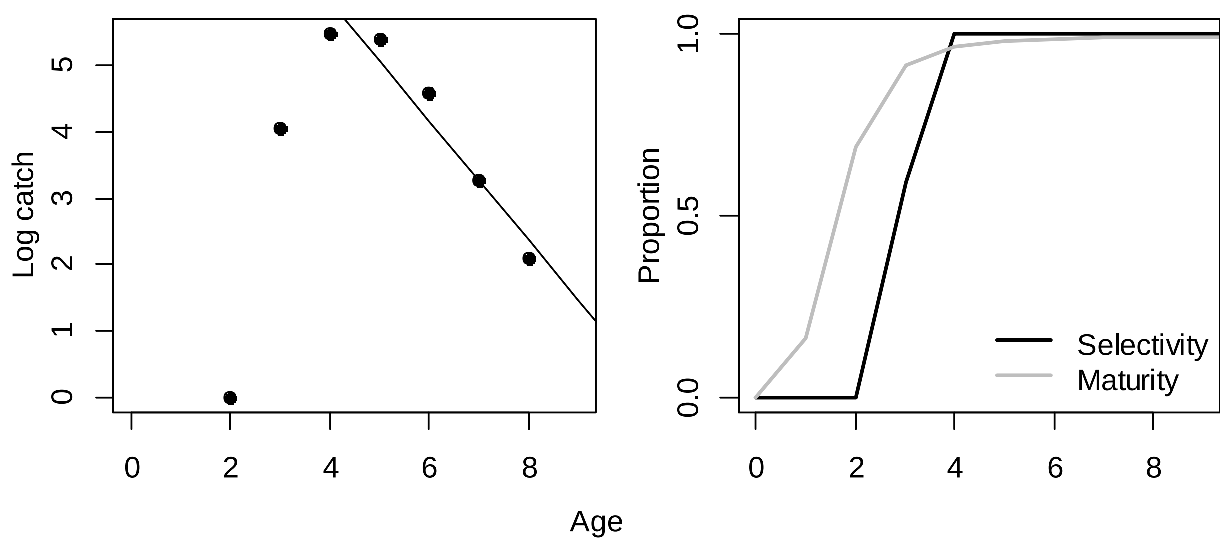


Figure 18: Catch curve and selectivity and maturity ogives for the eastern Blue Mackerel stock.

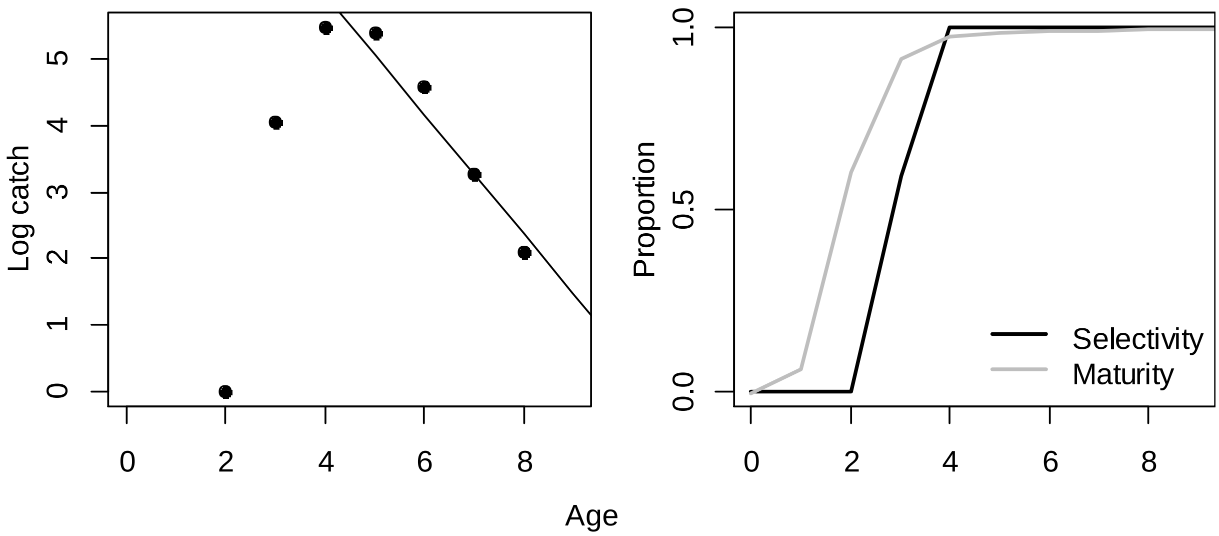


Figure 19: Catch curve and selectivity and maturity ogives for the western Blue Mackerel stock.

For Blue Mackerel, unlike the other species examined here, it is evident that the selectivity ogive is to the right of the maturity ogive but there is considerable uncertainty about the form of selectivity. For the purposes of the simulations, selectivity was set equal to maturity to prevent unreasonable behaviour in the model (such as inability to deplete the stock at high exploitation rates).

Table 16: Growth and maturity parameters for Blue Mackerel.

Parameter	East	West
L_∞ (mm)	378.88	392.64
K (yr^{-1})	0.43	0.45
t_0 (yr)	-1.12	-0.61
Ω_1	4.9E-6	4.9E-6
Ω_2	3.169	3.169
Ω_3	11.79	11.79
Ω_4 (mm^{-1})	-0.045	-0.045

Identification of reference points

Profiles of exploitation rate vs. depletion and exploitation rate vs. relative catch are shown in Figure 20. Reference points are shown in Table 17.

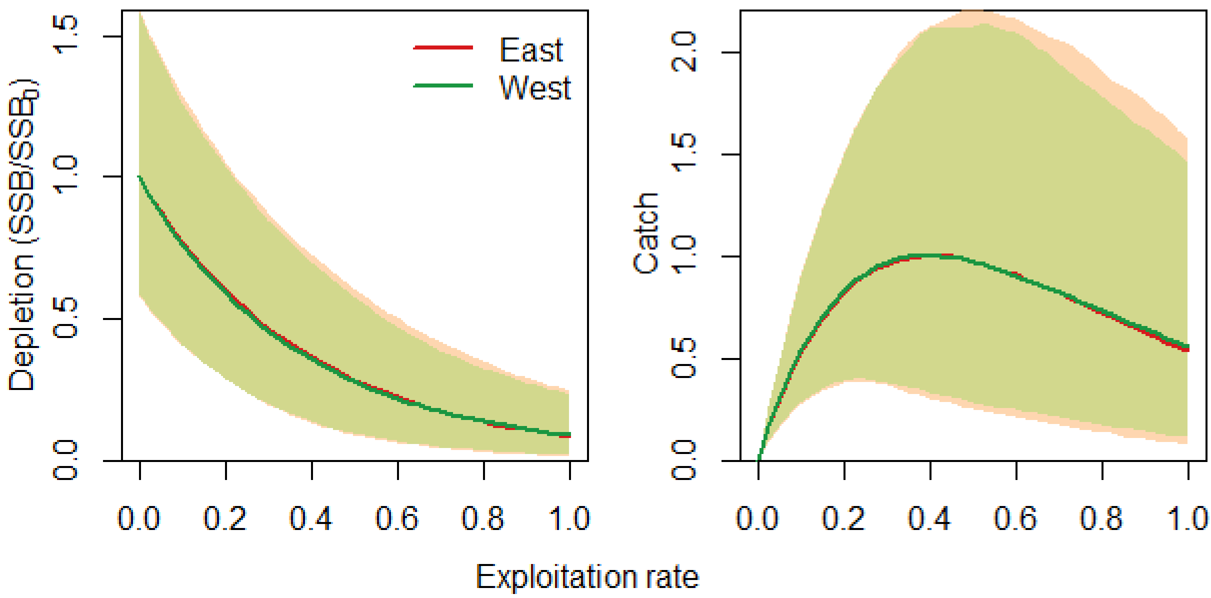


Figure 20: Profiles of exploitation rate vs. depletion and relative catch for Blue Mackerel. Shaded regions show the 95% simulation interval. Solid lines are means.

Table 17: Reference points for Blue Mackerel. Values are the exploitation rates necessary to achieve a given depletion. E_{MSY} is the exploitation rate that maximizes expected catch.

Ref. Point	East	West
Emsy	0.40	0.40
Emsy Dep	0.36	0.36
Target Dep		
0.9	0.039	0.038
0.8	0.084	0.082
0.7	0.136	0.133
0.6	0.198	0.193
0.5	0.272	0.265
0.4	0.362	0.354

MSE, base cases

Results for the base cases are shown in Table 18 for the eastern stock and Table 19 for the western stock. See the methods section under objective 2 for description of the scenarios. None of the scenarios for either stock result in the HSP risk criterion being breached. This is a direct result of the finding that the species matures before it is selected by the fishery, thus making it unlikely for severe depletion to occur.

Table 18: MSE results for Blue Mackerel, east stock.

Scenario	1	2	3	4	5	6	7	8	9	10
Index										

Mean Dep.	1	0.6	**0.67**	0.67	0.65	0.68	0.73	0.71	0.7	0.69
Mean Catch	0	0.82	**0.69**	0.62	0.67	0.66	0.36	0.64	0.63	0.62
P Dep. 0.60	6.2	58.2	**44.61**	44.91	46.2	43.89	35.88	37.75	39.02	40.4
P Dep. 0.50	1.84	38.9	**27.99**	29.72	32.27	27.59	23.2	20.29	23.52	27.15
P Dep. 0.40	0	19.66	**14.22**	17.4	19.32	13.7	12.43	7.73	10.45	15.01
P Dep. 0.30	0	6.21	**4.80**	9.03	9.84	4.74	5.29	1.67	3.14	6.91
P Dep. 0.20	0	0	**1.18**	4.53	4.36	1.1	1.97	0	0	2.71

Table 19: MSE results for Blue Mackerel, west stock.

Scenario	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Index										
Mean Dep.	1	0.59	**0.66**	0.7	0.65	0.67	0.72	0.71	0.71	0.7
Mean Catch	0	0.83	**0.69**	0.6	0.68	0.67	0.37	0.64	0.63	0.62
P Dep. 0.60	5.8	59.57	**45.06**	40.07	46.73	44.34	35.97	36.74	38.4	39.83
P Dep. 0.50	1.68	39.35	**28.12**	25.19	32.36	27.76	23.32	19.54	22.27	26.28
P Dep. 0.40	0	19.87	**13.82**	13.42	19.55	13.56	12.32	7.05	9.61	14.04
P Dep. 0.30	0	5.9	**4.7**	6	9.29	4.55	5.24	1.49	2.75	6.26
P Dep. 0.20	0	0	**1.09**	2.45	4.18	1.13	1.88	0	0	2.3

MSE, sensitivity cases

Results for the sensitivity cases are shown in Table 20 for the eastern stock and Table 21 for the western stock. See the methods section under objective 2 for description of the scenarios. The HSP risk criterion is not breached for any of these scenarios.

Table 20: MSE sensitivity results for Blue Mackerel, east stock.

Scenario	**3**	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**
Index										
Mean Dep.	0.67	0.67	0.63	0.71	0.65	0.69	0.78	0.51	0.7	0.63
Mean Catch	0.69	0.67	0.75	0.62	0.72	0.66	0.8	0.52	0.72	0.64
P Dep. 0.50	27.99	29.26	34.37	22.99	31.28	25.51	16.54	55.15	23.98	34.27
P Dep. 0.30	4.8	7.37	7.57	2.93	6.13	3.81	2.31	16.01	3.35	7.61
P Dep. 0.25	2.51	4.6	4.33	1.47	3.32	1.85	1.04	9.24	1.43	4.23
P Dep. 0.20	1.18	2.94	2.36	0	1.66	0	0	4.58	0	2.31

Table 21: MSE sensitivity scenarios for Blue Mackerel, west stock.

Scenario	**3**	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**
Index										
Mean Dep.	0.66	0.66	0.62	0.7	0.64	0.68	0.76	0.52	0.7	0.61
Mean Catch	0.69	0.68	0.75	0.63	0.73	0.66	0.8	0.54	0.73	0.64
P Dep. 0.50	28.12	29.43	34.67	22.63	31.46	25.28	17.05	53.74	22.95	36.61
P Dep. 0.30	4.7	6.85	7.31	2.82	5.78	3.61	2.29	14.43	2.69	8.47
P Dep. 0.25	2.41	4.48	3.99	1.44	3.14	1.85	1.18	8.21	1.21	4.84
P Dep. 0.20	1.09	2.64	2.17	0	1.6	0	0	3.96	0	2.75

4. AUSTRALIAN SARDINE (*Sardinops sagax*)

Parameterisation

Data for Australian Sardine (*Sardinops sagax*) were derived from Ward *et al.*. (2012b), Ward *et al.*. (2012a), Rogers and Ward (2007), and Giannini *et al.*. (2010). Two stocks (east and west) were Parameterised separately. The value for steepness used was 0.59 (Giannini *et al.*. 2010). Natural mortality was set at 0.62yr^{-1}. Annex 1 shows the numerical values used for all parameters. Figure 21 shows the length-at-age and weight-at-age relationships. Table 22 gives the parameters used for these relationships. Since no data were available for eastern Sardine, it was assumed that growth was similar to the western stock.

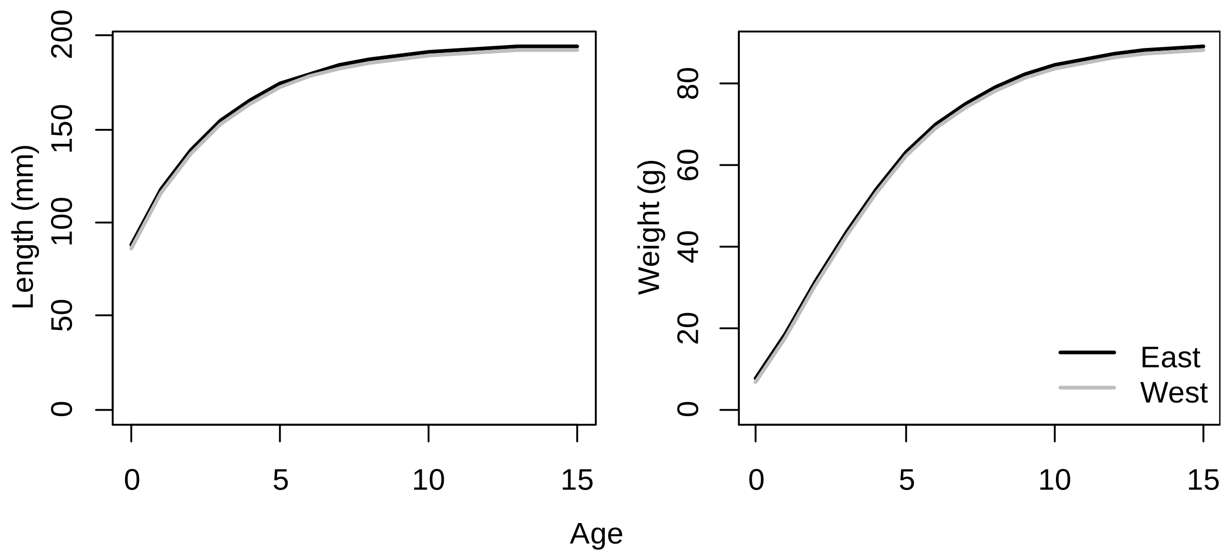


Figure 21: Length- and weight-at-age for Australian Sardine.

Selectivity was derived using a catch curve from catches reported in Ward *et al.*. (2012b) and Ward *et al.*. (2012a). A catch curve (i.e. a linear model) was fit to the log of sampled fish-by-age, for those ages above the age at which the catch is highest. Selectivity for ages above this age was assumed to be 1, while for those ages below it was defined as the ratio between the catch curve and the log of sampled fish-by-age.
Maturity was taken from Ward *et al.*. (2012a) and parameters are shown in Table 17. No maturity data were available for the eastern stock so maturity was assumed to be similar to that of the western stock. The catch curve and the selectivity and maturity ogives are shown in Figure 22 for the eastern stock and Figure 23 for the western stock.

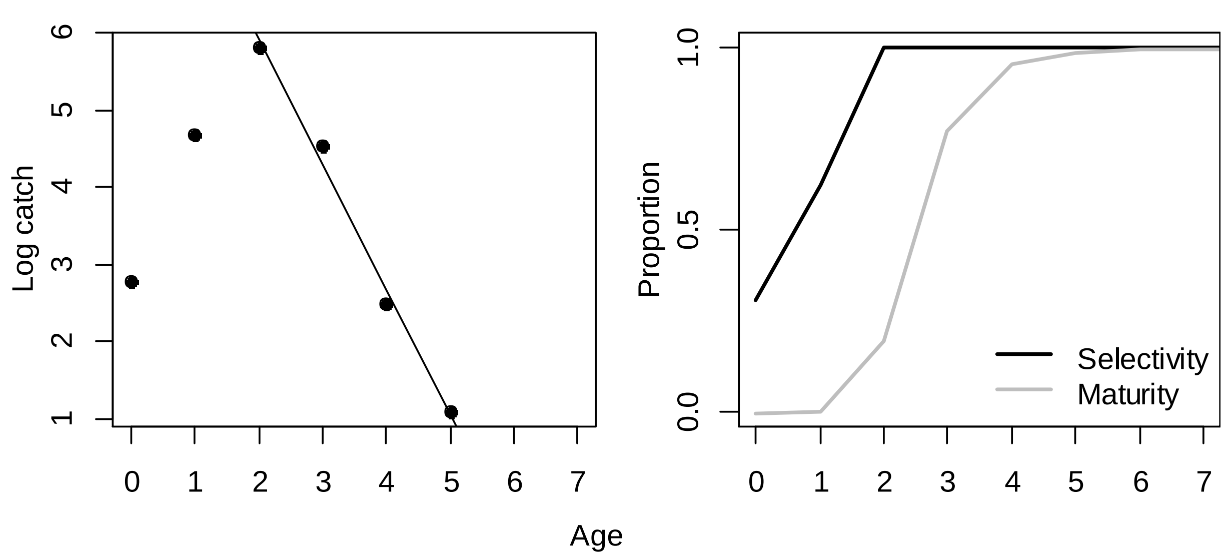


Figure 22: Catch curve and selectivity and maturity ogives for the eastern Australian Sardine stock.

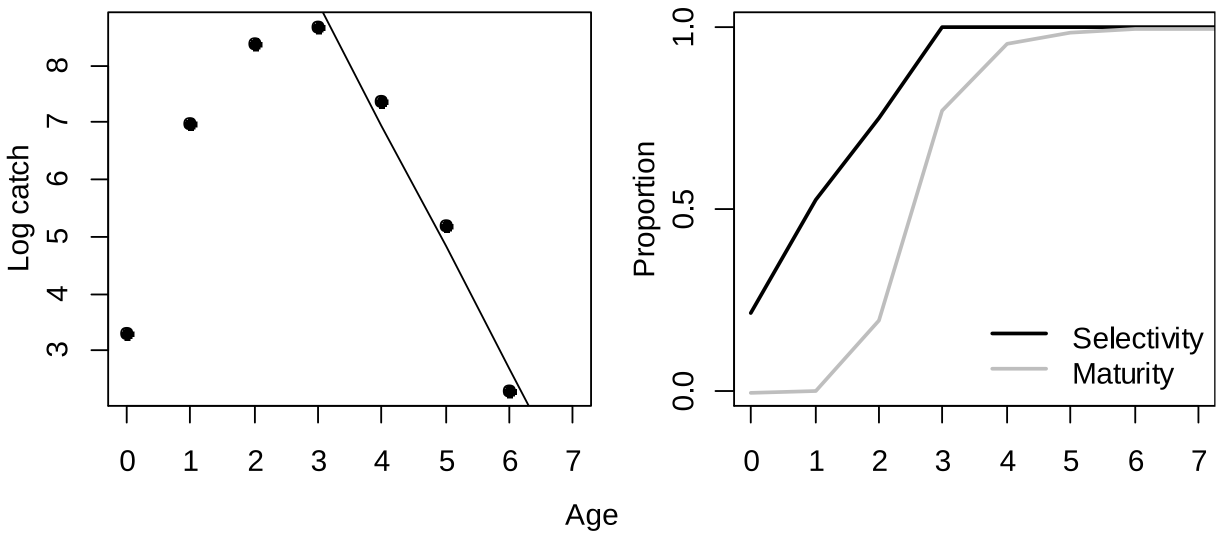


Figure 23: Catch curve and selectivity and maturity ogives for the western Australian Sardine stock.

Table 22: Growth and maturity parameters for Australian Sardine.

Parameter	East	West
L_∞ (mm)	195.44	195.44
K (yr^{-1})	0.32	0.32
t_0 (yr)	-1.88	-1.88
Ω_1	7.1E-6	7.1E-6
Ω_2	3.1	3.1
Ω_3	25.04	25.04
Ω_4 (mm^{-1})	-0.17	-0.17

Identification of reference points

Profiles of exploitation rate vs. depletion and exploitation rate vs. relative catch are shown in Figure 24. Reference points are shown in Table 23.

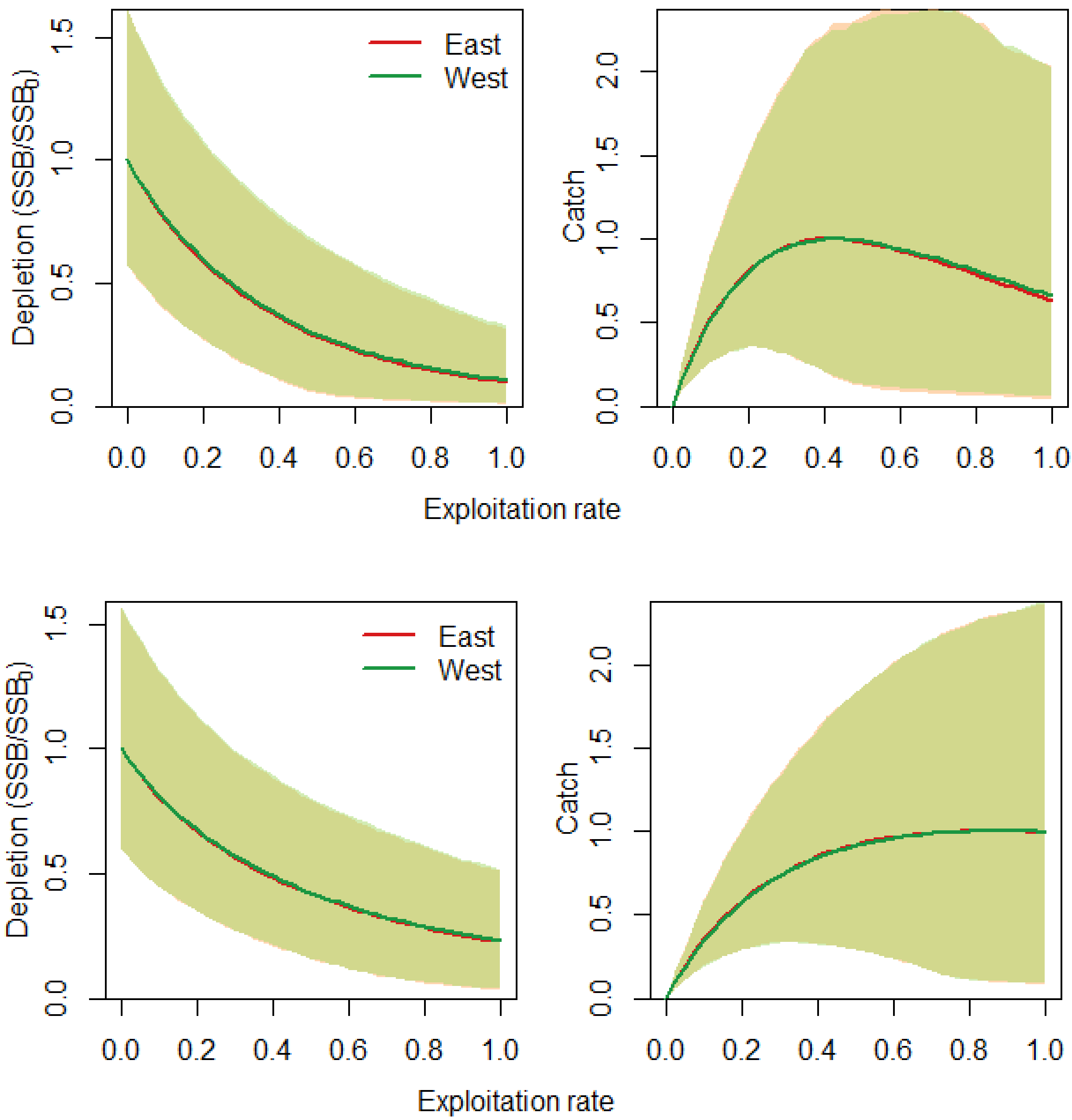


Figure 24: Profiles of exploitation rate vs. depletion and relative catch for Australian Sardine. Shaded regions show the 95% simulation interval. Solid lines are means.

Table 23: Reference points for Australian Sardine. Values are the exploitation rates necessary to achieve a given objective. E_{MSY} is the exploitation rate that maximizes expected catch.

Objective	East	West
E_{MSY}*	0.850	0.875
Depl = 0.9	0.047	0.048
Depl = 0.8	0.104	0.107
Depl = 0.7	0.174	0.178
Depl = 0.6	0.264	0.269
Depl = 0.5	0.379	0.386
Depl = 0.4	0.535	0.544

*Depletion levels for E_{MSY} are 0.27 for east and west.

MSE, base cases

Results for the base cases are shown in Table 24 for the eastern stock and Table 25 for the western stock. See the methods section under objective 2 for description of the scenarios. Results for the two stocks are nearly identical so they are discussed together. The probability of breaching the HSP risk criterion is low for the base case scenario 3 (constant exploitation rate of 15% with DEPM surveys every 5 years). The mean depletion of 0.72 is quite high and the average catch of 68% of MSY quite low, indicating that this harvest strategy results in under-exploitation of the stock relative to MSY. This reflects the relatively high productivity of this resource. The HSP risk criterion is only breached for scenario 5, where DEPM surveys are only conducted every 10 years, even though the Tier 2 exploitation rate of 7.5% is applied for years 6 to 10.

Table 24: MSE results for Australian Sardine, east stock.

Scenario	1	2	3	4	5	6	7	8	9	10
Index										
Mean Dep.	1	0.67	**0.73**	0.84	0.72	0.74	0.78	0.8	0.8	0.8
Mean Catch	0	0.58	**0.47**	0.29	0.47	0.45	0.24	0.36	0.36	0.36
P Dep. 0.60	5.16	44.86	**34.33**	20	35.91	33.88	29	22.64	23.54	25.35
P Dep. 0.50	1.17	25.06	**18.61**	8.94	22.54	18.12	16.28	9.2	10.81	13.03
P Dep. 0.40	0	9.68	**7.15**	2.67	10.95	6.97	6.75	2.42	3.23	4.59
P Dep. 0.30	0	2.06	**1.85**	0	4.59	1.94	2.37	0	0	1.05
P Dep. 0.20	0	0	**0**	0	1.81	0	0	0	0	0

Table 25: MSE results for Australian Sardine, west stock.

Scenario	1	2	3	4	5	6	7	8	9	10
Index										
Mean Dep.	1	0.67	**0.74**	0.84	0.73	0.74	0.78	0.8	0.8	0.8
Mean Catch	0	0.58	**0.47**	0.29	0.47	0.45	0.24	0.37	0.37	0.36
P Dep. 0.60	5.22	44.01	**33.7**	19.56	35.37	33.22	28.54	23.09	24.04	25.94
P Dep. 0.50	1.18	24.39	**18.15**	8.74	21.94	17.81	15.96	9.36	11.13	13.5
P Dep. 0.40	0	9.21	**6.88**	2.6	10.51	6.77	6.55	2.52	3.37	4.84
P Dep. 0.30	0	1.96	**1.81**	0	4.36	1.9	2.22	0	0	1.34
P Dep. 0.20	0	0	**0**	0	1.56	0	0	0	0	0

MSE, sensitivity cases

Results for the sensitivity cases are shown in Table 26 for the eastern stock and Table 27 for the western stock. See the methods section under objective 2 for description of the scenarios. The HSP risk criterion is not breached for any of the scenarios, though it comes closest for S7, the low steepness (low productivity) scenario.

Table 26: MSE sensitivity results for Australian Sardine, east stock.

Scenario	3	S1	S2	S3	S4	S5	S6	S7	S8	S9
Index										
Mean Dep.	0.73	0.73	0.7	0.76	0.72	0.75	0.68	0.77	0.74	0.73
Mean Catch	0.47	0.47	0.53	0.43	0.5	0.45	0.44	0.5	0.48	0.47
P Dep. 0.50	18.61	20.13	23.06	14.96	20.58	16.55	24.75	14.67	17.37	19.24
P Dep. 0.30	1.85	3.3	3.1	1.21	2.39	1.58	2.93	1.39	1.77	2.13
P Dep. 0.25	0	2.02	1.5	0	1.09	0	1.36	0	0	0
P Dep. 0.20	0	1.34	0	0	0	0	0	0	0	0

Table 27: MSE sensitivity scenarios for Australian Sardine, west stock.

Scenario	3	S1	S2	S3	S4	S5	S6	S7	S8	S9
Index										
Mean Dep.	0.74	0.74	0.7	0.77	0.72	0.75	0.68	0.78	0.75	0.73
Mean Catch	0.47	0.46	0.52	0.42	0.49	0.44	0.43	0.5	0.48	0.46
P Dep. 0.50	18.15	19.43	22.32	14.67	20.13	16.27	24.08	14.25	17.09	18.89
P Dep. 0.30	1.81	3.08	2.97	1.15	2.26	1.51	2.82	1.33	1.72	1.95
P Dep. 0.25	0	1.94	1.46	0	1.02	0	1.29	0	0	0
P Dep. 0.20	0	1.26	0	0	0	0	0	0	0	0

Stage 2

Having examined the trophic sensitivities related to objective 1, and evaluated the performance of the current SPF harvest strategy and some variations on that (objective 2, stage 1), both results were discussed with the SPF Resource Assessment Group in May 2014. Discussions arising from this presentation led to the suggestion that further evaluations be undertaken based around a target biomass of 50% unexploited biomass (B_{50}) for the Tier 1 strategy, where application of the harvest strategy should result in a 50% chance of being above the target (also equivalent to a 50% chance of being below the target). This requirement corresponds to a median (rather than mean) depletion of B_{50}. The results from these analyses follow.

First, the harvest rates that result in a 50% probability of biomass to be at B_{50} were identified. This was done with a constant harvest rate applied to the results from DEPM surveys every 2 years and every 5 years, with no assessment uncertainty. The harvest rates that achieve this objective are effectively identical in both cases. Probabilities are expressed as percentages.

Table 28: Harvest rates and performance statistics for Tier 1 and surveys every 2 years

Stock	Redbait E	Redbait W	Jack Mackerel	Blue mack. E	Blue mack. W	Sardine E	Sardine W
Target HR	0.091	0.095	0.116	0.242	0.238	0.330	0.337
Mean Dep.	0.549	0.589	0.552	0.634	0.625	0.692	0.697
P Dep. 0.30	1.550	1.535	1.963	10.049	9.239	8.083	8.249
P Dep. 0.25	0.000	0.000	0.000	4.141	3.686	3.283	3.232
P Dep. 0.20	0.000	0.000	0.000	1.006	0.731	0.226	0.479

Table 29: Harvest rates and performance statistics for Tier 1 and surveys every 5 years

Stock	Redbait E	Redbait W	Jack Mackerel	Blue mack. E	Blue mack. W	Sardine E	Sardine W
Target HR	0.091	0.095	0.115	0.233	0.229	0.325	0.332
Mean Dep.	0.550	0.591	0.554	0.63	0.625	0.682	0.687
P Dep. 0.30	2.297	2.289	3.389	14.431	13.282	14.48	14.706
P Dep. 0.25	0.000	0.000	0.699	8.395	7.341	8.553	8.743
P Dep. 0.20	0.000	0.000	0.000	3.904	3.258	4.862	5.001

The results in Tables 28 and 29 show that mean depletion is higher than median depletion, the latter being set to B_{50} or 0.5. This is particularly the case for the shorter lived species – Blue Mackerel and Sardine. This is a result of recruitment variability leading to occasional very high biomass levels, increasing the average biomass and so the average depletion. The relationship between median and mean depletion as a function of exploitation rate is shown in Figure 25.

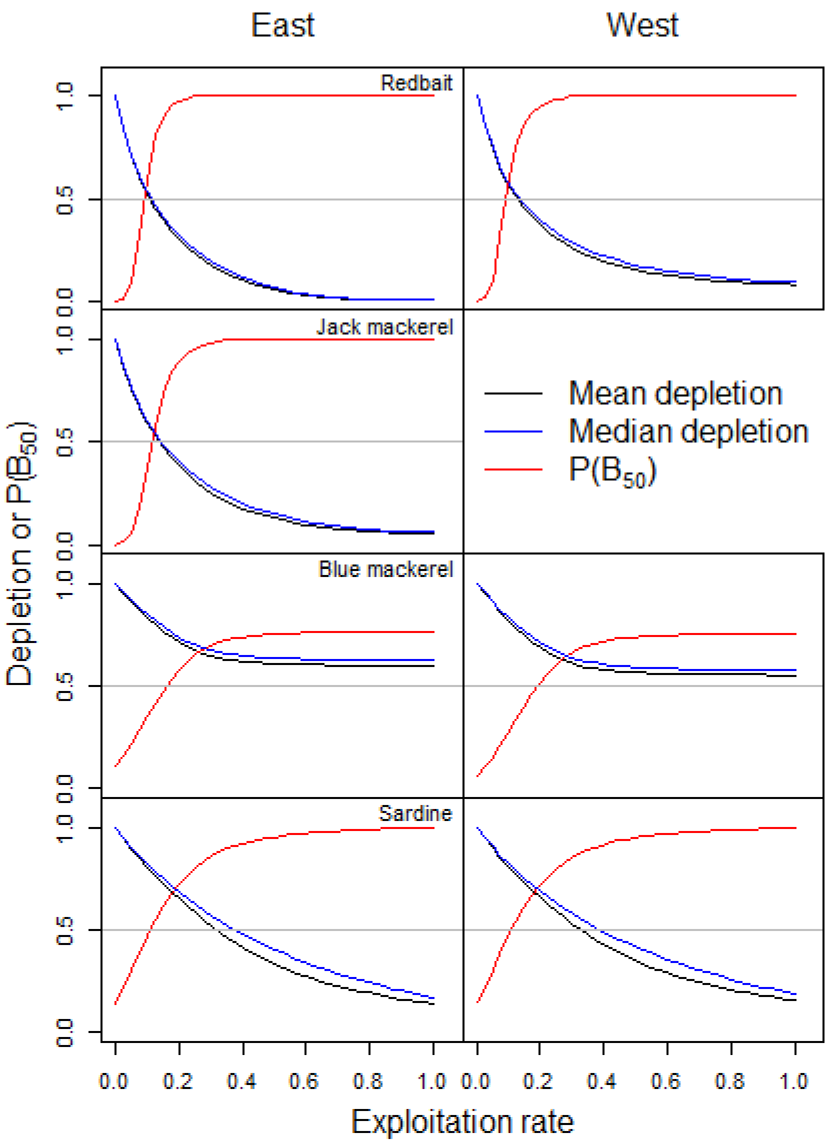


Figure 25: Relationship between exploitation rate and mean and median depletion of stocks.

Sensitivities by stock are shown in the following Tables. The 'Base' scenario corresponds to Tier 1 with surveys every 5 years. As for Stage 1, the sensitivities explored are:

- Scenario S1: DEPM survey CV is 0.5.
- Scenario S2: DEPM survey positive bias of 50%.
- Scenario S3: DEPM survey negative bias of -50%.
- Scenario S4: DEPM survey positive bias of 25%.
- Scenario S5: DEPM survey negative bias of -25%.
- Scenario S6: High steepness.
- Scenario S7: Low steepness.
- Scenario S8: Selectivity curve shifted right by one year.
- Scenario S9: Selectivity curve shifted left by one year.

The same sensitivity analyses are then performed for Tier 2, with only one survey at the beginning of the time series, a period of five years exploitation at Tier 1, and Tier 2 then applied with no further surveys undertaken. The harvest rate for Tier 2 is set equal to half of that for Tier 1 (Table 29).

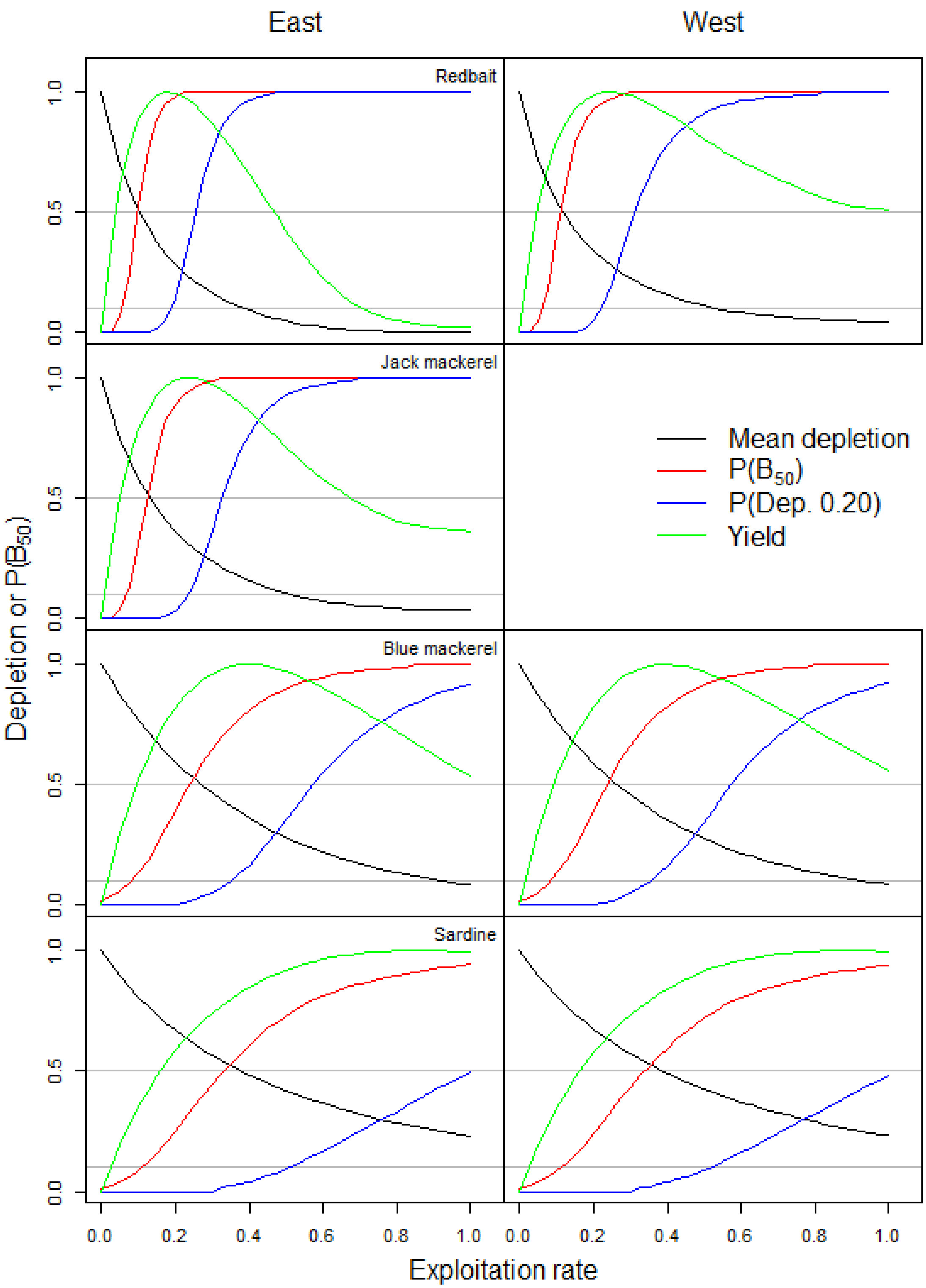


Figure 26: Relationship between exploitation rate and levels of depletion and yield.

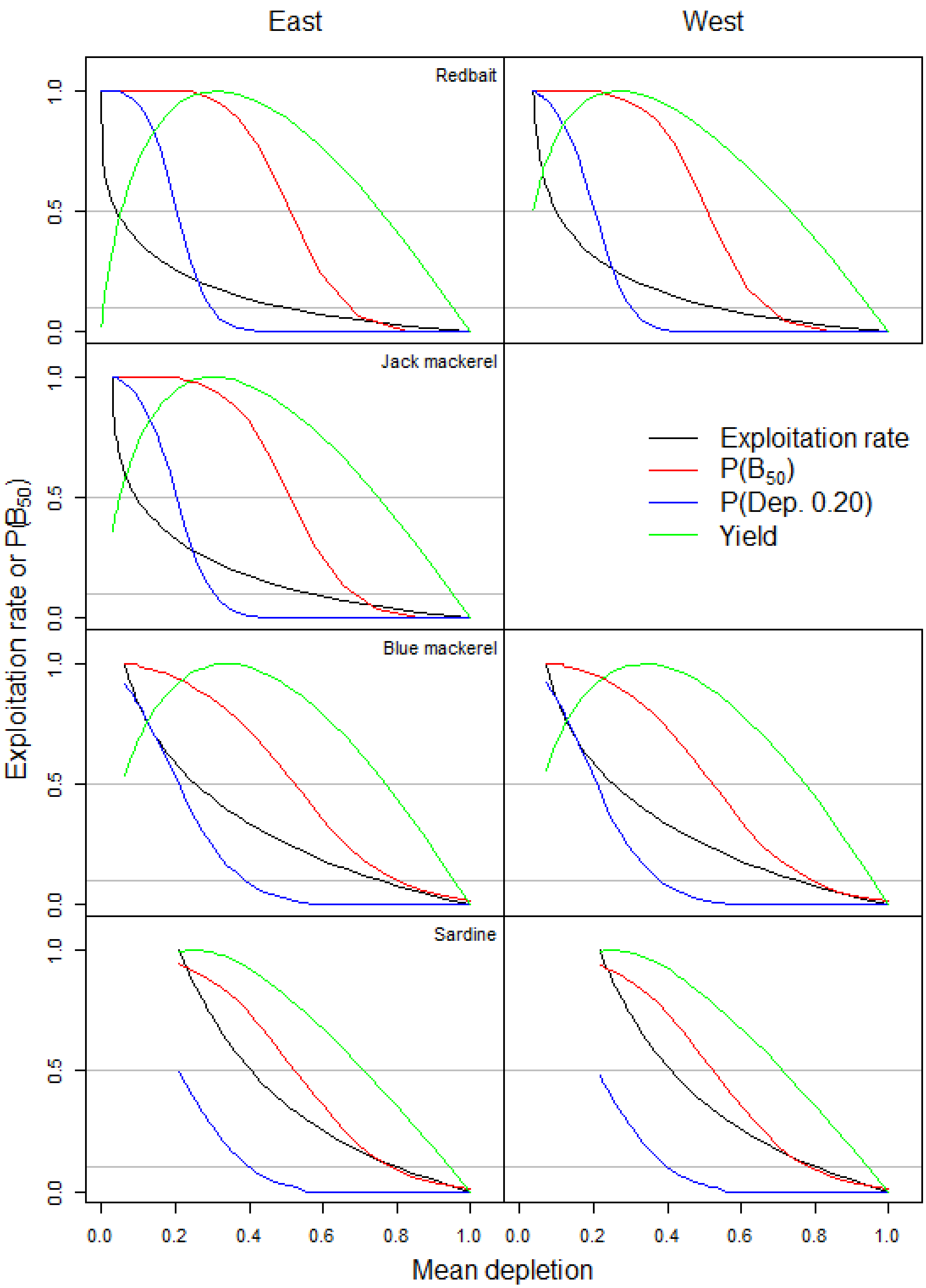


Figure 27: Relationship between mean depletion and exploitation rate, depletion and yield.

Results for Tier 1

Table 30: Sensitivity scenarios for Redbait east stock Tier 1

Scenario	Base	S1	S2	S3	S4	S5	S6	S7	S8	S9
Mean Dep.	**0.55**	0.55	0.5	0.59	0.53	0.57	0.61	0.45	0.58	0.51
Mean Catch	**0.37**	0.54	0.41	0.33	0.39	0.35	0.4	0.31	0.38	0.35
P Dep. 0.50	**49.77**	49.06	63.4	36.64	56.67	42.78	32.18	75.97	40.13	61.78
P Dep. 0.30	**4.06**	8.6	8.98	1.74	6.25	2.65	1.68	14.8	2.37	7.74
P Dep. 0.25	**1.33**	4.46	3.2	0	2.22	0	0	5.87	0	2.7
P Dep. 0.20	**0**	2.85	1.22	0	0	0	0	1.64	0	0

Table 31: Sensitivity scenarios for Redbait west stock Tier 1

Scenario	Base	S1	S2	S3	S4	S5	S6	S7	S8	S9
Mean Dep.	**0.59**	0.59	0.55	0.63	0.57	0.61	0.64	0.52	0.61	0.57
Mean Catch	**0.34**	0.49	0.38	0.3	0.36	0.32	0.36	0.3	0.34	0.33
P Dep. 0.50	**49.96**	48.35	62.22	37.96	55.79	43.74	36.92	69.3	44.72	55.81
P Dep. 0.30	**3.92**	7.63	8.29	1.78	5.68	2.66	2.11	10.21	2.9	5.44
P Dep. 0.25	**1.33**	3.88	2.93	0	1.98	0	0	3.98	0	1.86
P Dep. 0.20	**0**	2.3	1.15	0	0	0	0	0	0	0

The results for both Redbait stocks are similar. There is a low probability of the HSP risk criterion being breached for any of the scenarios tested. However the mean catch relative to the "MSY" catch for this target exploitation rate is quite low – varying between 30 and 50% of theoretical MSY.

Table 32: Sensitivity scenarios for Jack Mackerel Tier 1

Scenario	Base	S1	S2	S3	S4	S5	S6	S7	S8	S9
Mean Dep.	**0.55**	0.55	0.51	0.6	0.53	0.58	0.6	0.48	0.59	0.51
Mean Catch	**0.39**	0.54	0.44	0.35	0.41	0.37	0.42	0.35	0.4	0.37
P Dep. 0.50	**49.35**	48.71	61.49	37.9	55.4	43.32	37.22	68.99	40.28	61.76
P Dep. 0.30	**5.78**	10.67	11.42	2.8	8.02	3.91	3.4	13.56	3.58	11.2
P Dep. 0.25	**2.51**	6.26	5.08	1.02	3.48	1.67	1.57	6.06	1.45	4.87
P Dep. 0.20	**0**	3.76	2.32	0	1.66	0	0	2.33	0	2.18

The results for the Tier 1 exploitation rate for Jack Mackerel also indicate a low probability of breaching the HSP risk criterion. The mean depletion varies from about 50 to 60% and the average catch varies from 35 to 54% of MSY.

Table 33: Sensitivity scenarios for Blue Mackerel, east stock Tier 1

Scenario	Base	S1	S2	S3	S4	S5	S6	S7	S8	S9
Mean Dep.	**0.54**	0.53	0.49	0.58	0.51	0.56	0.65	0.38	0.58	0.47
Mean Catch	**0.85**	0.82	0.89	0.8	0.87	0.82	1.02	0.6	0.9	0.75
P Dep. 0.50	**50.03**	49.9	59.36	41.05	54.83	45.57	33.18	77.62	42.17	60.54
P Dep. 0.30	**17.03**	19.57	23.71	11.13	20.42	13.71	8.86	40.08	10.41	25.46
P Dep. 0.25	**10.41**	13.52	16.24	6.59	13.04	8.22	5.55	29.05	5.39	17.77
P Dep. 0.20	**6.07**	9.12	9.83	3.78	7.65	4.85	3.48	***18.64***	2.43	***11.54***

Table 34: Sensitivity scenarios for Blue Mackerel, west stock Tier 1

Scenario	Base	S1	S2	S3	S4	S5	S6	S7	S8	S9
Mean Dep.	**0.54**	0.54	0.49	0.58	0.51	0.56	0.64	0.39	0.59	0.46
Mean Catch	**0.85**	0.82	0.89	0.8	0.87	0.83	1.01	0.61	0.91	0.73
P Dep. 0.50	**49.35**	48.91	59.26	40.44	54.6	44.86	33.6	76.56	40.11	63.2
P Dep. 0.30	**15.75**	18.26	22.42	10.3	18.92	12.64	8.43	37.35	8.47	27.09
P Dep. 0.25	**9.51**	12.4	14.99	5.9	11.79	7.62	5.13	26.19	4.14	19.07
P Dep. 0.20	**5.31**	8.05	8.79	3.32	6.7	4.33	2.96	***15.78***	1.58	***12.55***

The Tier 1 exploitation rates for Blue Mackerel are generally robust to uncertainty about scenarios, though S7 (low steepness or productivity) and S9 (selectivity shifted left) fail the HSP risk criterion. The mean depletion ranges from 38 to 65% across the two stocks, while mean catch varies from 60 to 100% of MSY.

Table 35: Sensitivity scenarios for Australian Sardine, east stock Tier 1

Scenario	**Base**	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**
Mean Dep.	**0.53**	0.53	0.49	0.58	0.51	0.55	0.47	0.58	0.55	0.52
Mean Catch	**0.75**	0.72	0.79	0.7	0.77	0.73	0.66	0.82	0.78	0.74
P Dep. 0.50	**50.1**	49.79	57.13	42.54	53.48	46.2	60.31	42.35	46.58	50.89
P Dep. 0.30	**16.81**	20.86	23.68	12.09	20.15	14.29	23.56	13.34	15.35	17.6
P Dep. 0.25	**11.69**	15.84	16.86	7.56	13.83	9.46	15.99	8.82	10.15	11.9
P Dep. 0.20	**7.57**	11.73	11.57	4.59	9.32	5.94	***10.22***	5.87	6.53	7.76

Table 36: Sensitivity scenarios for Australian Sardine, west stock Tier 1

Scenario	**Base**	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**
Mean Dep.	0.53	0.53	0.49	0.58	0.51	0.55	0.47	0.58	0.55	0.52
Mean Catch	0.75	0.73	0.8	0.7	0.78	0.73	0.67	0.82	0.78	0.74
P Dep. 0.50	50.2	49.91	57.13	42.53	53.61	46.34	60.48	42.51	46.7	51.52
P Dep. 0.30	17.25	20.59	23.84	12.08	20.34	14.23	23.63	13.58	15.56	17.97
P Dep. 0.25	11.64	15.6	16.88	7.71	13.88	9.62	16.11	9.21	10.24	12.32
P Dep. 0.20	7.61	11.59	11.6	4.68	9.41	6	10.15	6.09	6.58	8.09

The results for the two Sardine stocks are very similar. Mean depletion varies from 47 to 55% across scenarios, while catch varies from 66 to 82% of MSY.

Results for Tier 2

Table 37: Sensitivity scenarios for Redbait, east stock. Tier 2.

Scenario	Base	S1	S2	S3	S4	S5	S6	S7	S8	S9
Mean Dep.	**0.48**	0.5	0.36	0.58	0.42	0.53	0.62	0.28	0.56	0.38
Mean Catch	**0.63**	0.52	0.57	0.63	0.61	0.63	0.78	0.42	0.77	0.5
P Dep. 0.50	**46.1**	42.44	62.4	32.49	55.27	39.32	28.12	75.12	36.64	60.13
P Dep. 0.30	**25.66**	28.36	42.53	14.96	33.55	19.92	13.36	53.35	17.9	39.76
P Dep. 0.25	**23.34**	26.76	39.3	12.98	30.47	17.89	11.54	49.39	15.53	36.97
P Dep. 0.20	***21.66***	***25.41***	***37.17***	***11.38***	***28.41***	***16.32***	9.96	***46.45***	***13.51***	***34.36***

Table 38: Sensitivity scenarios for Redbait, west stock. Tier 2.

Scenario	Base	S1	S2	S3	S4	S5	S6	S7	S8	S9
Mean Dep.	**0.5**	0.52	0.4	0.59	0.45	0.55	0.61	0.35	0.56	0.45
Mean Catch	**0.69**	0.6	0.71	0.65	0.71	0.67	0.78	0.52	0.76	0.59
P Dep. 0.50	**45.36**	41.35	61.08	32.23	52.46	38.62	31.24	67.83	39.22	52.17
P Dep. 0.30	**22.98**	25.84	37.11	13.2	29.35	17.71	12.58	42.92	17.47	28.89
P Dep. 0.25	**20.21**	23.85	33.15	10.76	26.08	15.21	10.15	38.09	14.13	25.45
P Dep. 0.20	***18.09***	***21.89***	30	8.85	***23.6***	***13.23***	7.96	***34.54***	***10.8***	***23.09***

Table 39: Sensitivity scenarios for Jack Mackerel. Tier 2.

Scenario	Base	S1	S2	S3	S4	S5	S6	S7	S8	S9
Mean Dep.	**0.48**	0.51	0.37	0.58	0.43	0.53	0.6	0.32	0.58	0.36
Mean Catch	**0.65**	0.55	0.62	0.63	0.64	0.64	0.78	0.44	0.78	0.45
P Dep. 0.50	**46.77**	42.88	62.75	33.61	55.28	40.03	32.52	69.84	36.2	62.65
P Dep. 0.30	**27.07**	29.67	44.08	16.25	35.17	21.46	15.81	49.01	16.34	44.29
P Dep. 0.25	**24.8**	28.13	41.03	14.35	32.23	19.45	13.88	46.4	13.35	41.12
P Dep. 0.20	***23.14***	***26.83***	***38.93***	***12.82***	***30.19***	***17.77***	***12.13***	***43.49***	***10.13***	***39.02***

Table 40: Sensitivity scenarios for Blue Mackerel, east stock. Tier 2.

Scenario	Base	S1	S2	S3	S4	S5	S6	S7	S8	S9
Mean Dep.	**0.48**	0.5	0.35	0.59	0.41	0.54	0.74	0.16	0.65	0.35
Mean Catch	**0.47**	0.39	0.4	0.49	0.43	0.5	0.71	0.17	0.73	0.32
P Dep. 0.50	**51.11**	48.15	65.51	39.11	58.49	44.07	24.63	86.44	34.82	65.01
P Dep. 0.30	**36.54**	36.17	52.98	23.92	45.03	28.61	13.01	76.74	13.58	52.09
P Dep. 0.25	**34.57**	34.91	50.95	21.9	43.05	26.75	11.48	74.5	9.59	50.18
P Dep. 0.20	***32.94***	***33.83***	***49.7***	***20.41***	***41.49***	***25.37***	***10.2***	***72.62***	6.1	***48.8***

Table 41: Sensitivity scenarios for Blue Mackerel, west stock. Tier 2.

Scenario	Base	S1	S2	S3	S4	S5	S6	S7	S8	S9
Mean Dep.	**0.49**	0.51	0.37	0.59	0.43	0.54	0.74	0.17	0.67	0.31
Mean Catch	**0.54**	0.47	0.51	0.54	0.53	0.55	0.75	0.2	0.74	0.28
P Dep. 0.50	**50.91**	47.33	64.7	38.68	57.74	44.06	23.96	85.23	33.01	69.77
P Dep. 0.30	**35.62**	35.25	51.8	23.19	43.07	28.44	10.27	74.92	10.51	57.75
P Dep. 0.25	**33.32**	33.81	49.5	20.96	40.94	26.49	8.32	72.64	6.61	56
P Dep. 0.20	***31.54***	***32.7***	***47.65***	***19.13***	***39.19***	***24.91***	6.63	***70.79***	3.7	***54.72***

Table 42: Sensitivity scenarios for Australian Sardine, east stock. Tier 2.

Scenario	Base	S1	S2	S3	S4	S5	S6	S7	S8	S9
Mean Dep.	**0.51**	0.53	0.4	0.6	0.46	0.55	0.37	0.62	0.54	0.49
Mean Catch	**0.5**	0.41	0.45	0.5	0.48	0.5	0.37	0.58	0.53	0.49
P Dep. 0.50	**48.06**	44.48	60.63	36.76	53.72	42.8	64.82	35.6	44.67	49.95
P Dep. 0.30	**28.04**	29.3	42.72	17.88	34.59	22.81	46.16	17.17	25.18	30.23
P Dep. 0.25	**25.27**	27.32	39.73	15.68	31.42	20.22	42.91	15.16	22.46	27.27
P Dep. 0.20	***23.33***	***25.98***	***37.25***	***13.77***	***29.11***	***18.59***	***40.54***	***13.36***	***20.67***	***25.28***

Table 43: Sensitivity scenarios for Australian Sardine, west stock. Tier 2.

Scenario	Base	S1	S2	S3	S4	S5	S6	S7	S8	S9
Mean Dep.	**0.51**	0.53	0.4	0.6	0.46	0.55	0.36	0.62	0.55	0.49
Mean Catch	**0.5**	0.41	0.44	0.5	0.48	0.49	0.37	0.59	0.6	0.48
P Dep. 0.50	**48.18**	44.61	60.75	36.91	53.93	43	65.07	35.63	44.05	50.66
P Dep. 0.30	**28.33**	29.5	42.98	18.13	34.91	23.14	46.46	17.27	23.77	30.81
P Dep. 0.25	**25.5**	27.49	40.01	15.91	31.65	20.64	43.4	15.21	20.88	27.8
P Dep. 0.20	***23.55***	***26.11***	***37.64***	***13.99***	***29.48***	***19***	***40.99***	***13.38***	***18.71***	***25.83***

Results for all stocks for Tier 2 are that the strategies are not compliant with the HSP risk criterion when applied over a long time frame. The explanation can be seen in Figure 28 below.

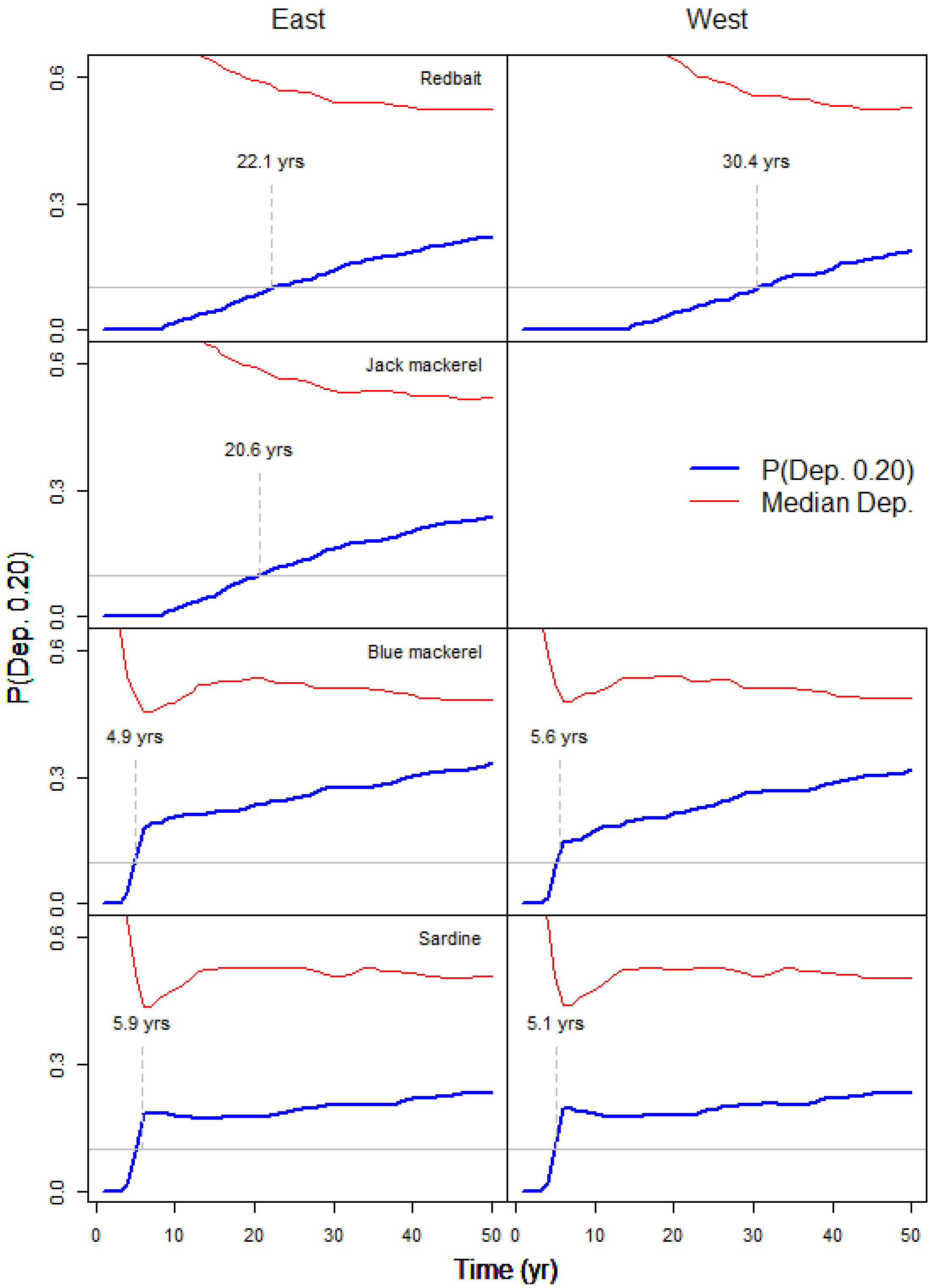


Figure 28: Time series of median depletion (red) and probability of depletion below B_{20}. The horizontal grey line is at the HSP risk tolerance for proability of depletion (10%).

Figure 28 shows the probability of depletion to B_{20} for all the stocks. This is for the Tier 2 base case. Stocks start at B_0 and are fished at a Tier 1 HR for the first five years. After that, they are fished at a Tier 2 rate, i.e. at half of the Tier 1 HR. The horizontal gray line indicates 0.1, the risk tolerance under the HSP for falling below B_{20}. Figure 28 shows that the chances of depletion below the LRP are high for Blue Mackerel and Sardine and increase over time. It takes longer to reach the risk threshold for Redbait and Jack Mackerel (over 20 years). The problem for Blue Mackerel and Sardine in particular is that the Tier 1 harvest can deplete the stock quite quickly. Although the stock starts at unfished levels, a fixed harvest is applied for five years under Tier 1 which can be problematic if the initial survey estimate is high. If further surveys are undertaken and the stock stays at Tier 1 there is an automatic correction mechanism. However moving straight to Tier 2 with no further surveys can create problems even though the Tier 2 rate (and catch) is half the Tier 1 rate. The real problem is lack of feedback through surveys.

The Tier 1 harvest rates that achieve an 8% probability of 20% depletion in 50 years are shown in Table 44. These rates are applied for the first five years (Tier 1) and then half those rates are applied for the remaining time under Tier 2. Figure 29 shows the risk over time, and can be compared with Figure 28. The target rates are considerably lower than those in Table 29, which just considered Tier 1 performance. For example, the target rate for Blue Mackerel east drops from 23% to 17%, and for Sardine east from 33% to 24%. This could be considered the "risk premium" associated with adopting a Tier 2 strategy for a long period of time. Note that this assumes no additional assessment under Tier 2 and no ability to detect severe depletion. An alternative approach to achieve the same level of risk would be to 1) reduce the time period for which Tier 2 applies (for Redbait and Jack Mackerel); or 2) keep the Tier 1 rates in Table 29, but reduce the fraction of the Tier 1 rate applied at Tier 2 below half.

Table 44: Harvest rates (and performance statistics) for Tier 2. Tier 1 harvest rates are selected such that the probability of 20% depletion in 50 years is 8%.

Stock	**Redbait E**	**Redbait W**	**Jack Mackerel**	**Blue mack. E**	**Blue mack. W**	**Sardine E**	**Sardine W**
Target HR	0.070	0.073	0.076	0.171	0.156	0.237	0.242
Mean Dep.	0.660	0.674	0.689	0.766	0.766	0.767	0.770
P Dep. 0.30	10.380	11.663	11.573	10.785	10.460	11.220	11.308
P Dep. 0.25	8.885	9.545	9.528	9.115	9.002	9.348	9.433
P Dep. 0.20	8	8	8	8	8	8	8

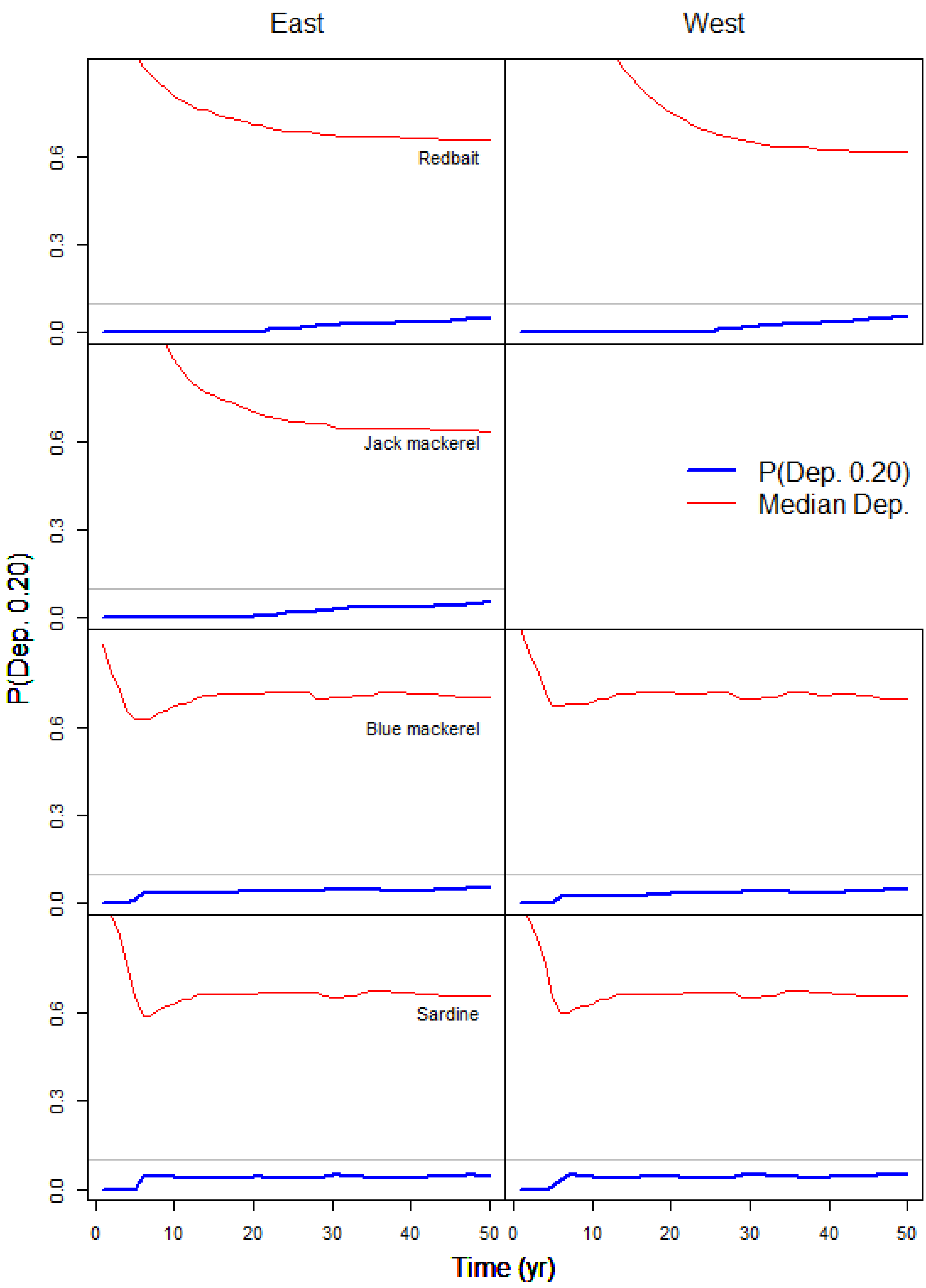


Figure 29: Time series of depletion probabilities under the Tier 2 harvest rates shown in Table 44.

Summary of numerical values for parameters for all stocks

Table 45: Summary of biological parameters for all stocks

Parameter	Redbait E	Redbait W	Jack Mackerel	Blue mack. E	Blue mack. W	Sardine E	Sardine W
Max Age	10	10	12	6	6	5	5
M	0.26	0.26	0.26	0.62	0.62	0.62	0.62
Steepness	0.74	0.74	0.75	0.59	0.59	0.8	0.8
L_∞ (mm)	288	305.2	362.8	378.88	392.64	195.44	195.44
K (yr^{-1})	0.24	0.14	0.29	0.43	0.45	0.32	0.32
t_0	-1.61	-4.94	-0.81	-1.12	-0.61	-1.88	-1.88
Ω_1	2.00E-06	2.00E-06	9.40E-06	4.90E-06	4.90E-06	7.10E-06	7.10E-06
Ω_2	3.342	3.342	3.06	3.169	3.169	3.1	3.1
Ω_3	3.24*	2.5*	13.4	11.79	11.79	25.04	25.04
Ω_4 (mm^{-1})	-1.62*	-0.56*	-0.05	-0.045	-0.045	-0.17	-0.17
Steepness (high)	0.89	0.89	0.90	0.71	0.71	0.9	0.9
Steepness (low)	0.59	0.59	0.60	0.47	0.47	0.6	0.6

*For Redbait, maturity is Parameterised in terms of age. It also uses equation (4), but uses age instead of length (*L*).

Table 46: Selectivity-at-age for all stocks

Selectivity *Age*	Redbait E	Redbait W	Jack Mackerel	Blue mack. E	Blue mack. W	Sardine E	Sardine W
0	0	0	0	0.01	0	0.3	0.3
1	0	0	0	0.17	0.06	0.62	1
2	0.95	0.95	0.68	0.69	0.60	1	1
3	1	1	0.86	0.91	0.92	1	1
4	1	1	1	0.97	1	1	1
5	1	1	1	0.98	1	1	1
6	1	1	1	0.99	1	*NA*	*NA*
7	1	1	1	*NA*	*NA*	*NA*	*NA*
8	1	1	1	*NA*	*NA*	*NA*	*NA*
9	1	1	1	*NA*	*NA*	*NA*	*NA*
10	1	1	1	*NA*	*NA*	*NA*	*NA*
11	*NA*	*NA*	1	*NA*	*NA*	*NA*	*NA*
12	*NA*	*NA*	1	*NA*	*NA*	*NA*	*NA*

Discussion, conclusions and implications

This project has explored aspects of the harvest strategy for the four main target species in the SPF and examined alternatives to the current harvest strategy. The study is built around addressing two objectives.

Objective 1: Provide advice on best practice reference points for the four main target species in the SPF

This objective was explored using a new variant of the Atlantis ecosystem model developed for this study – Atlantis-SPF. This version of Atlantis is built on previous Atlantis models for southern and eastern Australia, but focuses in particular on the target species in the SPF and their role in the food web. This model was used to examine the effects on other parts of the food chain of depleting SPF target species to various levels. This analysis followed the approach of several previous studies that have used similar models to explore the trophic consequences of fishing low trophic level or "forage" species (Smith *et al.*, 2011; Pikitch *et al.*, 2012).

The results from modelling the effects of fishing the four target species on other parts of the food chain are quite clear. Whether singly or in combination, depleting these target species in Atlantis-SPF has only minor impacts on other parts of the ecosystem. This suggests that it should not be necessary to alter target or limit reference points for this fishery to take specific account of ecosystem impacts. In reaching this conclusion, the following points should be born in mind.

1. Retuning the Atlantis model to focus on the small pelagic fishery and its target species proved more difficult than anticipated. Only one credible Parameterisation was found for the model, so testing the robustness of the conclusions to alternative Parameterisations was not possible.

2. The food web in southern and eastern Australia does not appear to be highly dependent on SPF target species, unlike some other regions which show higher levels of dependence on similar species, such as in Peru and the Benguela system (Smith *et al.*, 2011). None of the key higher trophic level predators in SE Australia, such as seals, penguins and tunas, has a high dietary dependence on these species. A species not targeted by the fishery, anchovies, appears to show greater sensitivity.

3. The form of predation modelled in Atlantis allows considerable levels of diet switching by predators which tends to minimise the effects of depleting particular prey species. However studies using other ecosystem models such as Ecosim in the same region have also reached similar conclusions (Goldsworthy *et al.*, 2013; Bulman *et al.*, 2011).

So what target and limit reference points should be selected for these main commercial species in the SPF? Equilibrium B_{MSY} for these species ranged from about 30 to 35% of unfished levels. However these levels are uncertain and it might be more appropriate to use the default values from the Commonwealth harvest strategy policy with B_{MSY} set at B_{40} (40% of unfished levels) and the default B_{MEY} set at 1.2 times this level, close to B_{50}. **This study therefore suggests that the target reference point for these SPF target species be set at B_{50} and the limit reference point at B_{20}, in line with the HSP default settings**. The results presented in this report, combined with evidence from other studies, suggest that these levels are safe from an ecosystem perspective, and provide reasonable levels of yield relative to MSY.

Objective 2: Provide advice on suitable exploitation rates to achieve management targets for the four main target species in the SPF

Results presented in this study suggest that target exploitation rates (ERs) for the SPF should be species-specific and possibly even stock-specific. The results from the Stage 1 analysis suggest that the current average Tier 1 harvest rate of 15% is too high for eastern Redbait. Taking account of some of the sensitivity scenarios, it may also be too high for western Redbait and Jack Mackerel. This is not too surprising as these are the longer-lived and therefore lower productivity species. The Tier 2 ER of 7.5% is almost certainly too high for eastern Redbait.

The results from the stage 2 analysis help inform the choice of suitable ERs for each of the species and stocks. For Tier 1, the analyses focus on achieving the reference points recommended for objective 1. In particular, the aim is to achieve a median depletion of 0.5 or B_{50}, while maintaining less than a 10% chance of falling below the suggested limit reference point of B_{20}, in line with the harvest strategy policy. The base case exploitation rates that achieve this target, assuming surveys every five years, are as follows:

- Eastern Redbait 9%
- Western Redbait 10%
- Jack Mackerel 12%
- Eastern Blue Mackerel 23%
- Western Blue Mackerel 23%
- Eastern Sardine 33%
- Western Sardine 33%

Note that western Sardine is not managed as part of this fishery but is managed under South Australian jurisdiction.

These Tier 1 ERs are generally safe with regard to meeting the HSP risk criterion across the range of sensitivity tests conducted. The results are based on applying the Tier 1 rates for up to five years after a DEPM survey, and repeating this sequence over time.

In line with the current harvest strategy, Tier 2 rates were set at half the Tier 1 rates in this study. It is assumed that Tier 2 would only be applied after 5 years of exploitation at Tier 1, and that no further surveys would take place. Figure 28 and the associated Tables illustrate that it is generally not safe to apply Tier 2 for long periods of time unchecked. Particularly for the shorter lived species (Blue Mackerel and Sardine), this can result in unacceptable probabilities of depletion in quite short periods of time (5 or 6 years), while the period is on the order of 20 years for the other two species. This suggests that either surveys should be conducted on a regular basis (i.e. at least every 5 years), allowing maintenance of Tier 1 exploitation rates, or that overall exploitation rates should be reduced as shown in Table 44. The alternative approach would be to keep the Tier 1 rates at the levels indicated above, but make the Tier 2 rate more precautionary (i.e. less than half the Tier 1 rate) and/or reduce the period over which it is applied (e.g. not more than 5 years).

The Tier 1 ER recommendations are based around achieving a median target of B_{50} (a 50% chance of being above or below this level of depletion). For the shorter-lived species (Blue Mackerel and Sardine) in particular, this corresponds to an average depletion much higher than B_{50}, for Sardine around B_{80}. Potential foregone yield is considerable at these depletion levels (Figures 26 and 27), so clarification on whether the median or mean depletion is the more appropriate target is required. However further analysis would be required to make sure that the HSP risk criterion is not breached if the target depletion level shifts from the median toward the mean. Shorter-lived species fluctuate more in overall abundance for the same level of recruitment variability, so the risks of low stock sizes increase as the mean depletion reduces.

This study has mainly examined fixed ERs at Tier 1, rather than a set of rates that reduces over time following a DEPM survey. These could be examined if needed, but following previous results it is the average ER over the five year period that is likely to determine performance.

The Tier 2 results are based on 50 year projections suggesting that suitable rates could be applied indefinitely (provided productivity is not badly overestimated). However this conclusion should be heavily qualified. An indefinitely applied Tier 2 strategy is essentially a constant catch strategy with no feedback and these are known to be risky. The model results may underestimate the risks of low stock sizes, driven for example by longer-term environmental changes or disease outbreaks, such as those previously seen in Sardines. The obvious way to deal with this issue is to formalise the "assessment" phase of the Tier 2 strategy, such that stock declines can be clearly detected and appropriate management responses made. This would allow formal testing of such strategies.

Recommendations

The findings have implications for the target and limit reference points that should be selected for the main commercial species in the SPF.

1. Equilibrium B_{MSY} for these species ranged from about 30 to 35% of unfished levels. However, these levels are uncertain and it may be more appropriate to use the default values from the HSP with B_{MSY} set at B_{40} (40% of unfished levels) and the default B_{MEY} set at 1.2 times this level, close to B_{50}. This study suggests that the target reference point for these SPF target species should be set at B_{50} and the limit reference point at B_{20}, in line with the HSP default settings. The results presented in this report, combined with evidence from other studies, suggest that these levels are safe from an ecosystem perspective and provide reasonable levels of yield relative to MSY.

2. Population modelling suggests that target exploitation rates (ERs) for the SPF should be species-specific and possibly even stock-specific. The current average Tier 1 harvest rate of 15% appears to be too high for eastern Redbait. Taking account of some of the sensitivity scenarios, it may also be too high for western Redbait and Jack Mackerel.

3. Our results help inform the choice of suitable ERs for each of the species and stocks. For Tier 1, the analyses focus on achieving the reference points recommended by the ecosystem modelling, that it is to achieve a median depletion of 0.5 or B_{50}, while maintaining less than a 10% chance of falling below the suggested limit reference point of B_{20}. The base case exploitation rates that achieve this target, assuming surveys every five years, are as follows:

- Eastern Redbait 9%
- Western Redbait 10%
- Jack Mackerel 12%
- Eastern Blue Mackerel 23%
- Western Blue Mackerel 23%
- Eastern Sardine 33%
- Western Sardine 33%

4. In the current harvest strategy Tier 2 rates are set at half the Tier 1 rate. We assumed that the Tier 2 rate would only be applied after 5 years of exploitation at Tier 1, and that no further surveys would take place. It is generally not safe to apply Tier 2 for long periods of time unchecked. Particularly for the shorter lived species (Blue Mackerel and Sardine), this can result in unacceptable probabilities of depletion in quite short periods of time (5 or 6 years), while the period is on the order of 20 years for the other two species. An alternative approach would be make the Tier 2 rate more precautionary (i.e. less than half the Tier 1 rate) and/or reduce the period over which it is applied (e.g. not more than 5 years).

Extension and Adoption

Investigators have liaised extensively with AFMA and SPFRAG throughout the course of this project. Results will be used by the RAG to refine the reference points (e.g. biomass depletion levels) and settings (e.g. exploitation rates) for the four main target species in the harvest strategy for the SPF. Results have and will be presented at stakeholder forums conducted by AFMA to inform the community about assessment and management of the SPF.

APPENDICES

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