GREAT AUSTRALIAN BIGHT RESEARCH PROGRAM

RESEARCH REPORT SERIES

Knowledge integration of socio-ecological systems of the Great Australian Bight: Ecosystem Modelling

Final Modelling Report GABRP Project 7.1

E.A. Fulton, S.D. Goldsworthy, C.M. Bulman. H.R. Pethybridge and P.J. Rogers

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CONTACTS

Dr Elizabeth Fulton
CSIRO
e: Beth.Fulton@csiro.au

Prof Simon Goldsworthy
SARDI
e: simon.goldsworthy@sa.gov.au

FOR FURTHER INFORMATION

www.misa.net.au/GAB

GREAT AUSTRALIAN BIGHT RESEARCH PROGRAM

The Great Australian Bight Research Program is a collaboration between BP, CSIRO, the South Australian Research and Development Institute (SARDI), the University of Adelaide, and Flinders University. The Program aims to provide a whole-of-system understanding of the environmental, economic and social values of the region; providing an information source for all to use.

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1. EXECUTIVE SUMMARY

The Great Australian Bight (GAB) is the dominant geographic feature of Australia's southern coastline. It encompasses a diverse variety of habitats including coastal and gulf, benthic and neritic shelves and slopes, pelagic oceanic and deep abyssal habitats. The GAB supports valuable Commonwealth (e.g. southern bluefin tuna) and State (e.g. southern rock lobster, abalone, and sardine) fisheries operating in coastal waters and over the continental shelf and slope. Aquaculture leases occur in southern Spencer Gulf and along the coast of the western Eyre Peninsula between Coffin Bay and Ceduna. Large marine parks have been established and the region supports important ecotourism ventures. The GAB is also a resource frontier with high prospectivity for oil/gas production. In natural resource management, conservation planning and marine and socioecological science more generally, modelling has been found to be an effective way of combining information in a consistent way, providing a synthesis of current understanding and how it is interconnected.

The GAB Research Program (GABRP) generated extensive new knowledge of the key physical, chemical and biological drivers of ecosystem structure (Themes 1 and 2); the vulnerability of key habitats/assemblages (Themes 3 and 4), trophic pathways and species to potential ecosystem stressors and their combined effects (Theme 7, this report); and the socio-economic and ecological trade-offs associated with multiple use (Theme 6). Integration of this new information with data from existing regional data was achieved through the development of an Ecopath with Ecosim (EwE) model and a spatially explicit Atlantis whole-of-system ecosystem model to represent system dynamics in coastal and oceanic regions.

The GAB-Atlantis model was forced using time-series data from a hydrodynamic model and parameterised using growth, life-history and diet information derived from the literature. The EwE model was forced using time series projection data from a different regional oceanographic model, and parameterised with data on the biology, biomass and diets from the GABRP Themes project results or the literature. Parameterisation of the Atlantis fishing model and the EwE model were based on catch and effort data and time series from Commonwealth and three State fisheries, and recent stock assessments.

The results of a small exemplar set of scenarios are described here. These scenarios provide illustrative examples of what can be done with the models and provide a basis for future use of the models. Specifically, we examined the ecological consequences, i.e. changes in trophic linkages and biomass flow, of changes in sea temperature, fishing pressure, stock abundances, and spatial management or in the event of shipping oil spills.

Scenarios of high fishing had the greatest negative impact on relative biomasses of individual functional groups, while scenarios of ocean warming saw largest impacts on the indicators of ecosystem structure and integrity. Scenarios of spatial management found that closures were insufficient in isolation as pressures and processes in the system were patchy. Scenarios of oil spills caused by potential off-shore shipping accidents impacted groups in the immediate vicinity of the collision and spill but had very little long-term impact on the system. However, these results only reflect acute (direct contact and mortality) outcomes as chronic effects mediated by uptake and transmission through the food web are not represented.

As they stand the models represent a synthesis of the best available information. As such they represent the best available means of using that information to inform strategic thinking of the region – to explore potential outcomes of shifts in the system, whether environmentally driven or as a consequence of shifts in human use. This does not mean that there is no uncertainty. The sheer

size of the GAB means that new information will continue to come to light and the models would need refining accordingly. Future model improvements would include any new information from areas beyond the scope of the GABRP, particularly to the west. Representation of the dynamic nature of fisheries in the region would benefit from the use of spatially-resolved State fisheries catch and effort data currently unavailable due to confidentiality issues; the current fishing mortality based representations of fisheries are sufficient for exploring scenarios, but a more dynamic representation would allow for a more sophisticated exploration of the potential fisheries response and outcomes of any potential accidents, extreme events or environmentally driven broad scale shifts in the region. Explicit handling of economics and compliance decisions, exploration of cumulative impacts and modelling the bioaccumulation effects of potential oil spills would also improve model representativeness and the application and relevance of model outputs for management, and should be a priority of future work for the oil and gas industry.

1.1 Acknowledgements

This study was funded as part of the Great Australian Bight Research Program, a collaboration between BP, the Commonwealth Scientific and Industrial Research Organisation (CSIRO), the South Australian Research and Development Institute (SARDI), the University of Adelaide and Flinders University. The Program aims to provide a whole-of-system understanding of the environmental, economic and social value of the region; providing an information source for all to use.

2. INTRODUCTION

2.1 Overview

The Great Australian Bight (GAB) is the dominant geographic feature of Australia's southern coastline, the longest south facing coastline in the world (Kirkman 1989, Rogers *et al.* 2013b). The region is large and remote and encompasses a diverse variety of habitats including coastal and gulf, benthic and neritic shelves and slopes, pelagic oceanic and deep abyssal habitats. It is a region of high conservation significance and supports a wide range of anthropogenic activities. Coastal waters are significant for the region's indigenous communities and support iconic recreational fisheries. Valuable Commonwealth (e.g. southern bluefin tuna) and State (e.g. southern rock lobster, abalone, and sardine) fisheries operate in coastal waters and over the continental shelf and slope. Aquaculture leases are spread along the coast. Large marine parks have been established and the region supports important ecotourism ventures.

The GAB is also a resource frontier with high prospects for oil/gas production. In January 2011, BP was awarded four exploration permits about 300 km south-west of Ceduna and committed to a work program that includes drilling four exploration wells. In 2011, Bight Petroleum was also awarded two leases west of Kangaroo Island and south of the Eyre Peninsula. In 2013, Statoil acquired a 30% share in BP's exploration program; Chevron was awarded two permits east of the BP/Statoil leases; and Santos/Murphy was awarded a lease further west. In 2016, BP abandoned their intention to drill for oil in the Bight. In 2017, in a deal with BP, Statoil acquired 100% equity in two of four BP leases and took over the two exploration permits from BP. Their intention is to drill by the end of 2019 subject to National Offshore Petroleum Safety and Environmental Management Authority (NOPSEMA) approvals.

Future management of the GAB should be based on a sound knowledge of the ecological, economic and social values of the GAB and the interactions among human activities and their impacts on the ecosystem. In natural resource management, conservation planning and marine and socioecological science more generally, modelling has been found to be an effective way of combining information in a consistent way, providing a synthesis of current understanding and how it is interconnected. This provides a basis for exploring system structure and function, but also as a test-bed for investigating indicators, monitoring, potential responses to perturbation and the like. Without using a common language and framework (e.g. as provided by models) it can be difficult to present information in a consistent way, leading to unintentional mismatches of scale, inconsistent assumptions and other flaws that can ultimately undermine the learning that can come from trying to understand the dynamics of a system of the size and complexity of the GAB.

Best practice for system modelling in support of ecosystem-based management (EBM) requires multi-model inference. That is to apply at least two models when considering an EBM question to ensure that any underlying analytical biases, assumptions, and calculations are not skewing model outputs and resulting conclusions. If multiple models based on differing premises or methods provide similar responses, the confidence in the robustness of the general result is heightened. This approach is analogous to ensemble modelling commonly used to address uncertainty in atmospheric and climate sciences (Tebaldi and Knutti 2007). Moreover, different kinds of models can take on complementary roles in EBM, each with their own specific function, but also building a larger common understanding. This multi-model approach allows for considerable flexibility in addressing

specific questions as they arise during project development while simultaneously providing a basis for teaching those interested in the system about the problems that arise when trying to manage complex nonlinear systems (something few people have an intuitive feel for; Boschetti *et al.* 2010). In terms of modelling the GAB the three stage modelling approach outlined below provides a sound basis for the system assessment:

Conceptual models, which summarise system understanding and focus on the main drivers of a system and highlight what needs to be incorporated in the other models. These are represented diagrammatically and descriptively; and are often developed in conjunction with stakeholders and topic experts. These conceptual models are summarised in Ward *et al.* (2017).

Shuttle models, which incorporate the minimum number of processes that capture all the crucial components for a basic understanding of the ecosystem. These models provide a means of communication between stakeholders and modellers, and allow further training building upon experience gained with the conceptual models (i.e. increasing trust, understanding and democratisation of knowledge). They also provide further understanding on key mechanics that can be shuttled into the full system model. Ecopath with Ecosim (EwE) functions in this role, focusing on trophodynamics and a selective set of the drivers of the system.

Full-system models, such as the Atlantis modelling platform, synthesise all the information collected on the system, include some representation of all the major parts of the system (physical, ecological, economic and social) and can address stakeholder concerns and trial alternative management options under cumulative stressors.

This multi-model approach not only provides information and tools in direct support of decision-making, but also addresses system uncertainty (perhaps the biggest concern in ecosystem modelling).

The GAB Research Program generated extensive new knowledge about the GAB, which needed to be integrated to improve our understanding of how the GAB ecosystem functions. We have new knowledge of the key physical, chemical and biological drivers of ecosystem structure (Themes 1 and 2); the vulnerability of key habitats/assemblages (Themes 3 and 4), trophic pathways and species to potential ecosystem stressors and their combined effects (Theme 7, this report); and the socio-economic and ecological trade-offs associated with multiple use (Theme 6). The integration of existing and new information was achieved through the three model types described above, summarising current knowledge of the system and implications for future research, monitoring and management. The EwE and Atlantis models and the results of a small exemplar set of scenarios are described here. These scenarios provide illustrative examples of what can be done with the models and provide a basis for future use of the models.

2.2 Objectives

The original objectives for the ecological modelling components of Theme 7 were to:

1. Establish and test trophodynamic (Ecopath with Ecosim) and whole-of-system (Atlantis) models of the structure and function of the socio-ecological systems of the GAB.

   a. Examine the sensitivity of key species, trophic pathways, habitats and assemblages to potential ecosystem stressors, including climate variability and change scenarios, fisheries, aquaculture and oil/gas activities to inform future monitoring, management and research.

b. Explore the synergistic, cumulative and potential impacts of multiple stressors and identify socio-economic and ecological trade-offs associated with multiple use of the GAB.

As with most large research programs, the evolution of the field programs in the GABRP necessitated a reshaping of the broader program of research. This meant that some of the research projects on the human dimensions were reduced in size or omitted, reducing available information for use in the synthesis. Moreover, the time frame of availability of the field data meant the available period for synthesis was curtailed. Despite the best efforts of all involved this meant the objectives for the ecosystem modelling had to be simplified. Ultimately it was agreed that the new objectives for the ecological modelling in Theme 7 were (i) to synthesise the new and historical understanding of the ecosystem by developing the ecosystem models to a point where they were scenario ready, and (ii) to provide a demonstration of the models' capacity via example scenarios, which demonstrate the kinds of questions the models could address, even without further development.

To deliver on these objectives this report is divided into three main sections: sections 3 and 4 provide technical detail on the development of the EwE (Section 3) and Atlantis models (Section 4). The final section provides details on the development and outputs of the various demonstration scenarios examined (Section 5).

3. AN ECOPATH WITH ECOSIM ECOSYSTEM MODEL OF THE GREAT AUSTRALIAN BIGHT: DEVELOPMENT AND PARAMETERISATION

3.1 Introduction

Ecopath with Ecosim (EwE) is the predominant ecological modelling software that has been used to describe a diverse range of aquatic ecosystems world-wide for over 30 years. It was developed by Polovina (1984) based on a simple steady-state trophic box model, and further developed by Christensen and Pauly (1992a) and Walters *et al.* (1997).The software comprises three modules: the Ecopath module enables description of the static state energy flow of an ecosystem at a particular point in time; the Ecosim module enables dynamic simulations based on the basic Ecopath parameterisation that allow the forecasting of ecosystem responses to environmental perturbations; and finally the Ecospace module enables two-dimensional spatial representation of the ecosystem. The ecological theory and mathematical equations that underpin the functions of EwE are extensively detailed elsewhere (e.g. Christensen & Pauly 1992, Walters *et al.* 1999, Christensen & Walters 2004, Steenbeek *et al.* 2013).

The EwE software has been applied across a breadth of topics to investigate impacts and questions focused around improving the management of aquatic ecosystems. Some recent examples of the breadth of topics include: climate change (Alva-Basurto & Arias-Gonzalez 2014, Christensen *et al.* 2015, Cornwall & Eddy 2015, Ruzicka *et al.* 2016, Suprenand & Ainsworth 2017); regime shifts (Heymans & Tomczak 2016, Ofir *et al.* 2016); hypoxia (de Mutsert *et al.* 2016); fishing impacts (Geers *et al.* 2016, Eddy *et al.* 2017b); single and multi-species fisheries management (Cornwall & Eddy 2015, Eddy *et al.* 2017a); ecosystem-based management (Lercari & Arreguin-Sanchez 2009, Jiang *et al.* 2017); ecosystem-based fisheries management (Alva-Basurto & Arias-Gonzalez 2014, Bourdaud *et al.* 2016, Jacobsen *et al.* 2016, Musinguzi *et al.* 2017, Sagarese *et al.* 2017), invasive species (Corrales *et al.* 2017, Haak *et al.* 2017, McGill *et al.* 2017); marine protected areas (Abdou *et al.* 2016); environmental impact assessment (Fretzer 2016); ecological indicators for evaluating the changing status and health of marine ecosystems (Coll *et al.* 2016, Gonzalez *et al.* 2016, Coll & Steenbeek 2017); nutrient and biological iron cycling impacts on primary productivity (Chaalali *et al.* 2015, Maldonado *et al.* 2016); impacts of decommissioning of power plants (Vasslides *et al.* 2017); oil spill restoration (Okey *et al.* 1999, Okey & Wright 2004, Sagarese *et al.* 2017) and contaminant tracing in marine ecosystems (Larsen *et al.* 2016).

In this chapter we provide the technical details on the synthesis and integration of both existing data and new knowledge acquired through the GAB Research Program (especially Themes 1, 2, 3, and 4) into a trophodynamic model using the EwE software (www.ecopath.org, Version 6.5). We describe the key ecological assemblages, species and trophic pathways that underpin the model and briefly describe the scenarios that we implemented complementary to the Atlantis ecosystem scenarios. The comparison of the two model outcomes are reported in Chapter 5, following the Atlantis model description in Chapter 4.

3.2 Model construction

The Ecopath model was constructed for the initial year of 2006, to coincide with initial year of the hydrodynamic models and the time from which a lot of biological data were collected. Time series of various data types such fishery data were compiled for the 10-year period (2006-2015) to calibrate or tune the Ecosim model. It was also the period over which the Atlantis model was constructed and calibrated and therefore facilitates direct comparison between model outputs.

The model domain extends from Cape Otway (Victoria) in the east to near Albany (Western Australia) in the west, encompassing an area of 1,578,450 km^2 (Figure 3.1). The east to west distance of the model domain is approximately 2,150 km, extending offshore variable distances from ~470km in the western margins of the domain area, to ~1,000 km in the central GAB and to approximately 680 km in the eastern margins of the domain area. The region encompasses about 19% shelf and gulfs (<200 m), 7% slope (200 – 2,000 m) and 74% open ocean (>2,000 m, Figure 3.1).

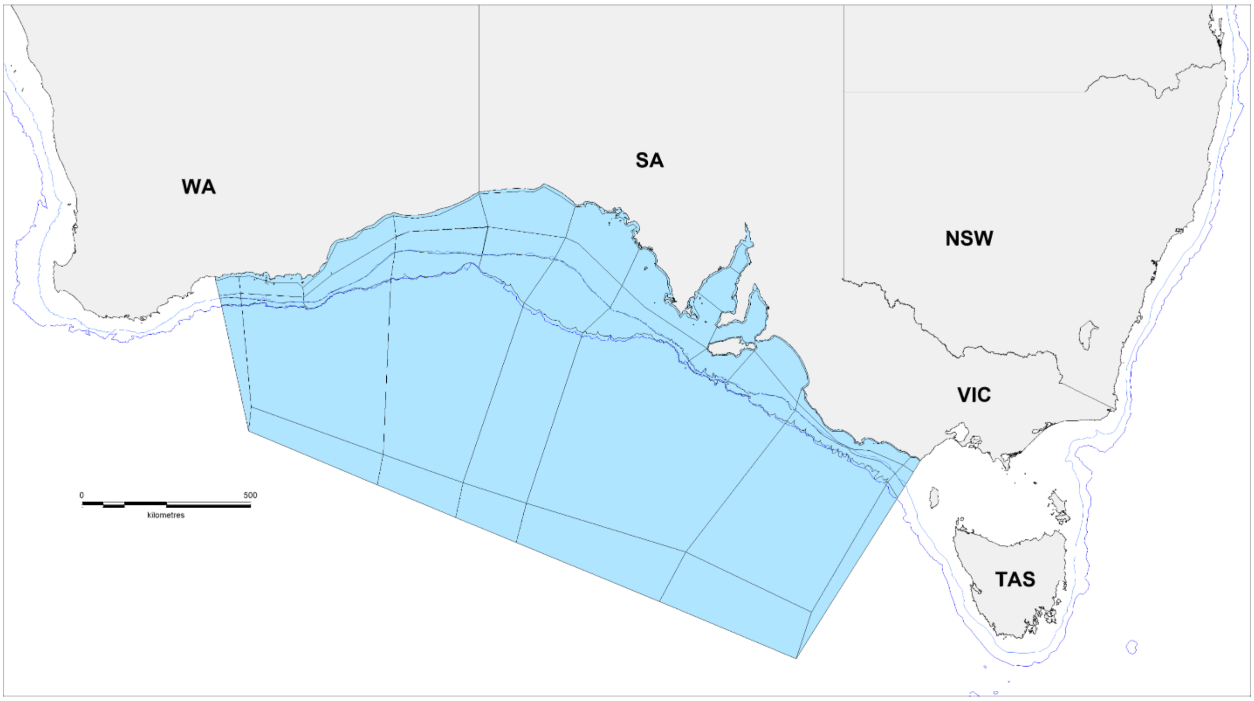


Figure 3.1 Area of Great Australian Bight (GAB) used to define the GAB ecosystem model domain (shaded blue). Atlantis model polygons with the domain area are indicated as are the 200 m and 2000 m contour.

A number of functional or trophic groups were used in the GAB ecosystem model, based on species similarity in terms of diet, habitat, foraging behaviour, size, consumption and rates of production (Table 3.1, Section 3.3). The GAB ecosystem model structure was built around 75 functional groups including: mammals (7), birds (8), chondrichthyans (6), teleosts (24), farmed finfish and shellfish (2), cephalopods (3), other invertebrates (17), bacteria and microbes (2), autotrophs (4), detritus (1) and discards (1). Some commercial fish and iconic species were modelled as separate groups to aid scenario testing and modelling, and facilitate the assessment of impacts and drivers. The groups were also structured to allow as direct a comparison with the Atlantis model structure as possible (Table 3.1). Each trophic group operates as a single biomass pool, despite groups often being composed of multiple species. However, by matching species for size, habitat and diet, dynamic parameters such as consumption and production rates are generally quite similar, and so reduces errors and uncertainty due to aggregation.

Central to EwE is the diet matrix. To populate this matrix, dietary information for trophic groups was sourced widely, with data with provenance to the GAB used in preference to data collected elsewhere. Core datasets were those developed for previous EwE models within the GAB region, including: the eastern GAB (Goldsworthy *et al.* 2011, 2013b); Spencer Gulf (Gillanders *et al.* 2015); and Gulf St Vincent (GSV) ecosystem models (Goldsworthy *et al.* 2017a). Data from other regional studies were used where appropriate, including the Eastern Bass Strait model (Bulman *et al.* 2006), and data from other south eastern Australian regional studies such as the Southern Program off the

east Tasmania (Bulman & Blaber 1986, Young & Blaber 1986, Blaber & Bulman 1987, May & Blaber 1989), the South east Fishery program (Bax & Williams 2000), the southeast Australian Orange Roughy program (Bulman & Koslow 1992, Bulman *et al.* 1994, Koslow *et al.* 1994a) and the Southern Hills (Seamount) program off Tasmania (Koslow *et al.* 1997, Williams *et al.* 2001, Bulman *et al.* 2002, Butler *et al.* 2002). Details of sources are provided for each trophic group in Section 3.3.

In addition to dietary information, Ecopath requires the values for four key parameters for each trophic group, in order to balance the model. These include biomass (B), consumption per unit of biomass (Q/B), production per unit of biomass (P/B) which under the steady-state assumption of the model this is equivalent to the instantaneous rate of total mortality *Z* used by fisheries biologists, and ecotrophic efficiency (EE). This last parameter represents the fraction of the production that is used in the system, or that is explicitly moved out of the system (e.g. by migration), and varies between 0 and 1 (approaching 1 for groups with considerable predation pressure). Values for three of these four parameters are required to be entered into the mode thereby creating a set of simultaneous equations which are solved to provide estimates of the final (fourth) parameter (typically EE). Where possible, the biomasses (t km^{-2}) of functional groups were estimated either from field surveys or stock assessments. A detailed description of the functional groups and how estimates of biomass, P/B and Q/B were derived are provided in Section 3.3.

Table 3.1 Summary and description of the functional groups (FG) used in the EwE GAB ecosystem model and their associated mapping to the Atlantis model functional groups.

EwE FG	Atlantis FG	Description (and representative species)
Pelagic invertebrates & flora		
Large phytoplankton	PL	>5 µm diatoms, most nanophytoplankton
Small phytoplankton	PS	<5 µm pico- and small nanophytoplankton, autotrophic nanoflagellates
Nanophytoplankton	PS	<5 µm Heterotrophic nanoflagellates
Microzooplankton	ZS	5-200 µm Heterotrophic flagellates
Small (meso) zooplankton	ZM	0.2-2cm Copepods, pteropods and ostracods, tunicates, chaetognaths (in water column)
Large zooplankton	ZL	2-20cm Euphausiids (krill), mysids, copepods and amphipods (in water column)
Gelatinous zooplankton	ZG	Jellyfish, pyrosomes, medusa, salps and ctenophores, pelagic tunicates
Detritus	DL	Detritus in water column and sediment that is turned over in weeks
Pelagic bacteria	PB	Pelagic bacteria
Squid and cuttlefish (shelf and deep/offshore)	CEP	Southern calamari, Australian giant cuttlefish
Benthic invertebrates & flora		
Macroalgae	MA	Kelps
Seagrass	SG	Seagrass
Rock Lobster	BRL	Rock lobster
Western King Prawn	PWN	Western king prawn
Meiobenthos	BO	small benthic organisms that live in sediments <1mm e.g. foraminiferans, nematodes, benthic ostracods, harpacticoid copepods
Benthic detritivores	BD	Infaunal detritivores: e.g. polychaetes , sipunculids, burrowing bivalves, percarid crustacea (isopods, amphipods, cumaceans, tanaids), holothurians (sea cucumbers), gastropods (sedentary)
Benthic carnivores	BC	Infaunal carnivores/scavengers: e.g. echinoderms (sea stars), gastropods, predatory polychaetes, slugs (fixed/sedentary), sea spiders

EwE FG	Atlantis FG	Description (and representative species)
Benthic grazers	BG BGU	Herbivorous echinoderms (sea-urchins), large gastropods, chitons
Abalone (Benthic grazer)	BGA	Greenlip/blacklip abalone
Deep filter feeders	BFD	Sessile megafauna > shelf break i.e. ~250 m e.g. bivalves, sponges, hydroids, seapens, seafans and deep-sea corals, anemones, crinoids, bryozoan, brachiopods, ascidians (benthic tunicates)
Shallow filter feeders	BFS	Sessile megafauna on the shelf e.g. bivalves (scallops, cockles, mussels, oysters), sponges, bryozoans, barnacles, seapens, crinoids, brachiopods
Commercial crabs	BMC	Blue, sand crabs, Balmain bug, other crabs, giant crab
Macrozoobenthos (shelf and deep)	BMS	Large, active, primarily carnivorous megafauna e.g. gastropods, decapod crustaceans (crabs, non-commercial prawns, large mysids), stomatopods, cephalopods- squids and octopus (Maori octopus, southern keeled octopus, southern sand octopus, and the southern hammer octopus)
not in EwE model	DR	Detritus slow turnover
Microphytobenthos	BB	Benthic bacteria and microflora
Aquaculture species		
Farmed finfish	AQT	Farmed SBT & Yellowtail kingfish
Farmed molluscs	AQM	Farmed oysters mussels
Fin-fish		
Sardines	FPS	*Sardinops sagax*
Anchovy	FPA	*Engraulis australis and others sprats and small planktivores*
Mackerels	FPJ	*Trachurus declivis, T. murphyi & Scomber australasicus, T. novaezelandiae*
Southern Garfish	FSG	*Garfish*
Redbait	FPB	*Emmelichthys nitidus*
King George Whiting	FKG	*Sillaginodes punctatus*
Deepwater flathead	FFH	*Platycephalus conatus*
Pink snapper	FSN	*Chrysophrys auratus*
Bight Redfish	FRD	*Centroberyx gerrardi*
Shelf demersal piscivores Small Large Shelf pelagic piscivore large Offshore pelagic piscivore (large)	FVS	*Demersal(small)*: stargazers, red cod, small tooth flounder, Perch, butterfly fish, boarfish, cobblerfish, red mullet and goatfishes, silverbelly *Med/Large:* silver trevally, john dory, trumpeter, stargazers, john dory *Pelagic(med/large):* Australian salmon, herring, barracouta, long-fin pike, tommy rough, tailor, snook, mackerel tuna, teraglin, dolphinfish, mulloway, yellowtail kingfish *Offshore pelagic*: Ray's bream, southern Ray's bream, moonfish, oilfish, short sunfish, trevallas, rudderfish
SBT	FVB	Southern bluefin tuna *Thunnus maccoyii*
Tuna and billfish	FVT	frigate mackerel or tuna, skipjack tuna, albacore tuna, yellowfin tuna, bonito, bigeye tuna, billfish, striped marlin, black marlin, blue marlin, swordfish
Mesopelagics	FMM	Diel vertical migrating mesopelagic fishes largely from Myctophidae
Non-migratory mesopelagics	FMN	Bathypelagic and non-migratory fishes
Deep demersal fishes Small invertivores Small piscivores Large invertivores Large piscivores Offshore pelagic invertivores (large)	FDD	*Piscivores*: e.g. southern roughy, sandpaper fish, Zeidae, Cyttidae , gemfish, ling, *Invertivores*: e.g. oreos dories, pink ling, *Piscivores*: gemfish, blue grenadier, hapuku, cucumber fish, painted gurnard, long-finned gemfish, silverside, whiptails, imperador, redfish, cardinalfish, ribaldo *Offshore pelagic*: blue warehou, silver warehou, blue-eye trevalla, butterfish
Shallow demersal fishes Small invertivores	FDS	*Invertivores (small):* e.g. deep velvet fish, scarlet cardinal, smooth cardinal fish, southern crested weed fish, old wife, four-spine

EwE FG	Atlantis FG	Description (and representative species)
Large invertivores		leather jacket, smoothspine leather jacket, pygmy leatherjacket, gulf gurnard perch, little gurnard perch, rainbow cale, sculptured seamoth, common bullseye, slender bullseye, spotted grubfish, wavy grubfish, Derwent flounder, spotted flounder, barber perch, many banded sole, orange barred puffer fish, prickly toadfish smooth toadfish, soldier fish, latchet, southern shortfin gurnard, spiny gurnard, southern school whiting (silver whiting), toothbrush leatherjacket, striped perch, ornate cowfish, Shaws cowfish, rough bullseye, leatherjackets (bridled, mosaic, velvet, Gunn's, Degens, rough), crested flounder, squareback butterflyfish, goblin fish, syngnathids ocean perch, latchet *Invertivores (large):* blue morwong, grey morwong, short boarfish, Small tooth flounder, nannygai, gurnard perch, rock ling, southern tongue sole, spikey globefish, common stink fish, spotted stinkfish, beaked salmon, senator wrasse, fringed stargazer, southern gobbleguts, and Chinaman leather jacket, jackass morwong, black bream, purple throated and blue wrasse
Shallow demersal invertivores (included above)	FDH	*Herbivores*: (silver) drummer, rock blackfish, luderick, dusky morwong, marblefish, fantail mullet, sea mullet, sand mullet, herring cale
Chondrichthyans		
Demersal sharks (shelf and deep)	SHD SHG SDG	Whiskery shark, broadnose shark, Port Jackson shark, carpet, wobbegong, saw shark, cat shark Gummy shark *Mustelus antarcticus* deepwater dogfish, gulper sharks School shark
Demersal piscivorous shark	SHS	
Pelagic sharks (coastal and offshore)	SHP	White, bronze & dusky whaler sharks, smooth hammerhead shark, Shortfin mako, blue shark
Skates and rays	SSK	Melbourne skate , southern fiddler ray, southern shovelnose ray, smooth stingray , coastal stingaree, sparsely-spotted stingaree, western shovelnose stingaree, white spotted skate
Top predators		
Gulls	SBG	Pacific and silver gulls
Small Petrels	SBA	Shearwaters, albatross, petrels
Gannets and terns Shags and Cormorants	SBD	Australian gannet, terns, Cormorants and shags
Little Penguin	SBP	*Eudyptula minor*
Australian fur seal	SFA	*Arctocephalus pusillus doriferus*
Long-nosed fur seal	SFL	*Arctocephalus forsteri*
Australian sea lion	SL	*Neophoca cinerea*
Baleen whales	WHB	Pygmy blue, humpback, southern right whale
Toothed whales	WHT	Sperm, beaked, pilot, killer
Bottlenosed Dolphins	DOB	*Tursiops truncatus*
Common dolphin	DOC	*Delphinus delphis*

3.2.1 Fishery data

Fishery data on landings, discards and effort were obtained for the GAB ecosystem region and allocated into 34 fishing fleets based around gear-type and target species (Table 3.2). The region includes areas where the fisheries are managed by the Australian Government (Commonwealth managed fisheries) usually between 3-200 nm offshore, as well State managed fisheries (Victoria, South Australia and Western Australia), usually within 3 nm of the coast. The main exception to these jurisdictional arrangement is off South Australia where the two main gulfs (Spencer Gulf, Gulf St Vincent) and the Investigator Strait are managed as State waters. Within the GAB ecosystem model, Commonwealth managed fisheries were separated into 8 fleets, Victorian managed fisheries into 6 fleets; South Australian managed fisheries into 13 fleets; and Western Australian managed fisheries into 6 fleets (Table 3.2).

Annual fishery landings and effort data were obtained (under appropriate licence agreements) for both state and federal jurisdictions that fell within the model domain for a 10-year period from 2006 to 2015 inclusive (or later). Information on both the landings and discards is required to estimate total catch but since discards were not always recorded or collected in state fishery logbooks, estimates often had to be made. Discard rates for several gear types derived from independent surveys conducted in South Australia (Currie *et al.* 2009, Fowler *et al.* 2009, Roberts & Steer 2010, Goldsworthy *et al.* 2011, Goldsworthy *et al.* 2013b, Gillanders *et al.* 2015, Goldsworthy *et al.* 2017a) were applied to other the state fisheries catch data where discard data were similarly lacking.

Table 3.2 Fishing fleets included in the EwE GAB ecosystem model. The fisheries are either managed by the Commonwealth (C); Victoria (Vic); South Australian (SA) or West Australian (WA) Governments.

Fleet No.	Fleet name	Main Target Species
1	C Tuna	Southern bluefin tuna
2	C Dem trawl	Deepwater trawl, blue-eye trevalla, bight redfish, blue grenadier
3	C Small pelagic	Jack mackerel, blue mackerel, Redbait
4	C Gillnet	Gummy, school, whiskery, and saw sharks
5	C Shark line	Gummy and school shark, snapper
6	C Scalefish line	Blue-eye trevalla, ling, hapuku, gummy shark
7	C Danish seine	Deepwater flathead
8	C Squid	Squid
9	Vic Rock lobster	Rock lobster
10	Vic Scalefish line	Wrasse, snapper, barracouta
11	Vic Scalefish net	King George whiting, barracouta
12	Vic Shark line	Gummy and school shark
13	Vic Pots	Snapper, octopus
14	Vic Abalone	Abalone
15	SA Sardine	Australian sardine
16	SA Lobster	Rock lobster
17	SA Prawn	Western King prawn
18	SA Pipi	Pipis
19	SA Abalone	Abalone
20	SA Haul	Garfish, Australian salmon, whiting
21	SA crab	Blue swimmer crab, Giant crab
22	SA Handline	Snapper, King George whiting
23	SA Longline	Snapper, whalers, snook

Fleet No.	Fleet name	Main Target Species
24	SA Jig	Squid
25	SA Charter	King George whiting, redfish, snapper
26	SA pots	Blue swimmer, sand, giant crab
27	SA Coorong	School and whaler shark, mulloway
28	WA Salmon	Western Australian Salmon
29	WA Gillnet	Gummy, whaler, hammerhead sharks,
30	WA Purse seine	Sardine
31	WA Abalone	Abalone
32	WA Lobster	Rock lobster
33	WA Scalefish Line	Yellow-eye redfish, blue eye trevalla
34	SA Recreational	Striped trumpeter, blue mackerel

3.2.2 Commonwealth fisheries

Fishery records were extracted from the Commonwealth fisheries database held at CSIRO for the GAB model domain (i.e. from broadly within longitudes 120°W to 143.5°W and latitudes 31.4°S to 43.7°S) using the GIS shapefiles for the model domain for the period 2005 -2016. The data were stored in an Access database for ease of storage and processing. The data were initially extracted and processed by Atlantis model polygon to input into the Atlantis model, and then re-grouped and processed for EwE model purposes. All fishery species were coded with both Atlantis and EwE functional group categories (Table 3.1). The relevant fishery operation and catch composition data were extracted from the database by functional group, polygon, fishery and gear code as appropriate.

There were 11 fisheries in the Commonwealth sector each containing from one to six gear codes resulting in a total of 27 fishery-gear code (sub-fishery) combinations. These 27 were aggregated into both Atlantis and EwE model fisheries (see Table 3.3). Some fisheries or gear codes were excluded from the analyses as they were either dubious records or so few as to not warrant a new "sub-fishery" type. While the VIT trawl and Danish seiners occur in Commonwealth waters they are in fact state fisheries (despite missing from the state records) and so were included in the state fisheries here.

Catch

For EwE, annual catches were calculated for each sub-fishery and functional group from which catch rates for the whole model domain were derived. Similarly, annual discards and discard rates were calculated directly from the fishery data where available. However, the discard information was very patchy particularly in the first half of the time period, therefore it was often necessary to estimate discard rates by one of the two following methods. Where operations were thought not to have changed significantly and the 2011-2016 data were more explicit, we applied the 2011-2016 discard rate to the earlier data. Where there were no relevant data from either period, discard rates were estimated from the Integrated Scientific Monitoring Program (ISMP) reports (Knuckey 2006, Tuck *et al.* 2013, Sporcic & Haddon 2016, Thomson & Upston 2016, Upston & Thomson 2016) or other reviews and applied instead. Only species, for which catches were >500 kg were included in the analysis/model implementation. Similarly, species caught only in one year, were ignored.

The 2006 catch and discard data were required to initialise the model and for the fisheries' dynamics. Therefore, when certain functional groups were not recorded in the initial input year, i.e.

2006, but were important later on, they needed to be "seeded" with a very small catch that could be scaled by the effort over subsequent years which would result in actual levels of catch reported in those years. For the Danish seine fishery in particular, the onset of the GAB Danish seine fishery in 2011 resulted in a very large change in catch and effort. For species that were not caught in 2006, values were thus seeded with 1/90 of the 2011 catches. This method assumes that species were caught and discarded but not recorded.

Table 3.3 Commonwealth fishing fleets and gear codes assigned to EwE fishery fleets

EwE Fishery #	EwE Fishery name	Fishery	Gear Code
1	Tuna	SBT	PS
		WST	PS
		WTB	LLP, PL
		WTF	TR
2	Demersal trawl	SET	TDO, TW
		GAB	OTT, TDO, TW, PTB
		VIT	TW
3	Small pelagic	SPF	PS, TMO, TDO
4	Gillnet	GHT	GN
5	Shark line	GHT	BL HL
6	Scalefish line	GHT	AL, DL, TL
		HSN	AL, Dl
7	Danish Seine	SET	DS
		GAB	DS
		VIT	DS
8	Squid	SQJ	J
Unassigned		GHT	RR
		SBT	RR

Effort

Ecosim uses either fishery effort or individual fishing mortality (F) rates (i.e. catch / biomass) to impose fishing pressure on the base Ecopath model, i.e. annual effort time series are required to "drive" the fishery dynamics. The amalgamation of different gear types with different effort measures across the sub-fisheries necessitated the determination of a common effort metric. We found that shots (operations) for each sub-fishery would best reflect corresponding annual catches in most cases. While this method is a coarse approach and won't capture the nuances of each fishery's behaviour, it was sufficient for driving the dynamics of this version of the GAB EwE model.

3.2.3 Victorian fisheries

Aggregated Victorian fishery data were provided by the Department of Economic Development, Jobs, Transport and Resources (DEDJTR) for the model area (i.e. from broadly within longitudes 120°W to 143.5°W) that occurred within the Victorian jurisdiction. The data were stored and partially analysed in an Access database held at CSIRO. These data were further aggregated into broader "EwE fisheries" by fishery and gear code (Table 3.4).

Table 3.4 Details of mapping of Victorian state fisheries and gear types into EwE fisheries.

EwE Fishery	Fishery	Gear code	Gear description
Pot	BF	CT	Crab Trap/Pot
	DF	CT	Crab & Fish trap
	OF	FT	Fish Trap
	OF	OP	Octopus Trap/Pot
Scalefish line	OF	DL	Drop Line
	OF	HJ	Hand Squid Jig
	OF	HL	Hand Line
	OF	SJ	Squid Jig
	OF	SN	Snapper Long Line
	OF	TR	Troll Line
	OW	DL	Drop Line
	OW	HL	Hand Line
Rock lobster	GC	RL	Lobster Pots
	GC	unknown	unknown
	RL	RL	Lobster Pots
	RL	unknown	unknown
Scalefish net	OF	H3	Haul Seine (Medium Mesh 30-59mm)
	OF	H4	Haul Seine (Large Mesh 60-100mm)
	OF	H5	Garfish Seine (Floating 25-29mm)
	OF	H6	Ringing Seine (Bottom Set 25-45mm)
	OF	M1	Multifilament Mesh < 60mm
	OF	M2	Multifilament Mesh 60-74mm
	OF	M3	Multifilament Mesh 75-94mm
	OF	M4	Multifilament Mesh 95-124mm
	OF	M5	Multifilament Mesh 125-130mm
	OF	M6	Multifilament Mesh > 130mm
	OF	N1	Non-shark Monofilament Mesh < 60mm
	OF	N2	Non-shark Monofilament Mesh 60-74mm
	OF	N3	Non-shark Monofilament Mesh 75-94mm
	OF	N4	Non-shark Monofilament Mesh 95-124mm
	OF	N5	Non-shark Monofilament Mesh 125-130mm
	OF	N6	Non-shark Monofilament Mesh > 130mm
	OF	OT	Otter Trawl (? Perhaps miscoded)
	OF	XX	Other Gear
	OP	PS	Purse Seine
Shark line	OF	SL	Shark Long Line
Victorian state trawl	TR	FR	Fish Trawl (sweeps attached)
	TR	PT	Prawn Trawl (no sweeps attached)

Catch and effort

All captured species were categorised into EwE functional group categories. The catch composition data were aggregated by EwE functional groups per year. The annual landing and discard or estimated discard data were converted into a landing and discard rates for the whole model domain ($t.km^{-2}$) and the 2006 annual landing and discard data were input into the model. The annual corresponding time series of catch from (2006-2016) were used to calibrate the Ecosim model.

To obtain the relative effort time series to drive the Ecosim model, operations data were assigned to an EwE model fishery according to Table 3.4 and efforts were calculated as the sum, across all fishing boats, of the numbers of days fished per year per boat.

The effort in the bait fishery and prawn trawl were low and infrequent so these fisheries were excluded. Effort in the State trawl was also very low but some of the effort attributed to State trawl in the records were probably incorrect – i.e. records pertaining to pipi capture were attributed to

"otter trawl" but we assumed these to be incorrect and re-assigned them to the "Scalefish" net fishery. This left the state trawl with very low and inconsistent effort and so it was also excluded.

3.2.4 South Australian fisheries

Targeted species catch and effort data for South Australian fisheries were obtained from PIRSA, and had been pre-processed into annual total catch, total effort and total catch per unit effort (CPUE) for each target species within the relevant fishery. The data were not complete due to confidentiality reasons.

Catch and effort

We allocated the target species into functional groups, and summed across species within a functional group to obtain annual catch per functional group. Some fishery methods were eliminated if there were too few data to be useful: in the Marine Scalefish Fishery cockle rake for vongole and fish trap for ocean jacket.

Discard data were not available therefore discard rates for South Australian fleets were estimated by applying relevant discard rates derived for bycatch/byproduct from fishery independent surveys (Currie *et al.* 2009, Fowler *et al.* 2009, Roberts & Steer 2010, Goldsworthy *et al.* 2011, 2013b, Gillanders *et al.* 2015, Goldsworthy *et al.* 2017a) to the catch data. We allocated discarded or estimated discarded species into functional groups and then summed across species within a functional group to obtain annual discard per functional group.

Annual effort per gear method or fishery was usually provided already, but in some cases, we summed effort if methods and effort measures were the same. We did not try to extrapolate for missing data as we were unable to judge how much and where the gaps occurred.

3.2.5 Western Australian fisheries

Catch and effort data for Western Australian fisheries in the South Coast region were obtained from the WA Department of Primary Industries and Regional Development. The fisheries which operated in the South Coast Bioregion within the model domain and for which we obtained data were: Abalone; Joint Authority Southern Demersal Gillnet and Demersal Longline Managed Fishery; South Coast Crustacean Managed Fishery; South Coast Purse-Seine Managed Fishery; South Coast Salmon Managed Fishery; South Coast Estuarine Managed Fishery; and Open Access in the South Coast Bioregion. These data were also incomplete due to confidentiality. Data were provided in various aggregated formats. Catch data per species was aggregated by year, month, method and block. Effort measured in days of fishing were aggregated by block and fishery.

These fisheries account for 19 gear types and map (more or less directly) into 6 broader fisheries for the EwE model –WA abalone, WA gillnet (includes estuarine/managed), WA rock lobster, WA purse seine, WA salmon and WA wetline (Table 3.5).

Catch and effort

Rather than discarding much of the information due to incompleteness, we made some assumptions in order to fill gaps. We usually had total annual catch data for individual species but often not their specific contribution to specific gear/fishery type. For those gaps, we subtracted the sum of the

known catches per species per gear type from the annual species total, and distributed the remainder across the gears assuming a distribution according to its usual proportion of catch if known or just equally if unknown. Overall these allocations were quite arbitrary but we considered that to discard large amounts of catches was even less desirable. Once again, catches were aggregated per functional group. There were no discard data so discard rates from SA estimated discard rates were applied to obtain annual discards (t.km^{-2}).

Effort (days fished) were combined across block and fishery, but about half of the data were missing; ~80% of data in the fisheries for salmon purse-seine and salmon managed (primarily beach seine), ~60% in the estuarine, crustacean and open access (primarily wet-line) and ~20 and 30% in the abalone and gillnet and longline fisheries respectively. For the first two (salmon fisheries), we estimated an annual effort time series using the salmon catches as a scalar of effort data. The annual effort time series for the other fisheries were not adjusted and while the missing data make the time series highly uncertain, the gaps in the data were fewer and mostly spread throughout the years (i.e. the numbers of blocks for which data were available were reasonably consistent from year to year).

Table 3.5 Western Australian fisheries and gear types

EwE fishery	Fishing Method	Abalone	Southern Demersal Gillnet and Demersal Longline Managed Fishery	South Coast Crustacean Managed Fishery	South Coast Purse-Seine Managed Fishery	South Coast Salmon Managed Fishery	South Coast Estuarine Managed Fishery	Open Access in the South Coast Bioregion
Abalone	Diving	x						
Gillnet	Gillnet		x			x	x	x
	Longline		x					
Rock Lobster	Potting			x				
	Octopus Pot							x
	Crab Trap			x				
Purse seine	Purse Seine				x			
Salmon	Beach Seine					x		x
	Haul Net / Ring Net					x	x	x
	Trap Net						x	
Wet line	Dropline							x
	Electric Gunwhale Mounted Reel							x
	Gunwhale Mounted Hand Operated Reel							x
	Handheld Reel					x		x
	Handline							x
	Hydraulic Gunwhale Mounted Reel							x
	Squid Jigging							x
	Trolling							x

3.3 Description of data sources, methods and assumptions in parameter estimation

3.3.1 Cetaceans

A total of 35 cetacean species have been recorded in the GAB, including 11 baleen (mystecete) whales and 24 toothed (odontocete) whale species (Theme 4 Project 4.1 Report, Gill *et al.* 2011). The most significant large cetacean species in the GAB includes the pygmy blue whale (*Balaenoptera musculus brevicauda*), sperm whales (*Physeter macrocephalus*) and southern right whales (*Eubalaena australis*). Pygmy blue whales are seasonal visitors to shelf and slope waters of the GAB, with major feeding aggregations associated with upwelling occurring between Cape Otway (Victoria) and south and west of the lower Eyre Peninsula (South Australia) between November and May (Theme 4 Project 4.1 Report, Gill *et al.* 2011). Continental slope waters of the central and eastern GAB, and off Albany in Western Australia have been identified as important areas for sperm whales where foraging is known to occur (Department of the Environment 2015). The largest breeding aggregation of southern right whales in Australia is located at the Head of Bight in the GAB. Southern right whales migrate from higher latitude foraging areas (between 40°S and 65°S) to the GAB arriving from May, where females spend 2-3 months nursing their calves before migrating offshore. Humpback whales (*Megaptera novaeangliae*) are also common visitors, but neither southern right whales nor humpback whales are thought to forage significantly in shelf and slope waters of the GAB. Slope waters of the GAB are home to a high biodiversity of smaller odontocete whales, especially beaked whales and pilot whales. For most of these species, information on occurrence in the GAB is limited to strandings or opportunistic sightings data. Shelf and coastal waters are dominated by the short-beaked common dolphin (*Delphis delphis*) and members of the bottlenose dolphin genus (*Tursiops* spp.). At least two species have potentially been documented from the region, the coastal Indo-Pacific bottlenose dolphin (*T. aduncus*) and common bottlenose dolphins (*T. truncatus*), the latter of which are predominantly distributed in shelf and oceanic waters further offshore than the former (Kemper & Ling 1991, Kemper 2004, Gibbs *et al.* 2011). More recently, a third species (the Southern Australian bottlenose dolphin) has been described from coastal regions of Victoria, South Australia and Tasmania (Moller *et al.* 2008, Charlton-Robb *et al.* 2011). There may also be hybridisation between species (Kemper 2004). Marked population structure has been found between coastal *Tursiops* spp. in Spencer Gulf and those in the GAB that may be associated with the oceanography of the Gulf region (Bilgmann *et al.* 2007).

1. Baleen whales

The predominant foraging baleen whale that occurs in the GAB is the pygmy blue whale. The total number of blue whales that forage in GAB waters is unknown, but based on estimates of sightability from aerial surveys; they may number 150 and are thought to remain in the upwelling system for approximately 6 months of the year (P. Gill pers. comm.). Estimates of the mass of pygmy blue whales range between 60 t and 150 t. We have used a conservative estimate of 80 t per whale to account for subadults (P. Gill pers. comm.). This gives a biomass estimate of 12,000 t within the GAB ecosystem.

Prey consumption was estimated using the methods presented by Barlow *et al.* (2008) for cetaceans feeding in the California Current ecosystem. They used models of the average daily ration (*R* in kg wet wt) and average daily metabolic requirements (*ADMR* in kJ d^{-1}) as follows:

$$R = \frac{ADMR}{\{0.8[3900Z + 5450(1 - Z)\}},$$

where:

$$ADMR = \beta(293.1M^{0.75}),$$

and 3900 and 5450 are the energy densities of crustaceans and fish, respectively ($kJkg^{-1}$ wet weight), Z is the fraction of crustaceans in the diet, 0.8 is the assimilation efficiency (Leaper & Lavigne 2007) and β = 2.5 (Kenney *et al.* 1997, Hooker *et al.* 2002, Laidre *et al.* 2004). These models were based on the Kleiber (1975) function for basal metabolic rate (*BMR*) related to the mass (*M*) of homeotherms:

$$BMR = 293.1M^{0.75},$$

and food consumptions models developed by Lavigne (1996) and Leaper and Levigne (2007). Total annual prey consumption was estimated as the product of the mean daily ration (365 x *R*) and the pygmy blue whale abundance (Barlow *et al.* 2008). Following this, we estimated the annual prey consumption of a pygmy blue whale weighing 80 t to be 408 t, and the total annual consumption of 150 whales to be 61,165 t. This provides a Q/B estimate of 5.097.

We have assumed that half (50%) of pygmy blue whale annual intake occurs in the summer/autumn feeding areas of the GAB ecosystem. As such dietary import is estimated to be 0.50. Baleen whale habitat area is estimated to represent 0.995 of the GAB ecosystem. As such the pygmy blue whale biomass in the habitat area is estimated to be 0.00764 $t.km^{-1}$.

Trites *et al.* (1999) estimated the P/B ratio of whales to be half the maximum population growth rate (r_{max}), which has been estimated at 4% (Reily & Barlow 1986). Hence, we used a P/B of 0.02.

Diet information was based on estimates for the eastern GAB (Goldsworthy *et al.* 2011, Page *et al.* 2011, Goldsworthy *et al.* 2013b), using information from Jarman *et al.* (2002) and Morrice and Gill (unpublished data).

2. Toothed whales

The predominate foraging and biomass species of odontocete whale occurring in the GAB was considered to be the sperm whale. In addition, there may be 20 or more smaller odontocetes, mainly composed of beaked whale and pilot species. The total number of individuals of each of these three groups in the GAB region is unknown, however, it is estimated that the mature sperm population off Albany, Western Australia, was reduced by 74% between 1955 and 1978 as a consequence of commercial whaling, where between 3000 to 5000 individuals were caught per year (Bannister 1974, Carroll *et al.* 2014). We nominally estimated the number of sperm whales, beaked whales (Ziphiidae, multiple species) and pilot whales (two species) that make up the bulk of the odontocete biomass and consumption in the GAB to be 10,000, 10,000 and 5,000, respectively. Estimates of mass were: 18,519 kg for sperm whale (based on mean male and female mass, Trites & Pauly 1998); 808 kg for beaked whales (based on the mean of male and female masses for 19 species of beaked whales, Trites & Pauly 1998); and 850 kg for pilot whales (Kenney *et al.* 1997). This gives a toothed whale biomass estimate of 197,518 t within the GAB ecosystem. Prey consumption was estimated to be 1,115,066 t per year, calculated for the three odontocete groups following the methods detailed above for baleen whales, providing an overall estimate for Q/B of 5.645.

We have assumed that all odontocetes in the model foraged in the region throughout the year (i.e. no import). The area of habitat was calculated as the entire slope plus upper shelf/slope areas of the GAB representing 0.983 of the GAB ecosystem. Habitat area fraction was used to weight the

estimated biomass of each odontocete group to give the estimated toothed whale biomass in the habitat area as 0.1353 t.km^{-1}. An estimate of P/B of 0.02 was used following Trites *et al.* (1999).

Diet of sperm whales was based on a study of the stomach contents of 36 stranded whales, mostly from the west and north-west coast of Tasmania (Evans & Hindell 2004). The diet of beaked whales was based on a synthesis of global dietary studies on 12 species presented in Pauley *et al.* (1998), while the diet of pilot whales was based on the stomach contents of 2 stranded whales in Tasmania (Gales *et al.* 1992).

3. Bottlenose dolphins

Biomass and consumption: Bottlenose Dolphin abundance was based on the mean density of dolphins (0.0325 km^{-2}) from aerial surveys conducted by Kemper *et al.* (2006) in South Australia, assuming that bottlenose dolphins made up ~40% of those dolphins surveyed (C. Kemper, pers. comm.). The mean mass of *Tursiops* was estimated to be 109 kg (Barlow *et al.* 2008), giving an overall estimate of biomass of 5,594 t or 0.01419 t km^{-2}assuming a habitat fraction of 0.250 (as these animals only inhabit shelf and slope areas). Estimates of *Q/B* followed the same approach as for common dolphins, providing an estimate of *Q/B* = 18.985. *P/B* was estimated at 0.08 based on Barlow and Boveng (1991).

The diets of bottlenose dolphins were assessed from stomach contents and stable isotope analyses of individuals that were found dead in southern Australia (Kemper & Gibbs 2001, Gibbs *et al.* 2011), and summaries compiled by Page *et al.* (2011).

4. Common dolphin

Biomass and consumption: Aerial survey data for common dolphins are available for Spencer, Gulf St Vincent and the Investigator Straight for the summer and winter of 2011 (L. Moller, G. Parra and K. Bilgmann, Flinders University, unpublished data), and the western Eyre Peninsula between Ceduna and Coffin Bay for winter 2013 (Theme 4, Project 4.1). These data formed the basis of estimates for common dolphin biomass and densities within the GAB ecosystem model area. Across the studies the mean common dolphin density was 0.550 dolphins per km^{-2} (range 0.315 to 0.997). The mean mass of *Delphinus* was estimated to be 79 kg (C. Kemper pers. comm.) giving overall estimates of biomass of 3,140 t or 0.04343 t km^{-2} assuming a habitat area fraction of 0.199 (i.e. shelf areas).

Prey consumption was estimated using the methods detailed above for cetacean species. Following this, we estimated a *Q/B* at 20.578; *P/B* was estimated at 0.09 for Common Dolphins based on Barlow and Boveng (1991).

The diets of common dolphins were assessed from stomach contents and stable isotope analyses of individuals that were found dead in southern Australia (Gibbs *et al.* 2011) and summaries compiled by Page *et al.* (2011). Common dolphins principally forage on pelagic fish such as sardines, anchovy and jack mackerel.

3.3.2 Pinnipeds

5. Long-nosed fur seal

Long-nosed fur seals (LNFS) are an abundant marine predator distributed throughout the GAB region with an overall annual pup abundance estimated to be 24,063 based on surveys undertaken between 2011 and 2014 (Goldsworthy *et al.* 2017b). Around 97% of the total Australia pup abundance is estimated to occur within the GAB region, based on a total estimated pup abundance in Australia of 24,821, with 758 pups (~3%) occurring outside of the GAB region (Goldsworthy *et al.* 2017b). The total estimated abundance of LNFS in the GAB is 114,540 (97,999 in SA; 15,941 in WA and 600 in western Bass Strait) (Goldsworthy *et al.* 2017b).

In SA, there has been about a 3.7-fold increase in pup production between 1989/90 and 2013/14 breeding seasons, equivalent to an annual growth rate of around 5.5% per year (Shaughnessy *et al.* 2014), although growth rates dropped to around 3.4% per year between 2005 and 2015. Pup production at a number of major breeding sites has stabilised and appears to have reached carrying capacity (Shaughnessy *et al.* 2014). A similar conclusion has been reached for populations off the south coast of WA (Campbell *et al.* 2014). The stabilisation of some populations is likely related to density dependent factors relating to space, with most of the available suitable breeding substrate now filled (Shaughnessy *et al.* 2014). The strong growth in LNFS populations over the last 30+ years has been attributed to recovery of the population from overharvesting by early Europeans from the early 19th century, which has been aided by protection of the species, especially since the mid-1970s (Kirkwood and Goldsworthy 2014, Shaughnessy *et al.* 2014).

Weaned pups and yearlings forage in oceanic waters (B. Page, A. Baylis and S. Goldsworthy unpublished data, Page *et al.* 2006) ,while adult males (once they reach reproductive age (first male tenure average 9 years, McKenzie *et al.* 2007b) forage in continental slope waters (Page *et al.* 2006). In contrast, satellite tracking studies of juvenile and subadult males tracked from southern Spencer Gulf and off the north coast of Kangaroo Island indicate that most of their foraging occurs within the Gulf and inner shelf regions, although animals tracked ranged extensively westward to the Nuyts Archipelago and eastward to Gulf St Vincent, south of Tasmania and into Bass Strait (B. Page and S. Goldsworthy unpublished data). Adult female fur seals forage in mid to outer shelf waters during the first 3-4 months of lactation, before directing their foraging effort towards oceanic areas of the sub-tropical front between 400 and 1,100 km to the south of breeding colonies (Baylis *et al.* 2008, Baylis *et al.* 2012). It is therefore possible that some adult females just forage beyond the southern margin of the GAB ecosystem model domain, although for the purpose of this study, individual fur seals from the GAB populations were considered to forage entirely within the model domain.

Biomass and consumption: The estimated pup production of long-nosed fur seals in the GAB region for the 2005/06 breeding season was 19,023 (Campbell *et al.* 2014, Goldsworthy *et al.* 2015). Life-

tables and age-mass relationships were used to estimate the size and biomass of the GAB population (Goldsworthy *et al.* 2003a, McKenzie 2006, Goldsworthy & Page 2007, McKenzie *et al.* 2007c). Age-specific survival relationships used were:

$$\text{Female } S = 0.627 - 0.073a + 0.003a^2 - (5.91 \times 10^{-5})a^3$$

$$\text{Male } S = 0.627 - 0.097a + 0.006a^2 - (0.140 \times 10^{-3})a^3$$

where *S* is survival and *a* is age in years. Maximum ages were 23.4 and 16.7 for females and males, respectively (McKenzie 2006, McKenzie *et al.* 2007a). Based on these relationships the total population size in the GAB in 2005/06 was estimated to be 86,456, and its biomass 2,351.1 t, or 0.00235 t km^{-2} assuming a habitat area fraction of 0.633.

A mass-based regression equation of field metabolic rate (FMR) based on seven otariid species (Goldsworthy *et al.* 2003a) was used to estimate daily energy requirement (*ER*):

$$ER_{at-sea} = 2.234M^{0.665},$$

where $ER_{at\text{-}sea}$ is MJd^{-1} and *M* is the mean mass of each age-class/sex. The average daily energy requirement of otariid seals is a function of the proportion of time spent at sea and on-shore (Costa & Gales 2000, Winship *et al.* 2002), with daily energy requirements at-sea being about 1.8 times greater than those on-shore ($ER_{on\text{-}shore}$) (Costa & Gentry 1986). As such the *ER* of each age-class/sex was estimated following Mecenero *et al.* (2006) as:

$$ER = (ER_{at-sea}p_{at-sea} + ER_{on-shore}p_{on-shore})/0.93,$$

Where the proportion of time spent at sea and on-shore is $p_{at\text{-}sea}$, $p_{on\text{-}shore}$, respectively. Estimates of $p_{at\text{-}sea}$, $p_{on\text{-}shore}$, were based on those in Goldsworthy *et al.* (2007), Goldsworthy and Page (2007) and Kirkwood *et al.* (2006). The estimated mean prey assimilation efficiency is 0.93 (Winship *et al.* 2002, Mecenero *et al.* 2006) and an average prey energy density of 4.985 MJ/kg (Goldsworthy *et al.* 2003a) was used to estimate the total annual prey consumption (*Q* t y^{-1}) of age/sex classes as:

$$Q = \left[\left(\frac{ER}{4.985}\right)365\right]/1000$$

Using these methods, prey consumption by long-nosed fur seals within GAB ecosystem area was estimated to be 111,738 t yr^{-1}; with *Q/B* = 47.525. Production per Biomass estimates (*P/B* = 1.184) was estimated for the entire population as: ((current biomass live + dead)/(previous year annual biomass alive)).

Diet data for the long-nosed fur seal were based on a recent synthesis and analysis of all dietary data available for South Australian populations – compiled as part of FRDC Project 2013/011 Assessment of the impacts of seal populations on the seafood industry in South Australia (SARDI unpublished data). This consisted of both faecal hard-part and faecal prey DNA analyses of over 3,400 samples collected across multiple sites, age-classes and years (SADRI unpublished data). A small amount of long-nosed fur seal diet was composed of fresh-water and estuarine species taken in the Coorong and Lower Lakes region of the Murray River, and was considered as import to the model. Based on the biomass and consumption models detailed above, age and sex based assessments of diet dietary data were weighed according to the estimated proportional consumption attributed to juveniles (0.263), subadult males (0.146), adult males (0.156) and adult females (0.435).

6. Australian fur seal

The Australian fur seal (*Arctocephalus pusillus doriferus*) is endemic to south-eastern Australian waters and is found from the coast of New South Wales (NSW), Tasmania to Victoria, and across to SA with the centre of their distribution in Bass Strait (Kirkwood *et al.* 2010). They have not been recorded in WA. There are 21 known breeding sites in Australia, eight of which have established in the past 10 to 15 years including North Casuarina Island, Williams Island and Baudin Rocks in South Australia (Kirkwood *et al.* 2010, Shaughnessy *et al.* 2010, McIntosh *et al.* 2014, Shaughnessy *et al.* 2014). The historical range of the species prior to colonial sealing (pre-1800s) is unknown. In the GAB region, there are five known breeding sites for the species, Lady Julia Percy Island and Cape Bridgewater in western Bass Strait (Victoria), and North Casuarina Island (off Kangaroo Island), Williams Island and Baudin Rocks (SA) (Goldsworthy *et al.* 2017b). There is a further breeding site in western Bass Strait at Reid Rocks, south-east of King Island, but it lies outside of the GAB ecosystem modelling domain, and is not including in this assessment (Goldsworthy *et al.* 2017b).

The largest population in the GAB region is at Lady Julia Percy Island in western Bass Strait. Surveys across all known breeding sites have been conducted in 2007 (Kirkwood *et al.* 2010) and 2013 were used to estimate pup abundance in 2006. These surveys suggested that the total pup abundance in the GAB region in 2006 was 6,238, with most (97%) in western Bass Strait. Pup production estimates of Australian fur seals have included a 15% pup mortality adjustment to account for pups that have died prior to surveys (Kirkwood *et al.* 2010). Application of this adjustments produces a total pup production estimate of 6,450 in the GAB region in 2007 (Goldsworthy *et al.* 2017b). Estimates of pup abundance and production in 2013 for the GAB region based on estimates by McIntosh *et al.* (McIntosh *et al.* 2014) were 2,862 and 3,291, respectively. The estimated exponential rate of change (r) based on these two estimates is -0.112, and was used to reconstruct a time-series of change in annual pup production between 2006 and 2015. Based on this approach, pup production in the GAB region in 2006 and 2015 was estimated to be 7,174 and 2,595, respectively.

Although the small emerging population in SA appears to be growing rapidly (Shaughnessy *et al.* 2014), the status of the main population centre in Bass Strait is unclear. The population at Lady Julia Percy Island was once the largest fur seal colony in Australia, producing 5,899 pups in the 2002/03 breeding season. By 2013/14, pup production had more than halved to 2,659 pups, suggesting ~7% decline per year over the 11-year period between the two surveys (McIntosh *et al.* 2014). It is not clear if the apparent decline between the 2007/08 and 2013/14 surveys is real or due to a poor pupping season in 2013/14, as there is no colony that is monitored on an annual basis (McIntosh *et al.* 2014).

Biomass and consumption: Life-tables for Australian furs seals were based on those developed by Goldsworthy *et al.* (2003b): females $S = 0.627 - 0.070a + 0.003a^2 - (5.10 \times 10^{-5})a^3$; males $S = 0.627 - 0.081a + 0.004a^2 - (8.27 \times 10^{-5})a^3$, where S is survival and a is age in years, with maximum ages set at 21 and 19 years for females and males, respectively (Warneke 1995). Age-mass relationships for females and males followed those developed for the species by Arnould and Warneke (2002), with parameter values of A, K and t of 85.400, 0.360 and -1.860 for females (von Bertalanffy equation),

and 228.500, 0.520 and 5.120 from males (Logistic equation), respectively. These were used to estimate a population biomass of 2,396 tonnes, and biomass density within the GAB of 0.08003 t km^{-2}, assuming a habitat fraction of 0.019, and a total pup production in the GAB region in of 7,174 pups in 2006.

Using the method of estimating pinniped prey consumption detailed above, consumption by Australian fur seals in the GAB region was estimated to be 65,450 t/yr; *Q/B* = 34.931 and *P/B* = 1.157.

Diet data for the Australian fur seal in the GAB region were based on the study of Page *et al.* (2005) and a recent faecal prey DNA analyses compiled as part of FRDC Project 2013/011 Assessment of the impacts of seal populations on the seafood industry in South Australia (SARDI unpublished data). All foraging by GAB populations was considered to occur within the model domain, as foraging by this species is almost entirely restricted to continental shelf waters (Kirkwood & Goldsworthy 2013).

7. Australian sea lion

Australian sea lions (*Neophoca cinerea*) are endemic to Australia and restricted to South and Western Australia. The most comprehensive assessment of the species status and trends in abundance in the GAB region is provided by Goldsworthy *et al.* (Goldsworthy *et al.* 2017b). In South Australian there are 42 breeding sites with total pup abundance in 2014/15 estimated to be 2,500; in the GAB region off the south coast of WA , there are 16 known breeding sites with a total estimated pup abundance of 301, giving a total GAB region estimate of 2,801 pups from 58 sites (Goldsworthy *et al.* 2017b). Pup abundance is presently declining by 2.9% per year in South Australia, and 2.1% off the south coast of Western Australia. Based on these values, total pup abundance in the GAB region was estimate to be 3,509 in 2007 and 2,721 in 2016.

Biomass and consumption: Following the methods detailed above for other pinnipeds, age-specific survival and pup production data were used to estimate the numbers of animals alive at each age stage. Life tables were based on those developed by McIntosh (2007) and modified to achieve stable growth by Goldsworthy *et al.* (2010), with maximum ages set at 24 and 21.5 years for females and males (McIntosh 2007). As Australian sea lions breed about every 18 months (Shaughnessy *et al.* 2006), survival was calculated for every 1.5 years. Age-mass relationships for females and males followed those developed for the species by McIntosh (2007), with parameter values of *A*, *K* and *t* of 86.437, 0.475 and -2.7252 for females (Logistic equation), and 271.008, 0.148 and -4.220 from males (von Bertalanffy equation), respectively. Total biomass in 2006 was thus estimated to be 1,032 t, or 0.00417 t km^{-2} assuming a habitat fraction of 0.157.

Using this approach prey consumption for the Australian Sea Lion population in the GAB region was estimated to be 30,381 t per yr; with *Q/B* = 29.445 and *P/B* = 0.792. Production (*P*) per Biomass estimates (*P/B*) were estimated as: ((current biomass live + dead)/(previous year annual biomass alive)).

Diet data for the Australian sea lion were based on a recent synthesis and analysis of all dietary data available for South Australian populations being compiled as part of FRDC Project 2013/011

Assessment of the impacts of seal populations on the seafood industry in South Australia (SARDI unpublished data). This consisted of both faecal hard-part and faecal prey DNA analyses of over 270 samples collected across multiple sites, age-classes and years (SADRI unpublished data, McIntosh *et al.* 2006, Fragnito 2013, Peters *et al.* 2014, Peters *et al.* 2015, Peters 2017). Information from a DNA metabarcoding study of sample of scats collected from the south coast of WA (Berry *et al.* 2017) were also incorporated.

3.3.3 Seabirds

8. Albatross

Biomass and consumption: The three most common albatross species in the GAB region include: one endemic breeder in Australia, the shy albatross (*Thalassarche cauta*) which breeds on three islands off Tasmania; and two non-resident species, the black-browed albatross (*Thalassarche melanophrys*) and Indian yellow-nosed albatross (*Thalassarche carteri*) which are present over shelf waters in most months but most frequently in May – October (Copley 1996).

The global population sizes of these species has been estimated to be: shy albatross ~65,000 (BirdLife International 2016b); black-browed albatross ~2,100,000 (BirdLife International 2016c) and Indian yellow-nosed albatross ~160,000 (BirdLife International 2017). We assumed that approximately 30%, 1% and 5% of the global populations of each species occurs within GAB region throughout the year, representing a total of approximately 48,500 individual birds, with biomass of 173.9 t (B = 0.000108 t km^{-2}assuming a habitat fraction of 9.985), and consumption of 12,263 t (assuming an average mass of 3.38 kg, FMR of 2390 kJd^{-1}, assimilation efficiency of 0.69 and mean prey energy density of 5 MJkg^{-1}). Based on these values, P/B was estimated to be 70.5, and P/B was estimated to be 1.00 based on Sakshaug (1997).

Dietary data for this group was based on diet studies of the shy albatross in western Bass Strait and in the eastern GAB Ecopath model (Hedd *et al.* 2001, Page *et al.* 2011, Goldsworthy *et al.* 2013b).

9. Shearwaters

Biomass and consumption: Numerically, the dominant petrel species in the GAB region are the abundant short-tailed shearwater (*Puffinus tenuirostris*), which breed across many of the islands in the GAB region especially in western Bass Strait and on islands off South Australia (Copley 1996); and the flesh-footed shearwater (*Ardenna carneipes*) which has major breeding colonies on islands off the south coast of WA and at two known sites in South Australia (Lewis and Smith Islands in lower Spencer Gulf) (Copley 1996, Goldsworthy *et al.* 2013a, Lavers 2014, Goldsworthy *et al.* 2017b);.

Of these species, data on the breeding ecology, diet and at-sea distributions are only available for the short-tailed shearwater, and only for areas south of South Australia. Short-tailed shearwaters undergo major migrations, overwintering in the North Pacific Ocean and Bering Sea, arriving in south-eastern Australia in September/October and leaving again in March/April (Weimerskirch & Cherel 1998). The return rate of fledged chicks at four years of age is estimated at 0.437 and adult annual survival at 0.92 (Wooller *et al.* 1990, Hunter *et al.* 2000). With the mean age of first breeding at ~7 years (Hunter *et al.* 2000), a simplified life-table based on these parameters suggests juveniles make up 47% of the population, while breeding pairs (adults) make up 53%. Using an estimate of the number of breeding pairs in the GAB region for short-tailed (1,277,800) and flesh-foot (33,854) shearwaters (Burbidge *et al.* 1996, Copley 1996, Norman *et al.* 1996, Lavers 2014, Goldsworthy *et al.* 2017b), the total number of shearwaters which utilise the GAB was estimated to be 5,010,518. Assuming a mean mass of 0.7 and 0.6 kg per bird, for short-tailed and flesh-foot shearwaters, respectively, the total biomass of shearwaters is estimated to be 3,494 t, or B= 0.00218 t km^{-2} assuming a habitat fraction of 0.985.

The active (965.9 kJ d^{-1}) and resting (296.9 kJ d^{-1}) metabolic rates for short-tailed shearwaters were estimated from regression equations in Warham (1996). Breeding pairs were assumed to spend 206 days in non-breeding foraging grounds, 14 days pre-incubation in waters adjacent to the GAB ecosystem, 55 days incubating the egg (incubation shared equally between the sexes) and 90 days rearing chicks (Weimerskirch & Cherel 1998, Einoder & Goldsworthy 2005, Einoder 2010). In South Australia, short-tailed shearwaters undertake on average 28 short foraging trips over shelf waters and 12 long trips into the Southern Ocean during the 90 day chick-rearing period (Einoder 2010). Assuming individual birds spend about 5 hours ashore in between foraging trips; birds were estimated to spend 10.2% of their time ashore and 89.8% at sea. The prey consumption equation of Daunt *et al.* (2008) was used, assuming an assimilation efficiency of 0.69, and based on information of dietary breakdown, prey energy density and 4.5 kg of prey being fed to the chick by each breeding pair (Einoder 2010). Annual total prey consumption (Q) of both shearwater species was estimated to be 527,506 t, but with 70% of foraging time during chick rearing spent on long trips into the Southern Ocean (about half of which would be spent outside of the GAB region) and 206 days spent undertaking the annual migration into the Northern Hemisphere. Consequently, it was assumed that most (~70%) prey consumption is imported (derived from outside the GAB region), assuming similar behaviour for flesh-footed shearwaters. Q/B is estimated to be 151.0. P/B was estimated to be 1.0 and was derived from an estimate for Antarctic seabirds (Cornejo-Donoso & Antezana 2008).

Diet data were based on dietary studies of short-tailed shearwaters undertaken in South Australia by Einoder (2010) and summarised by Page *et al.* (2011) and Goldsworthy *et al.* (2013b).

10. Small petrels

Biomass and consumption: The dominant small petrel species in the GAB region is the widespread white-faced storm petrel (*Pelagodroma marina*) (Copley 1996, BirdLife International 2016a). However, little is known of its abundance and ecology. The estimate of 274,870 breeding pairs of white-faced storm petrels was based on estimates for South and Western Australia (Burbidge *et al.*

1996, Copley 1996). Assuming breeding pairs make up 2/3 of the population, the total estimate of the GAB region population was 832,939. White-faced storm petrels are estimated to be present in southern Australia between October and March which includes a 45 day incubation and 51 day chick rearing period (Marchant & Higgins 1990b). Assuming a mean mass of 55 g (Marchant & Higgins 1990b), adults spending 82% of their time at sea, and at-sea and onshore metabolic rates of 223.7 kJ d^{-1} and 50.3 kJ d^{-1}, respectively (estimated from equations in Warham 1996), an assimilation efficiency of 0.69, a prey energy density of 5 MJ kg^{-1}, and a mean meal mass fed to chicks of 6.4 g (0.5 meals per night) (Marchant & Higgins 1990b); prey consumption per annum is estimated to be 29,318 t (using equations in Daunt *et al.* 2008). The overall estimate of biomass was 45.8 t, or 0.000029 t km^{-2} assuming a habitat fraction of 0.985. Based on the above estimates, *Q/B* was estimated to be 640.0 and *P/B* was estimated to be 1.0, based on Sakshaug (1997).

The diet of white-faced storm petrels was based on that detailed for the species by Imber (1981). Import of prey consumption from outside the GAB ecosystem was estimated to be 41.9%, assuming birds are only present in the GAB region from mid-August to mid-March (58.1% of the year) (Marchant & Higgins 1990a).

11. Australasian gannet

Biomass and consumption: Australasian gannets (*Morus serrator*) breed at seven sites in Australia, three of which occur in the GAB region; Lawrence Rocks (3,100 pairs) and Point Danger (600 pairs) in Victoria, and Margaret Brock Reef (~300 pairs) off Cape Jaffa in South Australia (Bunce *et al.* 2002, Lighthouses of Australia Inc 2004). The largest colony of the species in Australia occurs adjacent to the GAB region at Black Pyramid (12,339) in western Bass Strait, with the remaining three breeding sites occurring in Port Phillip Bay (507 pairs), and on Pedra Branca (3,013 pairs) and Eddystone Rock (189 pairs) off the south coast of Tasmania (Bunce *et al.* 2002). Assuming breeding pairs make up 2/3 of the population, the total estimate of the number of Australian gannets in Australia is 60,752. Assuming that birds in the Lawrence Rocks, Point Danger Margaret and Brock Reef populations are present in the GAB region 80%, those at Black Pyramid for 60% of the time. With individual gannets weighing approximately 2.5 kg (Daunt *et al.* 2008), the total GAB region Australasian gannet biomass is estimated to be 81.8 t, or 0.0000098 t km^{-2}, assuming at habitat area fraction of 0.189. Estimates of the energy needs of breeding and non-breeding birds (4,561 KJ d^{-1}), plus the energy costs of egg (201,100 KJ) and chick production (145,000 KJ) were derived from Bunce (2001). Assuming 0.63 chicks per pair, 0.75 assimilation efficiency and a mean prey energy density of 6.7 kJ g^{-1} (Bunce 2001), prey consumption was estimated using the formula of Daunt *et al.* (2008) to be 11,367 t. Based on these estimates, *Q/B* is 139.0 and *P/B* was estimated to be 1.0, based on Sakshaug (1997).

Dietary data were based on (Bunce 2001), as used in the eastern GAB model (Goldsworthy *et al.* 2011, Page *et al.* 2011, Goldsworthy *et al.* 2013b).

12. Terns

Biomass and consumption: The three most abundant resident (breeding) tern species that occur in the GAB region include the crested tern (*Sterna bergii*), Caspian tern (*Hydroprogne caspia*), and fairy tern (*Sternula nereis nereis*). As the crested tern breeds in large colonies, its biomass overwhelms the other species, for which there is limited information on their population size and ecology. The total population of crested terns in the GAB was estimated to be approximately 49,000 breeding pairs (taking the mid-estimate of 39,000 pairs for surveyed sites and up to 59,000 pairs based including unsurveyed sites, Goldsworthy *et al.* 2017b), or 148,485 individuals (assuming breeding pairs make up 2/3 of the population) and 51.97t biomass based on an average individual mass of 0.35 kg. The estimated number of breeding pairs (1,280), individuals (3,879) and biomass (2.64 t, assuming individual mean mass of 0.68 kg) of Caspian terns in the GAB region were based on estimates of abundance in Burbidge *et al.* (1996), Copley (1996) and Norman(1996). The estimated number of breeding pairs (1,050), individuals (3,182) and biomass (0.22 t, assuming individual mean mass of 0.07 kg) of fairy terns in the GAB region were based on estimates of abundance in Burbidge *et al.* (1996) and Copley (1996). Total biomass of terns in the GAB region was estimated to be 54.8 t, or 0.00000658 t km^{-2} assuming a habitat fraction of 0.189 for these shelf foragers. From estimates of daily energy needs of adults and chicks (406.3 kJ d^{-1}), breeding pairs each raising one chick over a 40-day period, an assimilation efficiency of 0.75 and mean prey density of 6.7 kJ g^{-1} (Chiaradia *et al.* 2002, Daunt *et al.* 2008), total prey consumption was estimated at 4,757 t yr^{-1}. Based on these estimates, *Q/B* is 86.8 and a *P/B* estimate of 1.0 was used based on Sakshaug (1997).

Dietary data were based on studies undertaken in South Australia by McLeay *et al.* (2009) and summarised in Page *et al.* (2011) and Goldsworthy *et al.* (Goldsworthy *et al.* 2013b).

13. Shags and Cormorants

Biomass and consumption: There are two main cormorant species that forage in marine ecosystems of the GAB region, the black-faced shag (*Phalacrocorax fuscescens*) and the pied cormorant (*Phalacrocorax varius*). Both species are winter breeding and nest in colonies. Abundance of each species in the GAB region was based on estimates of abundance for Western Australia, South Australian and Victoria in Burbidge *et al.* (1996), Copley (1996) and Norman (1996), respectively. These provided estimates of 15,379 individual black-faced shags and 57,045 pied cormorants. Assuming a mean mass of 1.6 kg (Riordan & Johnston 2013), the estimated biomass is 115.9 t, or *B* = 0.0000139 t km^{-2}, assuming a habitat area fraction of 0.189. Estimates of daily food consumption of 0.65 kg d^{-1} (outside chick-rearing period) and 0.836 kg d^{-1} (chick rearing x 90 days), assuming a prey calorific value of 5.03 kJ g^{-1} and an assimilation efficiency of 0.8 (Gomez-Laich *et al.* 2013), provides an annual prey consumption estimate of 8,969.4 t, and a *Q/B* estimate of 77.4. A *P/B* estimate of 1.0 was used based on Sakshaug (1997).

There are no published data on the diets of black-faced shags or pied cormorants from the GAB region. Information was taken instead from limited data available for black-faced shags (samples from SA and Victoria, Marchant & Higgins 1990b) and Pied Cormorants (samples from WA and Queensland, Blaber & Wassenberg 1989, Humphries *et al.* 1992). The proportions of prey taxa were weighted for each species by their estimated biomass. All consumption was considered to occur in the GAB region (i.e. no dietary import).

14. Gulls

Biomass and consumption: There are two species of gull that occur in the GAB region, the silver gull (*Chroicocephalus novaehollandiae*) and the Pacific gull (*Larus pacificus*). In many parts of Australia, silver gull numbers have increased substantially with increases in human populations. Estimates of the size of gull populations in the GAB region were based on estimates of abundance for Western Australia, South Australian and Victoria in Burbidge *et al.* (1996), Copley (1996) and Norman (1996), respectively. These provided estimates of 448,333 individual silver gulls and 1,667 Pacific gulls in the Gulf St Vincent region, assuming that adults make up 40% of the population (Coulson *et al.* 1982). With a mean estimated mass of 0.3 kg for silver gulls and 1.04 kg for Pacific gulls (Lindsay & Meathrel 2008) the combined biomass estimate was 219.6 t (or 0.0000192 t km^{-2}, assuming a habitat area fraction of 0.139. An estimated daily energy requirement of 400 kJ d^{-1}, was used for silver gulls whereas those summarised by Lindsay and Meathrel (2008) (393 kJ d^{-1} non-breeding adults; 600 kJ d^{-1} breeding adults; 120 kJ d^{-1} young chicks; kJ d^{-1} 325 kJ d^{-1} fledglings) were used for Pacific gulls. Based on these values, an assimilation efficiency of 0.75, a mean prey density of 4.985 kJ g^{-1} (Goldsworthy *et al.* 2003a), and the seabird consumptions models of Daunt *et al.* (2008), total prey consumption was estimated to be 17,644 t yr^{-1}. Based on these estimates, *Q/B* was 80.4 and a *P/B* estimate of 1.0 was used based on Sakshaug (1997).

The diet of silver gulls was based on data obtained from 108 samples for southern Spencer Gulf detailed in Harrison (2009), interpreted by (Page *et al.* 2011) and Goldsworthy *et al.* (2013b). No dietary information is available for Pacific gulls in South Australia, so data from Lindsay and Meathrel (2008) were used to infer the diet in the GAB region. Proportion of prey taxa was weighted for each gull species by estimated biomass. All consumption was considered to occur in the GAB region (i.e. no dietary import).

15. Little penguin

Biomass and consumption: There has not been a systematic survey of Little Penguins (*Eudyptula minor*) across the GAB region. Estimates used here were based on a synthesis of available summaries and estimates compiled in Goldsworthy *et al.* (Goldsworthy *et al.* 2017b). These provided a minimum estimate of 36,300 pairs, with an upper estimated range of 46,300 accounting for the many un-surveyed sites. Survival in little penguins is estimated to be 17%, 71% and 78% in each of the first three years, respectively, and 83% per year subsequently (P. Dann, pers. comm.). 50% of birds are mature and breed when they are two years of age, with the remaining birds breeding for the first time at three years (Dann & Cullen 1990). A simplified life-table based on these parameters and maximum longevity of ~26 years (Dann *et al.* 2005) suggests juveniles make up 27% of the population, while breeding pairs (adults) make up 73%. Using the estimate of 41,300 breeding pairs, the total population of little penguins in the GAB region was estimated to be 113,903. Assuming a mean mass of 1.2 kg per bird, the total biomass in the habitat area of the population is estimated to be 136.7 t, or B = 0.0000866 t km^{-2}, assuming a habitat fraction of 0.123. Non-breeding (juvenile) little penguins were estimated to consume 73.1 kg per year, based on prey consumption of 167 g kg^{-1} D^{-1} (Costa *et al.* 1986), while breeding little penguins are estimated to consume 114.0 kg of prey each year (including the food requirements for 0.85 chicks per year, 1.7 per pair) (Bethge *et al.* 1997). This provides an estimate of total annual prey consumption (Q) in the GAB region of 11,706 t and a Q/B of 85.6. A P/B estimate of 1.29 was derived from an estimate for Antarctic penguins (Cornejo-Donoso & Antezana 2008).

Dietary information for little penguins was based on that detailed for the South Australian population by Weibkin (2011a). These included 493 samples of stomach contents collected over seven sites in all seasons between 2003 and 2005 (Wiebkin 2011b). All consumption was considered to occur in the GAB region (i.e. no dietary import).

3.3.4 Elasmobranchs

16. Shelf pelagic sharks

The GAB encompasses habitats of several listed, threatened, endangered and protected pelagic shark species including white shark *Carcharodon carcharias*, bronze whaler *Carcharhinus brachyurus*, dusky shark *C. obscurus*, common thresher *Alopias vulpinus*, and smooth hammerhead *Sphyrna zygaena*. Catch and effort data were sourced from the SA State managed Marine Scalefish (SARDI databases), and Commonwealth managed Gillnet Hook and Trap fisheries. There were no species-specific discard data available for this group.

A biomass estimate of 0.021 t.km^2 in the habitat area (pers. comm. P. Rogers, SARDI) across all 5 species was made. The P/B values were therefore set equal to the total mortality rates $Z = F + M$, where F is the mean fishing mortality and M is the rate of natural mortality, following Allen (1971) (detailed in Huveneers and Goldsworthy unpublished data; summarised in Goldsworthy *et al.* 2011). Non-commercial species were considered to have an F = 0. The instantaneous natural mortality rate

(*M*) was preferably taken from direct estimation. However, only a few direct estimates of instantaneous natural mortality rate have been calculated for chondrichthyans (e.g. Gruber *et al.* 2001, Heupel & Simpfendorfer 2002). Instead, indirect estimates of mortality were obtained through methods based on predictive equations of life history traits. Natural mortality was derived from the empirical model of Pauly (1980). *Q/B* was calculated according to the empirical regression of Christensen and Pauly (1992b). The von Bertalanffy growth parameters were taken from the most recent studies in Australia or New Zealand (detailed in Huveneers and Goldsworthy unpublished data; summarised in Goldsworthy *et al.* 2011). When no studies from these areas were available, the arithmetic mean of the most recent studies from other locations was used. When available, growth parameters for combined sexes were used. Otherwise, the arithmetic mean between male and female growth parameters was used. An ecotrophic efficiency estimate of 0.95 was used. The average of P/B and Q/B estimates across all species was estimated to be 0.13 and 2.61, respectively.

White shark

The white shark has a cosmopolitan distribution in Australia (Last and Stevens 2009) and is mostly found in offshore gulf and continental shelf waters of the modelled area. Juvenile and adult white sharks from <2 to 5 m total length are known to occur in all coastal and shelf areas between Head of the Bight and Bass St, Victoria. For this species, P/B was assumed equivalent to *M* and calculated using the empirical equation of Pauly (1980). The von Bertalanffy growth parameters were used to estimate M (Cailliet *et al.* 1985, Wintner & Cliff 1999). Q/B was estimated using Christensen and Pauly's (1992b) equation with W_∞ estimated by the L-W regressions for combined sexes from Australia (Malcolm *et al.* 2001).

Dietary information for white sharks was sourced from South Africa from Hussey *et al.* (2012). The largest size class (> 2.85 m) was selected for the analysis as most sharks observed in SA waters are ≥3m, TL (P. Rogers, pers. comm.), and adjusting for local equivalent prey species, e.g. to account for consumption of rays (P. Rogers and C. Huveneers, unpublished data). Undifferentiated elasmobranch diet components were spread proportionally across know elasmobranch taxa.

Bronze whaler

Based on catch and effort data, the bronze whaler is predicted to be the most abundant coastal pelagic shark in the study region. P/B was assumed equivalent to M and calculated using the empirical equation of Pauly (1980). Von Bertalanffy growth parameters for combined sexes were taken from a study in South Africa by Walter and Ebert (1991) and a study in Western Australia by Simpfendorfer *et al.* (2002). Q/B was estimated using Christensen and Pauly's (1992b) equation with

W_∞ estimated from the length-weight (L-W) regression of Cliff and Dudley (1992) for Western Australia (J. Chidlow, pers. comm.). P/B was set at 0.095 and Q/B at 2.61, with estimates averaged across species and sexes.

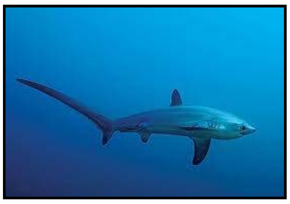
Dietary data for bronze whaler and dusky shark were sourced from recent PhD studies of M. Drew (SARDI, FUSA) and Rogers *et al.* (2012) based on samples collected in the Spencer Gulf, Gulf St Vincent and the GAB, between 2007 and 2015.

Smooth hammerhead

The smooth hammerhead is distributed throughout gulf, continental shelf and shelf slope waters of the modelled area. P/B was assumed equivalent to M and calculated using Pauly's (1980) empirical equation. Von Bertalanffy growth parameters for each sex were taken from a study in Mexico by Garza (unpublished data). Q/B was estimated using Christensen and Pauly's (1992b) equation with W_∞ estimated by the length-weight regression from Western Australia (McAuley & Simpfendorfer 2003). P/B is set to 0.21 and Q/B is 3.15, with estimates averaged across sexes.

Dietary data were based on analyses of 39 stomachs examined from samples collected from commercial catches in the Great Australian Bight and Spencer Gulf (Rogers *et al.* 2012).

Common thresher



The common thresher is also found in gulf, continental shelf and shelf slope waters. Von Bertalanffy growth parameters for each sex were taken from the most recent age and growth study (Smith *et al.* 2008). Q/B was estimated using Christensen and Pauly's (1992b) equation with W_∞ estimated by the length-weight regression from the Northwest Atlantic (Kohler *et al.* 1996). P/B is set at 0.2 and Q/B is 2.78, with estimates averaged across sexes.

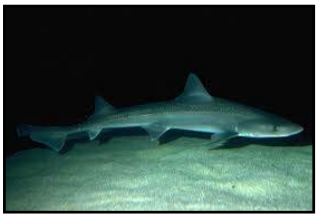
A total of 27 stomachs (63% containing prey items) were examined from samples in the GAB between 2007 and 2009. Dietary information was taken from the study of Rogers *et al.* (2012).

Group 17. Offshore pelagic sharks

Offshore or oceanic pelagic sharks found in the study area include shortfin mako, blue shark, porbeagle (Last & Stevens 2009, Rogers *et al.* 2015). Commercial fishery data were available from AFMA for the Commonwealth managed fisheries. The species are non-target bycatch. Species included in the model for which some data were available included the shortfin mako and the blue shark. Parameters were sourced from a previous summary of the literature (Huveneers and Goldsworthy unpublished data; summarised in Goldsworthy *et al.* 2011). Estimates of P/B of 0.20 and Q/B of 1.2 were used.

Diet data for shortfin mako were sourced from Rogers *et al.* (2012), and other species were sourced from the literature (detailed in Huveneers and Goldsworthy unpublished data; summarised in Goldsworthy *et al.* 2011).

Group 18. Shelf demersal sharks



Demersal sharks are among the most heavily exploited of the large marine fauna that inhabits southern Australian shelf waters. Shelf demersal sharks were represented by Gummy Shark (*Mustelus antarcticus*), Port Jackson Shark (*Heterodontus portusjacksoni*), Wobbegongs or Carpet Sharks (Orectolobidae), Catsharks (Scyliorhinidae and Parascylliidae), Angel Sharks (Squatinidae), Spurdogs and Dogfish (Squalidae), Elephant Fish (*Callorhinchus milii*), Cobbler Carpet Shark (*Sutorectus tentaculatus*), Piked Dogfish (*Squalus megalops*), Southern Sawshark (*Pristiophorus nudipinnis*) and Common Sawshark (*Pristiophorus cirratus*), Chimaeridae, whiskery shark (*Furgaleus macki*) and broadnose sevengill shark (*Notorynchus cepedianus*).

Commonwealth fisheries taking this group include the Gillnet Hook and Trap (GHAT) Fishery. Time series data from logbooks for annual catch and effort were included in the model. The main gear types were demersal gillnet, long-line and drop-line. The State managed (< 3 nm from shore) component of the catch was taken in the Marine Scalefish fishery using long-lines and hand-lines. There was limited discard information for State or Commonwealth fisheries, with the exception of the period between 2006 and 2008 in the shark gillnet component of GHAT fishery and for 2007 in the MSF fishery (Fowler *et al.* 2009). Biomass estimates were based on trawl surveys in Spencer Gulf (Currie *et al.* 2009, Currie & Sorokin 2010), and from Koslow *et al.* (2001). Estimates of *P/B* (0.55) and *Q/B* (2.6) were based on estimates of *F* (0.3) and *M* (0.25) (Froese & Pauly 2017) for gummy shark.

There is limited diet information of these species. Dietary information for gummy shark was based on Currie *et al.* (2010) and SARDI unpublished data.

Group 19. Shelf demersal piscivorous sharks

The school shark (*Galeorhinus galeus*) is a long-lived, highly mobile species with a low reproductive productivity (Olsen 1954, Hurst *et al.* 1999, Walker *et al.* 2005). Fisheries that take the species as bycatch in Australian fisheries management jurisdictions are managed via a stock rebuilding strategy. The stock is considered to be overfished (Punt *et al.* 2005, SAFS 2017). Ongoing declines in the abundance of mature individuals and environmental degradation in nursery areas are key management issues (Walker 1998). School shark is taken under bycatch quota allowances and the stock is considered over-fished (SAFS 2017). Nursery areas are thought to be limited to the south-eastern Australian range (Stevens & West 1997), with a paucity of information on the presence or distribution of neonates in other southern Australian regions (Rogers *et al.* 2017). Mature females migrate from inshore to offshore shelf waters of the central and eastern GAB (Rogers *et al.* 2017). School shark (biomass estimates were based on mean annual catch per species and an estimated fishing mortality (*F*) for school shark was 0.7, giving a biomass of 0.00071 t km^{-2}. Estimates of *P/B* set it at 0.17 and *Q/B* is set to 1.32 (Froese & Pauly 2017).

There is limited diet information for these species. Diet information was based on Currie *et al.* (2010) (n=1) and P. Rogers (pers. comm.). School sharks are known to prey on pelagic fishes (e.g. Barracouta and Jack mackerel) and cephalopods (Olsen 1954).

Group 20. Deep demersal sharks

The deep-water demersal shark group found mostly on the slope was not directly sampled during this project. Therefore, values from the literature were used to determine the likely composition of this group. Based on surveys of the south-eastern Australian mid-slope (800-1200m) documented in Koslow *et al.* (1994b), the species of sharks were primarily from the family Squalidae and were the second most abundant family in the eastern GAB. The species most commonly caught at these depths >20% occurrences *were Centroscymnus crepidater, C. owstoni, Deania calcea, Etmopterus baxteri, and Apristurus* sp., *Hydrolagus* sp., and *Rhinochimeara pacifica* (from other families). For the deep demersal shark group, the estimate of *P/B* was 0.16 and *Q/B* was 3.3 – averaged over the eight species using data from FishBase (Froese & Pauly 2017).

Group 21. Skates and rays

Skates and rays found in the study region include members of the families Dasyatidae and Urolophidae. Some of the species included Melbourne Skate (*Spiniraja whitleyi*), Southern Fiddler Ray (*Trygonorrhina dumerilii*), Southern Shovelnose Ray (*Aptychotrema vincentiana*), Smooth Stingray (*Dasyatis brevicaudata*), Coastal Stingaree (*Urolophus orarius*), Sparsely-Spotted Stingaree (*Urolophus paucimaculatus*), Western Shovelnose stingaree (*Trygonoptera mucosa*), and White Spotted Skate (*Dipturus cerva*). Biomass estimates were based on standardised surveys in the Gulf St Vincent (Goldsworthy *et al.* 2017a) and Spencer Prawn fishery areas using calculations of Currie *et al.* (2009) and Burnell *et al.* (2015). For the skates and rays group, *P/B* was set to 0.4 and *Q/B* was 1.8 based on Currie and Sorokin 2010. The main gear types that take these taxa as bycatch were demersal gillnet, bottom trawl, and long-line. The State managed component was mostly taken in

the MSF fishery. Most skates and rays tend to be discarded with the exception of the southern eagle ray (*Myliobatis australis*), which is occasionally retained. There was limited discard information available for State fisheries that take this model group as bycatch, with the exception of 2007, when a dedicated bycatch program was implemented in State waters (Fowler *et al.* 2009).

Dietary data were based on the analysis of (Currie & Sorokin 2010).

3.3.5 Teleosts

Group 22. Southern bluefin tuna

Southern Bluefin Tuna (SBT) (*Thunnus maccoyii*) is a highly migratory species managed under International quota setting arrangements by the Commission for the Conservation of Southern Bluefin Tuna (CCSBT) (CCSBT 2017). Juvenile SBT aggregate in the GAB study region during each summer and autumn (Young *et al.* 1996, Gunn & Young 1999), and adults are mostly present from autumn until spring (Ward *et al.* 2006). Most of the Australian component of the International catch is taken in the GAB region (Wilson *et al.* 2009), with the remainder taken off south-eastern Australia. Time series catch and effort data were accessed from Australian Fishery Management Authority (AFMA) databases managed by CSIRO. Australia's part of the TACC is mostly taken using pelagic purse seine nets and the catches are towed back to moored, floating pontoons in southern Spencer Gulf where they are maintained via feeding with local and imported baitfish (mostly sardine) for several months before being harvested for Japanese markets. PIRSA Fisheries and Aquaculture provided data for the grow-out component of the industry. There was limited discard information available for SBT.

Biomass data were available from Theme 4 and a biomass estimate for the resident population was estimated assuming the whole domain area and for 2000-5. A of P/B of 0.485 was estimated of natural and fishing mortalities per age class over age classes 1-4 from modelled output from the 2014 stock assessment (pers. comm. P. Eveson, CSIRO). The Q/B used in Bulman *et al.* (2006) was originally estimated in FishBase (Bulman *et al.* 2006, Froese & Pauly 2017) for 4+year olds based on Young *et al.* (1997), and was therefore modified to 3.65 to account for younger age classes. Diet data were sourced from Caines (2005), Ward *et al.*(2006) and Page *et al.* (2011).

Group 23. Tunas and billfish

Tunas (other than SBT) and billfish include albacore (*T. alalunga*), bigeye tuna (*T. obesus*), Australian bonito (*Sarda australis*), skipjack (*Katsuwonus pelamis*) and broadbill swordfish (*Xiphias gladius*). Purse-seiners are reported to periodically take schools of skipjack tuna (Ward *et al.* 2003). The main gear types used were pole, long-line and purse-seine. We assumed that the biomass of this group was likely to be more than the largely juvenile dominated SBT and a biomass of 0.05 t.km^{-2} was

arbitrarily chosen in lieu of data. *P/B* and *Q/B* estimates of 0.6 and 6.2, respectively were taken from the EBS model.   Diet data were sourced from Caines (2005) and Ward *et al.* (2006).

Group 24. Offshore pelagic piscivores

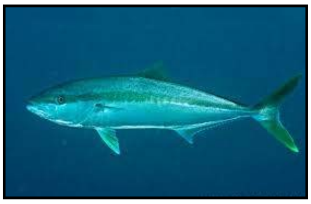
The offshore pelagic piscivores group was represented by species such as Rays bream *Brama brama,* southern Rays bream *Brama australis,* opah *Lampris guttatus,* southern moonfish *Lampris immaculatus,* oilfish *Ruvettus pretiosus,* short sunfish *Mola ramsayi,* rudderfish *Centrolophus niger,* shortnose lancetfish *Alepisaurus brevirostris* which were expected to be in the GAB based on distributions cited in Fishes of Australia (http://fishesofaustralia.net.au/ accessed 2017), Atlas of Living Australia (http://www.ala.org.au accessed 2017) or Codes for Australian Aquatic Biota (Rees 2017). Values of *P/B* and *Q/B* estimates were estimated from FishBase (Froese & Pauly 2017)) for each species and averaged across all species - 0.18 and 2.33 respectively. Diet data were sourced from Caines (2005), Ward *et al.* (2006) and Blaber and Bulman (1987).

Group 25. Offshore pelagic invertivore large

The offshore pelagic invertivore large group was represented by silver, blue and white warehou *Seriolella punctata*, *Seriolella brama* and *Seriolella caerulea,* blue eye trevalla *Hyperoglyphe antarctica* and ocean blue-eye trevalla *Schedophilus labyrinthicus,* southern ribbonfish *Trachipterus arawatae,* and oarfish *Regalecus glesne*. There were no biomass data for these species so we allowed the model to estimate it.

The values of *P/B* and *Q/B* for each species were derived from FishBase (Froese and Pauly 2017) and averaged across all species - 0.205 and 2.03 respectively. Diet data for the first three species were obtained from Bulman *et al.* (2006).

Group 26. Shelf pelagic piscivores large



Representative species in the offshore pelagic piscivores group include the yellowtail kingfish *Seriola lalandi*, *S. hippos*, tailor *Pomatomus saltatrix*, barracouta *Thyrsites atun*, snook *Sphyraena novaehollandiae* and Australian Salmon *Arripis truttaceus*.

Biomass estimates were only available for barracouta and snook, based on standardised surveys undertaken in the Spencer Gulf and Gulf St Vincent Prawn fisheries, using upper standard error estimate and the calculation followed the methods of Currie *et al.* (2009) and Burnell *et al.* (2015). However, this value was apparently too low to be representative of the whole group, so we allowed this parameter to be estimated by the model.

Values of P/B for each species were derived from FishBase (Bulman *et al.* 2006, Froese & Pauly 2017) and averaged to obtain a value of 0.27. Q/B estimates for barracouta, snook and Western Australian salmon of 6.64, 3.51 and 4.7 respectively were available (Currie and Sorokin, 2010) and for the remaining species we used estimates (Bulman *et al.* 2006, Froese & Pauly 2017). The average *Q/B* was 3.34. Barracouta, snook and Western Australian salmon diet data were sourced from Caines (2005) and Page *et al.* (2011).

Group 27. Sardine

The sardine *Sardinops sagax* is an abundant small pelagic fish in gulf and shelf waters. The commercial catch is taken at night using purse seine nets and the South Australian Sardine Fishery is based out of Port Lincoln. Spawning biomass is estimated using the Daily Egg Production Method (DEPM), which is a fishery independent method that estimates the spawning stock biomass across the extent of the expected spawning area, which is the central and southern gulf and shelf waters (Ward *et al.* 2015). Annual DEPM based estimates available for the period between 1995 and 2016 (inclusive) have ranged from between 37,000 t (following a mortality event in 1995) to 243,925 t in 2014 (95% CI = 72,208–105,933 t) (Ward *et al.* 2015, Ward *et al.* 2016) so the biomass used here was 1.717 t km^{-2}. The *P/B* and *Q/B* estimates were 1.6 and 5.04, respectively (Currie & Sorokin 2010, Froese & Pauly 2017). Diet was based on analyses of 218 stomach samples collected in South Australia (Daly 2007, Page *et al.* 2011).

Group 28. Shelf pelagic planktivores (Anchovy and other small pelagics)

The inshore small planktivores group included Australian anchovy *Engraulis australis*, blue sprat *Spratelloides robustus*, sandy sprat *Hyperlophus vitattus* and maray *Etrumeus teres*. Australian anchovy is an abundant small pelagic species. Spawning biomass in the SA Gulfs during the 2000 season was estimated at 25,374 t (survey area of 9561 km^{-2}) or 0.26535 t km^{-2} (upper 95% CL) (Dimmlich *et al.* 2009). However, this value was too low and the value of 1.27 t km^{-2} from the eGAB model (Goldsworthy *et al.* 2011) was used instead. This value was estimated from DEPM surveys in SA gulfs and shelf waters (Dimmlich *et al.* 2009).

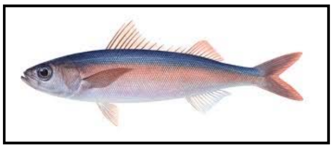
The averaged *P/B* and *Q/B* estimates of all four species were 1.56 and 11.25, respectively (Currie & Sorokin 2010, Froese & Pauly 2017). Diet data were sourced from (Daly 2007, Page *et al.* 2011). The two sprat species are common in the gulf regions of the study area (Rogers *et al.* 2003, Rogers & Ward 2007) but no biomass data were available for these species. Diet information for the blue sprat was available based on the analyses of 17 stomach samples from South Australia (Daly 2007, Page *et al.* 2011).

Group 29. Mackerel

Jack mackerel *Trachurus declivis*, yellowtail scad *Trachurus novaezelandiae*, and blue mackerel *Scomber australasicus* are common pelagic fish in the model area. Biomass of Jack and Yellowtail Mackerel had been estimated from data standardised surveys undertaken in the Gulf St Vincent Prawn fishery (Currie *et al.* 2009, Burnell *et al.* 2015). Blue mackerel biomass estimates based on DEPM estimates of spawning biomass 56,228 t within the EGAB region (Ward *et al.* 2007) were also available. However, the combined estimate of 0.465 $t.km^{-2}$ was too low for even initial parameterisation of the model. Compared with trawl surveys in eastern Bass Strait from which estimates of jack mackerel alone of ~ 6 $t.km^{-2}$ were made (Bulman *et al.* 2006), we decided to let the model estimate this parameter.

The average of P/B and Q/B estimates for the three species were 0.42 and 3.18 respectively (Currie & Sorokin 2010, Froese & Pauly 2017). Diet information for jack and blue mackerel were based on the analyses of 41 and 17 stomach samples collected off South Australia (Daly 2007, Page *et al.* 2011, Goldsworthy *et al.* 2017a).

Group 30. Redbait



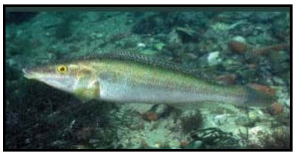
Redbait (*Emmelichthys nitidus*) is a pelagic species found in shelf waters at 20–200 m. They form pelagic schools according to size and by depth, with smaller fish being captured in shallower water (Emmelichthys nitidus in Fishes of Australia, accessed 10 Sep 2017, http://fishesofaustralia.net.au/home/species/2429). The species is taken in the Commonwealth SPF and trawl fishery as a bycatch. The estimates of *P/B* and *Q/B* were 0.36 and 3.9 (Bulman *et al.* 2006, Froese & Pauly 2017). Diet was based on the analysis of 55 stomach samples collected off South Australia (Daly 2007, Page *et al.* 2011, Goldsworthy *et al.* 2017a). Diets from southeastern Australia (Bulman *et al.* 2001, McLeod *et al.* 2012) were also used for reference.

Group 31. Shelf demersal piscivores small

Representative species of this group were Silver sweep *Scorpis lineolatus*, barber perch *Caesioperca rasor*, mado *Atypichthys strigatus*, butterfly gurnard *Lepidotrigla vanessa*, eastern orange perch *Lepidoperca pulchella*, spiny gurnard *Lepidotrigla papilio*, and frogfishes (Antennariidae, Tetrabrachiidae, Lophichthyidae) (Fishes of Australia). Many of these species occur also in south eastern Australia and data were taken from the eastern Bass Strait model (Bulman *et al.* 2006) where applicable.

The average values of P/B and Q/B estimates for the first five species for were estimated to be 0.55 and 4.6,respectively (Bulman *et al.* 2006, Froese & Pauly 2017). Dietary data for those species was obtained from the eastern Bass Strait area Bulman (Bulman *et al.* 2001)

Group 32. Shelf demersal invertivores small



The demersal invertivores found on the shelf is extensive and a list of species included in this group is provided in Table 3.5. Many of the species in this group are bycaught when deepwater flathead and other scalefish were targeted on the shelf, and western king prawn are targeted in State waters. Biomass based on surveys for the Spencer Gulf was estimated to be 1.58 t.km-2 (Currie *et al.* 2009) but this estimate was considered unlikely to be representative of this whole group. When we were unable to balance the model with this value we allowed the model to estimate the biomass of the group.

Values of P/B and Q/B were estimated for velvet leatherjacket *Meuschenia scaber*, *leatherjacket Paramonacanthus filicauda*, bigscale bullseye *Pempheris multiradiata*, rosy wrasse *Pseudolabrus psittaculus*, Australian burrfish *Allomycterus pilatus*, cocky gurnard *Lepidotrigla modesta*, roundsnout gurnard *Lepidotrigla mulhalli*, common bellowsfish *Macroramphosus scolopax*, silverside *Parequula melbournensis*, common stinkfish *Foetorepus calauropomus*, banded fin flounder *Azygopus pinnifasciatus*, white ear *Parma microlepis* and eastern school whiting *Sillago flindersi*. Individual values for P/B ranged from 0.4 to 1.09, and Q/B ranged from 3.1 to 6.4 (Bulman *et al.* 2006, Currie & Sorokin 2010, Froese & Pauly 2017). The average estimates of P/B and Q/B were 0.66 and 5.70.

Diet for this group was based on diets from the southeastern Australia (Bulman *et al.* 2001) and the summarised diet for a similar group in the Eastern Bass Strait model (Bulman *et al.* 2006).

Table 3.6. Summary of species in Group 32 - Shelf demersal invertivores small.

Common name	Species / Genus
Velvet Leatherjacket	*Meuschenia scaber*
Silverbelly	*Parequula melbournensis*
Common Bullseye	*Pempheris multiradiatus*
Eastern School Whiting	*Sillago flindersi*
Bridled leatherjacket	*Acanthaluteres spilomelanurus*
Australian burrfish	*Allomycterus pilatus*
Ornate cowfish	*Aracana ornata*
Silversides	Atherinidae
Bandedfin flounder	*Azygopus pinnifasciatus*
Western Pigfish	*Bodianus vulpinus*
Flounder	Bothidae, Psettodidae & Pleuronectidae
Soles	Cynoglossidae, Soleidae
Globefish	*Diodon nicthemerus*
Messmate Fish	*Echiodon rendahli*
Slingjaw Wrasse	*Epibulus insidiator*
Common Stinkfish	*Foetorepus calauropomus*
Silver biddies	Gerreidae - undifferentiated
Goby	Gobiidae
Soldier fish	*Gymnapistes marmoratus*
Blue weed whiting	*Haletta semifaciata*
Shortfin Seabat	*Halieutaea brevicauda*
Sea horse	*Hippocampus spp.*
Cocky gurnard	*Lepidotrigla modesta*
Roundsnout gurnard	*Lepidotrigla mulhalli*
Brushtail pipefish	*Leptoichthys fistularius*
Common bellowsfish	*Macroramphosus scolopax*
Scorpionfish	*Maxillicosta*
Whiting	*Merlangius sp*
Common Veilfin	*Metavelifer multiradiatus*
Goatfishes	Mullidae
Gurnards	*Neosebastes spp.*
Thetis Fish	*Neosebastes thetidis*
Weed whiting	*Odacidae*
Slender bullseye	*Parapriacanthus elongatus*
Silverbelly	*Parequula melbournensis*
White ear	*Parma microlepis*
Sculpted seamoth	*Pegasus lancifer*
Western striped trumpeter	*Pelates octolineatus*
Bigscale Bullseye	*Pempheris multiradiata*
Temperate basses & rockcods	Percichthyidae, Serranidae

Common name	Species / Genus
Common Seadragon	*Phyllopteryx taeniolatus*
Righteye flounders	Pleuronectidae
Rosy wrasse	*Pseudolabrus psittaculus*
Parrotfishes	Scaridae
Shortfin Worm Eel	*Scolecenchelys australis*
Rough Leatherjacket	*Scolinichthys granulatus*
Banded Sweep	*Scorpis georgiana*
Striped Scat	*Selenotoca multifasciata*
Southern School Whiting	*Sillago bassensis*
Sand Whiting	*Sillago ciliata*
Yellowfin Whiting	*Sillago schomburgkii*
Wood's siphon fish	*Siphaemia cephalotes*
Pipefish	Syngnathidae
Striped Grunters	Terapontidae
Toadfishes	Tetraodontidae
Degens leatherjacket	*Thamnaconus degeni*
Moonlighter	*Tilodon sexfasciatus*
Weeping Toado	*Torquigener pleurogramma*
Roughy	*Trachichthys australis*
Blue-striped Goatfish	*Upeneichthys lineatus*
Goatfish	*Upeneichthys sp.*
Red Mullet	*Upeneichthys vlamingii*
Cardinal fish	*Vincentia sp.*
Bluetooth Tuskfish	*Xiphocheilus typus*
Blackspot Boarfish	*Zanclistius elevatus*
Velvet Leatherjacket	*Meuschenia scaber*
Silverbelly	*Parequula melbournensis*
Common Bullseye	*Pempheris multiradiatus*
Eastern School Whiting	*Sillago flindersi*
Bridled leatherjacket	*Acanthaluteres spilomelanurus*
Australian burrfish	*Allomycterus pilatus*
Ornate cowfish	*Aracana ornata*
Silversides	Atherinidiae
Bandedfin flounder	*Azygopus pinnifasciatus*

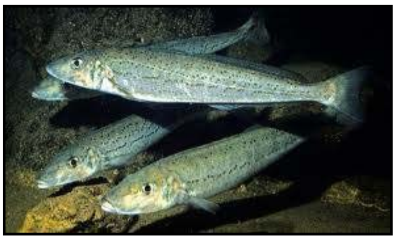
Group 33. Shelf demersal piscivores large

The shelf demersal piscivores group consists of medium to large sized species that primarily consume fish. This group included small tooth flounder *Pseudorhombus jenynsii*, common stargazer *Kathetostoma laeve*, tiger flathead *Platycephalus richardsoni*, red cod *Pseudophycis bachus*, tasselled anglerfish *Rhycherus filamentosus*, flathead species *Platycephalus* sp including the longhead flathead *Leviprora inops*, sergeant baker *Aulopus purpurissatus*, mulloway *Argyrosomus japonicus*, striped trumpeter *Latris lineata*, skipjack trevally *Pseudocaranx wright*i, and silver trevally *P. dentex*. These species were grouped due to dietary similarities identified by Currie and Sorokin (2010). Biomass estimates and diets were based on Currie and Sorokin (2010). The average of *P/B* and *Q/B* estimates across all species were 0.33 and 3.1 (Bulman *et al.* 2006, Froese & Pauly 2017). The diet data in Currie and Sorokin (2010) is based on samples collected from Spencer Gulf.

Group 34. Shelf demersal invertivores large

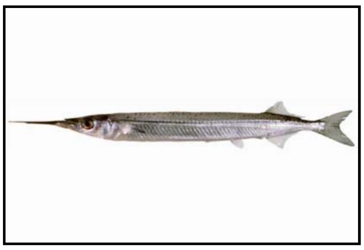
The “shelf demersal invertivores large” group consists of Gurnard perch *Neosebastidae*, Estuary catfish *Cnidoglanis microcephalus*, Globefish *Diodon nicthemerus*, Magpie Perch *Cheilodactylus nigripes*, Beaked salmon *Gonorynchus greyi*, Senator Wrasse *Pictilabrus laticlavius*, Blue throat wrasse *Notolabrus tetricus*, other Wrasses, Sweep *Scorpis aequipinnis*, Blue morwong *Nemadactylus douglasi*, Short Boarfish *Parazanclistius hutchinsi*, Butterfly Perch *Caesioperca lepidoptera*, and the Ocean jacket *Nelusetta ayraudi*. Biomass data were sourced from Currie *et al.* (2009). The P/B and Q/B estimates were 0.39 and 3.57, respectively (Fulton & Smith 2004, Currie & Sorokin 2010). Diet data were limited and sourced from Currie and Sorokin (2010).

Group 35. King George Whiting



King George Whiting *Sillaginodes punctatus* is an important commercially and recreationally caught species in South Australia. Estimates of biomass, exploitation rate and recruitment are available for this species as part of a dynamic, spatial age-length structure model (WhiteEst), developed to facilitate management of this fishery (McGarvey & Fowler 2002, Fowler *et al.* 2014). Legal-size population biomass was used as a starting estimate for overall biomass for the GAB region – estimated to be 0.063 t km^{-2} (Fowler *et al.* 2014). P/B and Q/B estimates were 0.55 and 2.29, respectively (Fulton & Smith 2004, Currie & Sorokin 2010). The species is carnivorous and feeds on invertebrates, shrimps, prawns and polychaetes. Diet data were limited and was based on samples collected in Spencer Gulf (Currie & Sorokin 2010).

Group 36. Southern sea garfish



Southern sea garfish *Hyporhamphus melanochir* is an important commercially and recreationally caught species in South Australia. Estimates of biomass are available from age-length structure model (GarEst) developed to facilitate management of fisheries that target this species (McGarvey *et al.* 2007, Steer *et al.* 2012). P/B and Q/B estimates were 0.33 and 4.73, respectively (Fulton & Smith

2004, Currie & Sorokin 2010). Diet data were based on a study that examined samples from Gulf St Vincent (Earl *et al.* 2011).

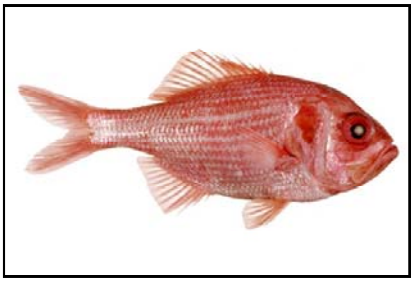
Group 37. Snapper

Snapper *Chrysophrys auratus* is an abundant demersal fish species that occurs throughout temperate and sub-tropical waters of the Indo-Pacific region (Paulin 1990, Kailola *et al.* 1993). Snapper is the most valuable species of fish in the Marine Scalefish Fishery in South Australia (Knight & Tsolos 2009), yet there have been recent declines in catches. This fishery is a multi-gear, multi-species fishery that operates throughout all coastal waters of the State. Snapper is mostly targeted using long lines and handline in the waters of both SA gulfs. Estimates of biomass, exploitation rate and recruitment are available for this species as part of dynamic, spatial age-length structure models developed to facilitate management of this fishery (Fowler *et al.* 2013); biomass was estimated to be 0.2083 t km^{-2}. P/B and Q/B estimates were 0.15 and 2.9, respectively (Fulton & Smith 2004, Froese & Pauly 2017). Diet data were sourced from samples collected from commercial catches during a recent Honours study (Lloyd 2010).

Group 38. Deepwater flathead

Deepwater flathead *Neoplatycephalus conatus* is a demersal species that lives on the continental shelf and slope of southern Australia from western Bass Strait to southern WA at depths of 70–510 m (*Platycephalus conatus* in Fishes of Australia, accessed 11 Sep 2017, http://fishesofaustralia.net.au/home/species/3358). The main gear types used are fish bottom trawl and Danish Seine in the Commonwealth managed GAB trawl fishery (managed via the TACC). P/B and Q/B estimates were 0.2 and 2.8, respectively (Bulman *et al.* 2006, Froese & Pauly 2017). The diet of deepwater flathead was based on that of tiger flathead *Platycephalus richardsoni* (Bulman *et al.* 2001, 2006) and Fishes of Australia.

Group 39. Bight redfish



Bight redfish *Centroberyx gerrardi* is endemic to southern Australian waters between Lancelin, Western Australia and Jervis Bay (NSW) (Gomon & Bray 2017). It occurs either solitary or in pairs on deeper rocky reefs and pinnacles on the continental shelf and upper slope in water depths of 10 to 260 m (Gomon & Bray 2017)). It is commonly confused with the main commercial species yelloweye redfish *Centroberyx australis* which occurs in the GAB and around to North West Cape (WA) (Bray 2017). This species is caught in the Bight with bottom trawl and Danish Seine in the Commonwealth managed GAB trawl fishery (managed via the TACC) (AFMA 2017). The P/B and Q/B estimates were 0.31 and 3.4, respectively (Bulman *et al.* 2006, Froese & Pauly 2017). Diet is based on that for *Centroberyx affinis* off southeastern Australia (Bulman *et al.* 2001, 2006).

Groups 40 and 41. Migratory mesopelagics and Non-migratory mesopelagics

Mesopelagic fishes typically occur along the shelf break and upper slope in high abundance (May & Blaber 1987) and collectively make up one of the components of the Deep Scattering Layer. Over 60 species were identified from Theme 2 surveys: some of the species for which we estimated P/B and Q/B were Hector's lanternfish *Lampanyctodes hectoris*, Blackring waryfish *Scopelosaurus meadi*, Dana lanternfish *Diaphus danae*, pennant pearlside *Maurolicus australis*, Silver lighthouse fish *Phosichthys argenteus*, big-scaled neoscopelid *Neosopelus macrolepidotus,* common black dragonfish *Idiacanthus fasciola*, Hansen's lanternfish *Hygophum hanseni*, Fangtooth dragonfish *Melanostomias niger*, and Belted lanternfish *Electrona paucirastra*. These species occur across a range of depths from 100m to more than 1600 m. They were divided into two groups: those that vertically migrate from ~400-600m to near surface on a daily basis—typically the Myctophidae—(group 40); and those that occurred at often deeper depths and/or do not migrate (group 41).

Lantern fish species are not targeted by commercial fisheries in the study region, but are found in the diets of some of the predator groups (e.g. fur seals). There were scant data available on the distribution, abundance or biomass of these species in the study region. The biomass was estimated from Theme 2 data but was unlikely to be a realistic estimate due to the limited sampling and gear used. We allowed the model to estimate the biomass of these two groups. Estimates of abundance from studies of the same or similar species in southern Australia vary from oceanic acoustic 2-6 $t.km^{-2}$ (Kloser *et al.* 2009) to upper and mid-slope trawl estimates of 224 $t.km^{-2}$ on the upper slope of eastern Tasmania (May & Blaber 1989) and a total of 101 $t.km^{-2}$ off southern Tasmania (29 shallow

migrators, 40 t.km^{-2} deep migrators and 32 t.km^{-2} non-migrators (Koslow *et al.* 1997). The model-estimated biomass for the balanced model was low compared to the slope studies and comparable to the oceanic acoustic estimates.

For the limited range of species above, which were found to be the most dominant species in other regions, and we used the estimates calculated for the Tasmanian Seamount model for the average P/B and Q/B to be 0.68 and 6.0, respectively for group 40 and 1.005 and 6.673 respectively for group 41 (Bulman *et al.* 2006, Froese & Pauly 2017). An average diet was estimated from diets from studies from the upper slope off eastern Tasmania ((Young & Blaber 1986) and upper and midslope off southern Tasmania (Williams *et al.* 2001).

Group 42. Slope small demersal invertivores

Representative species from this group were identified from the surveys of the slope off south eastern Australia (May & Blaber 1989, Koslow *et al.* 1994a), and from Fishes of Australia and CAAB: Grey whiptail *Coelorinchus fasciatus*, white deepsea cardinal fish *Epigonus denticulatus*, robust deepsea cardinalfish *Epigonus robustus*, big-eye cardinalfish *Epigonus lenim*en, three-spined cardinalfish *Apogonops anomalus*, blacktip cucumberfish *Paraulopus nigripinnis*, roughies Trachichthyidae, rosy dory *Cyttopsis rosea*, bigeye ocean perch *Helicolenus barathri*, butterfly gurnard *Lepidotrigla* spp., bigspine boarfish *Pentaceros decacanthus.* No biomass information was available for these species in the GAB and was model estimated.

The average P/B and Q/B were estimated for the first five species: 0.57 and 4.275 respectively (Froese and Pauly 2017). An average diet for most of these species was estimated from diets of the same species off southeastern Australia (Bulman *et al.* 2002).

Group 43. Slope small demersal piscivores

The representative species that represented this group were identified from the surveys of the slope off south eastern Australia (May & Blaber 1989, Koslow *et al.* 1994a), and Fishes of Australia and CAAB : they were gargoyle fish *Coelorinchus mirus*, falseband whiptail *Coelorinchus maurofasciatus*, deepsea scorpionfish *Trachyscorpia carnomagula*, splendid perch *Callanthias australis*, longfin pikes Dinolestidae. No reliable biomass information was available for these species in the GAB and was model estimated.

The average P/B and Q/B were estimated for the first two species: 0.42 and 3.5 respectively (Froese and Pauly 2017). An average diet for most of these species was estimated from diets of the same species off southeastern Australia (Blaber and Bulman 1987), Bulman *et al.* 2002).

Group 44. Slope large demersal invertivores

The representative species that represented this group were identified from the surveys of the slope off south eastern Australia (May & Blaber 1989, Koslow *et al.* 1994a), and Fishes of Australia and CAAB: they were Basketwork eels *Bassanago* species, toothed whiptail *Lepidorhynchus denticulatus*, banded whiptail *Coelorinchus parvifasciatus*, southern whiptail *Coelorinchus australis*, spikey oreo *Neocyttus rhomboidalis*, Darwin's roughy *Gephyroberyx darwini*, cosmopolitan rubyfish *Plagiogeneion rubiginosum*, knifejaw *Oplegnathus woodwardi,* pelagic armourhead *Pseudopentaceros richardsoni,* deepsea cardinalfish *Epigonus telescopus.*

The average P/B and Q/B were estimated to be 0.34 and 3.55 respectively (Froese and Pauly 2017). An average diet for most of these species was estimated from diets of the same species off southeastern Australia (Blaber and Bulman 1987, Bulman *et al.* 2002).

Group 45. Slope large demersal piscivores

Representative species in this group were identified from the surveys of the slope off south eastern Australia (May and Blaber 1989, Koslow *et al.* 1994), and Fishes of Australia and CAAB. They included hapuku *Polyprion oxygeneios,* dealfish *Trachipterus jacksonensis,* southern frostfish *Lepidopus caudatus,* speckled stargazer *Kathetostoma canaster, o*range roughy *Hoplostethus atlanticus,* common mora *Mora moro,* silver dory *Cyttus australis,* king dory *Cyttus traversi,* New Zealand dory *Cyttus novaezelandiae,* blue grenadier *Macruronus novaezelandiae,* blue eye trevalla *Hyperoglyphe antarctica,* pink ling *Genypterus blacodes,* tusk *Dannevigia tusca,* imperador *Beryx decadactylus,* alfonsino *Beryx splendens,* oxeye oreo *Oreosoma atlanticum,* smooth oreodory *Pseudocyttus maculatus,* black oreodory *Allocyttus niger,* rough oreodory *Neocyttus psilorhynchus,* ghost flatheads Hoplichthyidae*,* deepsea flathead *Hoplichthys haswelli,* bass groper *Polyprion americanus,* speckled stargazer *Kathetostoma canaster,* frostfish *Lepidopus caudatus.*

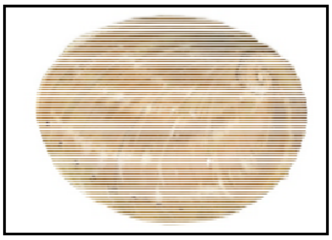
The average P/B and Q/B for the first fifteen species were estimated to be 0.234 and 2.54 respectively (Froese and Pauly 2017). Diet data for most of these species off southeastern Australia were taken from Bulman and Blaber (1986), Bulman *et al.* (2002) and Blaber and Bulman (1987).

3.3.6 Invertebrates

Group 46. Benthic grazers

The GAB study region is characterised by diverse herbivorous and carnivorous megabenthos communities. The group contains members of the Echinodermata, Sea urchin (*Amblypneusts pallidus*), Longspine sea urchin (*Centrostephanus rodgerii*), thorny sea urchin (*Goniocidaris tubaria*), flexible chiton (*Cryptoplax striata*), gastropods, pheasant shell (*Phasianella australis*), Sea slug/snail (*Philinoidea*), moon snails (Naticidae), top snail (*Callistoma armillatum*), bubble snails (*Bulla* sp.), Nassarius snail (Nassariidae), Turbolarians, Gastropoda, and the chiton (*Ischnochiton contractus*). From data from the benthic surveys (GABRP Theme 3 Report) we estimated a biomass of 0.04549 $t.km^{-2}$ for urchins initially. This value was too low to balance. The value of 0.1 $t.km^{-2}$ from the Southern Hills Seamount model was used (Bulman *et al.* 2002). Values for *P/B* for the benthic grazers group of 0.39 and a P/Q value of 0.30 were taken from the North Sea model (Mackinson & Daskalov 2007).

Group 47. Abalone



Five species of abalone occur in the GAB region. The greenlip (*Haliotis laevigata*) and blacklip abalone (*H. rubra*) are the two main commercially targeted species. No fishery independent biomass estimates were available for this group. A biomass estimate of 0.023 t km^{-2} was first input but Fulton and Smith (2004) used 0.699 t km^{-2}.

P/B and *Q/B* values of 0.73 and 12.41, respectively were taken from a Port Philip Bay model (Fulton & Smith 2004). Greenlip abalone are estimated to consume 70% red algae, 11% brown algae, 15% seagrass and 4% detritus and browsed organic matter, based on diet studies at Tiparra Reef, Spencer Gulf (Shepherd 1972). Blacklip abalone are estimated to consume 55% red algae, 7% brown algae, 34% seagrass and 5% detritus and browsed organic matter, based on diet studies at Tiparra Reef, Spencer Gulf (Shepherd 1972). An average of the two species diets was used.

Group 48. Benthic detritivores

The infaunal macrobenthos or detritivore group consists of polychaete worms, shrimps, isopods, and other infaunal invertebrates. The benthic detritivores included in the model are summarized in Table 3.7. Biomass was estimated from GABRP Theme 3 sample values for epifauna and infauna of the appropriate types. Estimates of 5 and 32 for P/B and Q/B, respectively, come from (Bulman *et al.* 2006). Diet data were sourced from (Bundy 2001, Bulman *et al.* 2006).

Table 3.7. Summary of taxa in Group 48. Benthic detritivores

Common name	Family	Genus/species
Comma shrimp	Cumacea	
Small shrimp	Tanaidacea	Tanaidacea
Astacillidae	Isopoda	Isopoda
Isopod	Isopoda	Cerceis *sp.*
Isopod (I037 & I051)*	Isopoda	Cymodoce *sp.*
Isopod	Isopoda	Cirolanidae
Isopod	Isopoda	Chitonopsis *sp.*
Isopod	Isopoda	Serolidae
Valviferan isopod		Isopoda
Astacillidae	Isopoda	Astacillidae
Crustacea	Isopoda	*Haswellia sp.*
Ghost shrimp	Amphipoda	Caprella acanthogaster
Ghost shrimp	Amphipoda	Caprellidae
Gammaridea	Amphipoda	Gammaridea

Common name	Family	Genus/species
Gammaridea	Amphipoda	Lysinassidae
Gammaridea	Amphipoda	Phoxocephalidae
Photidae Amphipods		Photidae
Copepod	Maxillopoda	Maxillopoda
Handsome Sea Cucumber		*Holothuria hartmeyeri*
Leptostraca	Leptostraca	
Nebaliacea	Nebaliacea	Nebalia
Peanut worms	Sipuncula sp.	
Spoon worms	Echiuroidea	Echiuroidea
Worm	Polychaeta	Polychaeta (other)
Trumpet worms	Polychaeta	Pectinariidae
Rag worms	Polychaeta	Nereidae
spaghetti worms	Polychaeta	Terebellidae
Polychaetes - DDF	Polychaeta	Capitellidae
Polychaetes - DDF	Polychaeta	Cirratilidae
Polychaeta (other)	Polychaeta	Polychaeta
Oligochaeta	Oligochaeta	
Horse-shoe worms	Phoronid	Phoronidae
Acorn worms	Hemichordata	
Beak-thrower worms	Polychaeta	Glyceriidae

Group 49. Benthic carnivore

The benthic carnivores comprised over 140 taxa identified from Theme 3 data. The species identified were from the polychaete families including the Aphroditidae, Eunicidae, Euphrosinidae, Lumbrineridae, Nereididae, Paralacydoniidae, Phyllodocidae, Polynoidae, Sigalionidae, from molluscan families including Epimeniidae, Hipponicidae, Velutinidae, and gammarid and caprellid copepods.

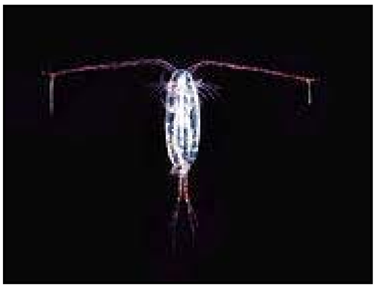
Biomass of 5.76 t.km^{-2} was estimated from GABRP Theme 3 sample values for epifauna and infauna of the appropriate types from the shelf stations. The benthic carnivores included in the model are summarised in Table 3.8. Estimates of P/B and Q/B were 2 and 22, respectively, came from Jurien Bay model (Loneragan *et al.* 2010). Diet was also based on Loneragan *et al.* (2010).

Table 3.8. Summary of taxa in Group 49. Benthic carnivores.

Common name	Family	Genus/species
Echinoderm	Asteroidea	
Echinoderm	Ophiuroidea	
Sea urchin	Temnopleuridae	
Southern Sand Star		*Luidia australiae*
Brittle Star	Ophiuroidea	Ophiuroidea
Sea slug		Philine angasi
Sea lice		*Natatolana* spp.

Common name	Family	Genus/species
Bobbit	Polychaeta	Eunicidae
Sea mice	Polychaeta	Aphroditidae
	Pycnogonida	
Beaked sea-spider	Hymenosomatidae	*Halicarcinus rostratus*

Group 50. Mieobenthos



Meiobenthic organisms comprise the invertebrates of < 1mm size classes - including harpacticoid copepods, turbellarians, ostracods, nematodes, polychaetes, mites, gastropods and bivalves, ciliates and foraminiferans.

Biomass of meiobenthos was calculated from Theme 3 data. Estimates of *P/B* and *Q/B* of 35 and 125, respectively, were used as model input data based on Spencer Gulf Model (Goldsworthy *et al.* 2016). Diet data were scant for this group.

Group 51. Filter feeders

The benthic filter feeders group comprised a range of species groups from the sand and zoobenthos, sessile epifauna. The group was mostly comprised of many species of bivalves and other molluscs, i.e. the cockles, oysters, mussels, barnacles and bryozoans summarized in Table 3.9. Estimates of *P/B* and *Q/B* of 1.6 and 6, respectively, were used as model input data based on Bulman *et al.* (2006). Biomass data were sourced from epifaunal and infaunal information collected as part of GABRP Theme 3 for shelf depths.

Table 3.9. Summary of the key taxa in the filter feeders group 51.

Common name/species group	Family	Genus / species
Cockle	Donacidae	*Plebidonax deltoides*
Cockle		*Tawera lagopus*
Bivalve cockle		*Solemya australis*
Mollusca	Bivalvia	*Donax* sp.
Mud cockle	Bivalvia	*Katelysia* sp.
Venus clam	Bivalvia	Veneridae

Common name/species group	Family	Genus / species
Mollusca	Mollusca	*Placamen flindersi*
Mollusca	Mollusca	*Phasionella australis*
Lima Lima (Bivalve)		*Lima vulgaris*
Southern Hammer Oyster		*Malleus meridian us*
Mud oyster		*Ostrea angasi*
Razorfish		*Pinna bicolor*
Corbula clam	Bivalvia	*Corbula coxi*
feather duster worms	Polychaeta	Sabellidae
Hairy Mussel		*Trichomya hirsuta*
Mussel		*Mytilus edulis*
Pacific Oyster		*C. gigas*
Barnacles	Cirripedia	*Cirripedia*
Brachiopoda	Brachiopoda	*Brachiopoda*
Bryozoa	Bryozoa	*Amathia sp.*
Bryozoa	Bryozoa	Other
Bryozoa	Bryozoa	*Bugularia* sp.
Bryozoa	Bryozoa	*Orthoscuticella* sp.
Bryozoa	Bryozoa (other)	
Entoprocta		
Goose barnacle	Pedunculata	*Ibla quadrivalvis*
Crinoidea		
Ascidiacea	Ascidiacea	Ascidian
Didemnidae	Didemnidae	
Tunicate		*Polycarpa pedunculata*
Cnidaria	Gorgonacea	Gorgonacea
Cnidaria	Hydroida	Hydroida
Cnidaria		Anthozoa
Porifera	Calcarea	
Doughboy scallop		*Mimachlamys asperrima*
Nuculana crassa	Bivalvia	*Nuculana crassa*
Queen scallop	Bivalvia	*Equichlamys bifrons*
Commercial scallop	Bivalvia	*Pecten fumatus*

Group 52. Deep filter feeders

The deep filter feeders included crinoids, bryozoans, ascidians, and fewer sponges. Estimates of P/B and Q/B of 2.8 and 5, respectively, were used as model input data based on Bulman *et al.* (2006).

Biomass is estimates were calculated for filter feeders from deep sites sampled in GABRP Benthic Theme 3.

Group 53. Shelf macrozoobenthos

The shelf macrozoobenthos group consisted of a highly diverse array of species, such as crabs, lobsters, and other mobile crustaceans. Examples include the Red Swimmer crab, spider crab, strawberry prawn and mantis shrimp. The full selection of species and species groups included in the model is described in Table 3.10.

Biomass is estimates for filter feeders from deep sites sampled in GABRP Benthic Theme 3.

Estimates of P/B and Q/B of 11.1 and 14, respectively, were used as model input data based on Theme 3.

Table 3.10. Summary of taxa in the shelf macrozoobenthos group 53.

Common name/species group	Family	Genus / species
Red Swimmer crab	Portunidae	*Nectocarcinus integrifrons*
Mud crab	Brachyura	Xanthidae
Pebble crab	Crustacea	*Ebalia intermedia*
Large Pebble Crab	Decapoda	*Bellidilia undecimspinosa*
Great spider crab	Crustacea	*Leptomithrax gaimardii*
Spider crab	Crustacea	*Naxia aurita*
Spider crab	Crustacea	Naxia sp.
Spider Crab (CJ-CP 4)*	Crustacea	*Prismatopus spatulifer*
Spider Crab (CJ)*	Crustacea	*Schizophrys rufescens*
Sponge crab	Crustacea	*Austrodromidia octodentata*
Squat lobsters	Crustacea	Galatheidae
Squat lobsters	Crustacea	*Munida* sp.
Hairy Crab	Pilumnidae	*Pilumnus tomentosus*
Facetted crab	Crustacea	*Actea calculosa*
Common hermit crab	Crustacea	*Paguristes frontalis*
Nut crab	Decapoda	*Ebalia* sp.
Hairy Crab	Pilumnidae	
Crabs	Crustacea	Brachyura (undefined)
Brachyura	Majidae	
Strawberry prawn		*Metapenaeopsis* sp.
Pandalid prawn	Pandalidae	Pandalidae
Southern velvet shrimp	Penaeidae	*Metapenaeopsis palmensis*
Velvet shrimps	Crustacea	*Metapenaeopsis* spp.
Mysidacea	Mysidacea	
Decapod	Decapoda	Decapoda
Crustacean - other	Crustacea	Crustacean
Caridean shrimp	Caridea	*Ogyrides delli*
Caridean shrimp	Decapoda	Caridea
Red tail ghost shrimp	Axioidea	*Axiopsis werribee*
Mantis shrimp	Stomatopoda	*Erugosquilla grahami*

Common name/species group	Family	Genus / species
Mantis shrimp	Stomatopoda	Squillidae
Snapping shrimps	Alpheidae	*Alpheus villosus*

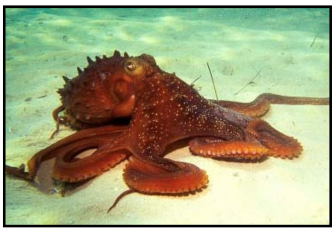
Group 54. Squid and cuttlefish shelf

The squid and cuttlefish group comprised Southern calamari (*Sepioteuthis australis*), Giant cuttlefish (*Sepia apama*), Nova cuttlefish (*Sepia novaehollandiae*), Southern dumpling squid (*Euprymna tasmanica*), and Jewel squid (*Histioteuthis sp*). Southern Calamari and Giant Cuttlefish are both targeted in the SA State managed MSF fishery. Southern calamari is a common and commercially harvested cephalopod in gulf waters and embayments. Other squids included the Nova Cuttlefish (*Sepia novaehol*landiae), Southern Bottletail Squid (*Sepiadarium austrinum*), Striped Pyjama Squid (*Sepioloidea lineolata*) and Braggi's Cuttlefish (*Sepia braggi*).

Biomass estimates for these species were based on standardised surveys undertaken in the Gulf St Vincent Prawn fishery, with biomass data for all species summed to 0.07 tkm^{-2}, following the methods of Currie *et al.* (2009) and Burnell *et al.* (2015). P/B and Q/B estimates used in the model were 1.825 and 18.25, respectively , taken from the East Bass Strait model (Bulman *et al.* 2006, Froese & Pauly 2017) . Other estimates of P/B and Q/B estimates were 2.37 and 5.80, respectively (Loneragan *et al.* 2010).

Diet was based on 85 stomachs examined by both macro and molecular analyses (Roberts 2005, in Page *et al.* 2011). Diet data were also sourced from Braley *et al.* (2010), Bulman *et al.* (2006), Grubert *et al.* (1999). Little is known about the diet of giant Australian cuttlefish. Literature suggests diets consist of crustaceans > fish > molluscs and we used a ratio of 7:2:1 (M. Steer, pers. comm.).

Group 55. Octopus shelf



The octopus group consists of several species including Maori octopus (*Octopus maorum*), southern keeled octopus (*Octopus berrima*), southern sand octopus (*Octopus kaurna*) and pale octopus (*Octopus pallidus*).

Biomass estimates for these species were based on standardised surveys in the Gulf St Vincent Prawn Fishery (0.02 t km^{-2}) following the methods of Currie *et al.* (2009) and Burnell *et al.* (2015). P/B and Q/B estimates were 2.37 and 7.90, respectively (Loneragan *et al.* 2010). Diet was based on Grubert *et al.* (1999), and studies therein. Biomass estimate of 0.003 t km^{-2} was based on

standardised surveys for the Spencer Gulf Prawn fishery, for *O. australis* and *O. berrima* (Currie *et al.* 2009, Currie & Sorokin 2010).

Group 56. Rock lobster

There is a significant recreational rock lobster fishery in the eastern GAB. The South Australian commercial fishery for the southern rock lobster (*Jasus edwardsii*) developed in late 1940-50. Currently 90% of the catch is exported live to overseas markets (Linnane *et al.* 2014). There is an important recreational fishery for lobsters and fishers use drop-nets, pots or SCUBA to take the species during November–May. The Northern Zone Rock Lobster Fishery (NZRLF) targets southern rock lobster in the central and eastern GAB. Lobsters are taken by recreational fishers using registered pots, diving and snorkelling, and by drop/hoop nets. Historically, the fishery has been managed through input or effort controls – commercial fishers supply catch and effort information through daily logbooks that are returned to SARDI Aquatic Sciences monthly.

We used estimates of 0.73 and 12.41 for P/B and Q/B, respectively (Fulton & Smith 2004). Starting biomass was estimated from the catch within the GAB (378.9 t) and assuming fishing mortality of 0.3 (0.087 t km^{-2}) (Fulton & Smith 2004). Diet was based on the study of Hoare (2008).

Group 57 Western king prawn

Three commercial western king prawn fisheries operate in South Australian State managed fishery jurisdictions, including the Spencer Gulf Prawn Fishery, the Gulf St Vincent Prawn Fishery, and the West Coast Prawn Fishery. Small juveniles recruit into shallow inshore areas and mostly in intertidal sand and mud-flats between shallow subtidal and intertidal seagrass beds and mangroves (Kangas & Jackson 1998, Tanner & Deakin 2001), whereas the adults are targeted in the central gulfs, and mostly in waters >15 m over sand and other soft substrates. Prawns are harvested at night using twin rigged, demersal otter-trawls that have bycatch reduction devices to reduce blue crab mega-fauna by-catch. Mechanised grading systems on-board sort the catch by size, process it on-board and return the by-catch overboard.

Biomass for this group was estimated from trawl surveys in Spencer Gulf to be 0.57055 t km^{-2} (Currie *et al.* 2009, Currie & Sorokin 2010) and assumed to be similar for the area over which the fishery operates outside Spencer Gulf. We used estimates of 7.57 and 37.90 for P/B and Q/B, respectively (Ayers *et al.* 2013). Minimal published information is available on the diet of these species, but King (1977) observed western king prawns feeding on algae and on the surfaces of seagrass and shells.

We also considered them to be opportunistic scavengers on small dead animals, and to take live annelids.

Group 58. Commercial crab species

The commercial crab group includes blue swimmer crabs (*Pelagicus armatus*), sand crabs (*Ovalipes australiensis*) and giant crabs. The giant crab (*Pseudocarcinus gigas*) is endemic to southern Australia. It has been taken as bycatch by the NZRLF for > 80 years (Ward and Loiterton 2000). The South Australian Giant Crab Fishery also operates in the modelled area. The giant crab fishery was controlled by the Commonwealth Government prior to 1992. Management was transferred to State Governments in 1997. The fishery is managed by input and output controls including a TAC. The export of giant crab is controlled by under the Commonwealth Environment Protection and Biodiversity Conservation Act 1999. There are currently no recreational bag or boat limits for this species and berried females must be returned to the water. The fishery comprises Miscellaneous Fishery licence holders, Rock Lobster licence holders with Giant Crab quota (RL-quota), and remaining Rock Lobster licence holders entitled to catch Giant Crab as a by-product (McLeay 2016). In 2014, the TACC was 22.1t and has remained unchanged since 2000. The distribution of catch among sectors in 2014 was 68% (11.8t) in the Miscellaneous Fishery sector, 30.2% (5.2t) in the RL-quota sector and 1.8% (0.3t) harvested as by-product by Rock Lobster fishers (McLeay 2016).

Blue swimmer crabs are one of the dominant crab species in Spencer Gulf and Gulf St Vincent and the eastern GAB bays. Biomass estimates were based on standardised surveys undertaken in the Spencer Gulf Prawn fishery using the upper SE estimate (0.68529 t km^{-2}) after calculations following the methods of Currie *et al.* (2009) and Burnell *et al.* (2015). Biomass estimates of sand crabs were based on standardised surveys in the Spencer Gulf Prawn fishery (0.0006 t km^{-2}) following the methods of Currie *et al.* (2009) and Burnell *et al.* (2015) (Gillanders *et al.* 2015). The overall biomass of crabs of 0.69 t km^{-2} was assumed to be the total of sand and blue swimmer crabs. *P/B* and *Q/B* estimates of 2.80 and 8.50, respectively, were taken from the Jurien Bay model (Loneragan *et al.* 2010).

Blue swimmer crabs have a predatory/scavenging lifestyle, feeding mainly on molluscs, crustaceans and polychaetes. The diet was based on the study by Edgar (1990) and descriptions in Bryars and Svane (2008). Little is known of the diet of sand crabs and was considered to have similar feeding behaviour and diet to the blue swimmer crabs, with bivalves being a main prey item (Bryars & Svane 2008). Overall diet was based on the blue swimmer crab diet (Edgar1990, Bryars and Svane (2008).

Group 59. Deep macrozoobenthos

The deep macrozoobenthos model group consisted of large, active, primarily carnivorous megafauna e.g. gastropods, decapod crustaceans (crabs, non-commercial prawns, large mysids) and

stomatopods. These were identified from epifaunal and infaunal species collected in GABRP Theme 3 data and collated.

Biomass of this group in the deep stations was estimated to be 16.96 t km^{-2}. Model input estimates of P/B and Q/B of 4.57 and 16.16, were averaged across four groups of mobile epifanuna in the Jurien Bay model (Loneragan *et al.* 2010, Lozano-Montes *et al.* 2011). Diet was also based on the Jurien Bay model diets (Loneragan *et al.* 2010, Lozano-Montes *et al.* 2011).

Group 60. Deep offshore squid

The deep offshore squid group is assumed to be made up of the pelagic (flying) squids (*Nototodarus gouldi*, and *Todarodes* spp.), which were historically fished across the shelf, outer shelf break and slope of western Bass Strait, Eastern GAB and the Bonney Upwelling by Japanese fleets (Smith 1983). An Australian commercial domestic jigging fleet targets arrow squid and catch data were available for Commonwealth waters for the Squid Jig, SET and GABT fisheries.

We estimated biomass for this group from two sources: from GABRP Theme 2 surveys, the maximum of the night and day averages of micronekton squid collected from the slope and offshore stations was estimated to be 0.15 t km^{-2} and from Theme 3 benthic surveys, benthic squid were estimated to be 0.0965 t km^{-2}. Since these estimates were different parts of the water column the two estimates were summed to give a total of 0.2465 t km^{-2}. P/B of 2.75 and Q/B of 8 were taken from (Bulman *et al.* 2010). P/B and Q/B estimates used were 1.8 and 10, respectively (Bulman *et al.* 2006, Froese & Pauly 2017). Diet data were sourced from Braley *et al.* (2010), Bulman *et al.* (2006), Grubert *et al.* (1999) and Page *et al.* (2011).

Group 61. Gelatinous zooplankton

The gelatinous zooplankton group consisted of jellyfishes, salps and ctenophores. The biomass estimate used in the model (0.44 tkm^{-2}) was based on the maximum of the night and day average across all stations of micronekton gelatinous zooplankton sampled by GABRP Theme 2. The P/B and Q/B were 64.9 and 218.5, respectively, were the averages for salps, siphonophores, ctenophora, hydromedusae, apendicularians in used in an enclosed sea model in the Chilean North Patagonian ecosystem which was particularly focussed on representing microbial loop dynamics Paves *et al.* (2013). Gelatinous zooplankton in the North Sea model had a P/B of 2.86 and Q/B of 0.10. Diet was based on Mackinson and Daskalov (2007).

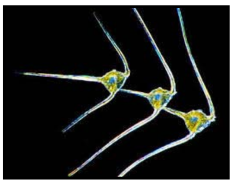
Group 62. Large zooplankton

The large zooplankton group consisted of Antarctic krill (*Nyctiphanes australis*), amphipods and isopods. The biomass estimate used in the model (0.79 tkm^{-2}) was the maximum of the averages across the micronekton stations sampled in GABRP Theme 2. Estimates of P/B and Q/B were 5.37 and 17.58 and were based on Euphausiacea in an enclosed sea model in the Chilean North Patagonian ecosystem which was particularly focussed on representing microbial loop dynamics Pavés *et al.* (2013). Similar estimates of P/B of 4 and Q/B of 12.5 were obtained by Mackinson and Daskalov (2007) in a North Sea ecosystem model and 7.3 and 15 by (Tomczak *et al.* 2012) in the Baltic Sea. Diet was based on those in Tomczak *et al.* (2012) and Mackinson and Daskalov (2007).

Group 63. Small zooplankton (meso)

The small (meso) zooplankton group comprised organisms of between 0.2 and 20 mm from the copepods, pteropods, claodecerans, tunicates, chaetognaths and ostracods. A biomass of 0.093 tkm^{-2} was estimated from the average total depth integrated mesozooplankton values from GABRP Theme 2. Data for mesozooplankton was also provided from GABRP Theme 3 from which we estimated a biomass of this group of 3.307 tkm^{2}. A total of 3.4 tkm^{-2} was input initially but was increased during balancing. The P/B and Q/B of 28.84 and 82 used in this model were the values for calanoid copepods in an enclosed sea model in the Chilean North Patagonian ecosystem which particularly focussed on representing microbial loop dynamics (Pavés *et al.* (2013). Values from the North Sea of P/B of 9.2 and Q/B of 30 (Mackinson & Daskalov 2007) and the Baltic Sea model for 4 mesozooplankton groups of between 8- 30 and Q/B 27-100 were also considered. Diet was based on those in Mackinson and Daskalov (2007) and Tomczak *et al.* (2012).

Group 64. Microzooplankton



The microzooplankton group comprised organisms of between 20 and 200 µm from the protozoa, rotifers, foraminiferans, tintinnids, ciliates and copepod nauplii. Biomass was derived from GABRP Theme 2 using dinoflagellate count data, average volume/cell, and wet weight conversion from C content per cell. Depth integrated values were estimated and averaged across eight stations on the

Central and Eastern GAB transects-shelf, upper slope, mid slope, offshore. We used estimates of P/B and Q/B of 46.03 and 131.37 for copepod nauplii in an enclosed sea in the Chilean North Patagonian ecosystem (Pavés *et al.* 2013). In the Baltic Sea, Tomczak *et al.* (2012) used P/B of 110 and Q/B of 275. Diet of microzooplankton was based on Tomczak *et al.* (2012).

Group 65. Nanozooplankton

The biomass estimates for the nanozooplankton group (which represents largely heterotrophic nanaoflagellates) were calculated based on information from GABRP Theme 2 dinoflagellate count data which were integrated through the water column depth and averaged across all eight stations in the central and eastern GAB shelf, upper slope, mid slope and offshore. The biomass was estimated to be 0.88 t.km^{-2}.

The P/B and Q/B values of 658 and 1441 for microflagellates were based on Pavés *et al.* (2013). They also had estimates for heterotrophic nanoflagellates of 710 & 1597. In the North Sea, Mackinson and Daskalov (2007) combined bacterioplankton and heterotrophic nanoflagellates into a planktonic microflora group with a P/B of 571 and Q/B of 1142. Diet was based on Tomczak *et al.* (2012).

Group 66. Pelagic bacteria

Estimated biomass of pelagic bacteria was calculated using data collected in GABRP Theme 2. The calculations used average volume per cell and wet weight conversion from C content per cell, which were depth integrated and averaged across 8 stations. AN enclosed sea model in the Chilean North Patagonian ecosystem was particularly focussed on representing microbial loop dynamics, Pavés *et al.* (2013) used a P/B of 794 and a Q/B pf 1249. Similarly, Mackinson and Daskalov (2007) represented microbial loop dynamics in the North Sea model and used a P/B of 571 and a Q/B of 1142. We found that the values for the North Sea model were less out of balance initially. We assumed that pelagic bacteria consumed only detritus.

Group 67. Farmed finfish

Southern bluefin tuna (SBT) farming began in 1991. Farmed SBT are mostly fed locally caught (in the SASF) or imported baitfish (e.g. from California, Chile or Peru), with 60,000 t distributed per annum (Harrison 2009). Aquaculture of SBT and finfish contributed well over half of the value of aquaculture production and about half of all seafood production in 2014/2015 (Econsearch 2016). Habitat area was estimated as the total area of the SBT licenced sites, which was 19 km^{-2}. Biomass

estimates and time series of SBT input into cages, and production out were provided by PIRSA Fisheries and Aquaculture and EconSearch reports online. The P/B was estimated as fished quota/harvest; Q/B was estimated as feed/fished quota less 1.3% feed lost to birds (Harrison 2009), and 1% lost to water column (Aguado *et al.* 2004, Forrestal *et al.* 2012).

Juvenile yellowtail kingfish (YTK) fingerlings are also dispatched into sea cages on farms to grow out to two different products of 1.5 and 4 kg independently (K. Rodda per comm.). Habitat area for these farms was estimated as the areas of sites used in YTK aquaculture (5 km^{-2}). Production figures were available from PIRSA Fisheries and Aquaculture. P/B was estimated as harvest/stock; Q/B as feed/catch.

The final combined biomass of 400.7 tonnes or was derived by bringing together the biomasses of farmed SBT and YTK with the habitat area assumed to be the combined total area of the SBT and YTK licenses used for production i.e. 0.000015 of the total GAB model domain. Biomass of fish farm feed was estimated as the total annual SBT feed for 2001 of 1.91 t km^{-2}, and P/B and Q/B were averaged across the two species resulting in 1.18 and 7.835 respectively.

Group 68. Shellfish aquaculture

The shellfish aquaculture group consisted of the moored [mussels, pacific oysters] and land land-based industries [abalone]. It occurs in a relatively minor portion of the GAB ecosystem i.e. only in 0.09% of the area. Together they contribute ~10% to the value of the total aquaculture in South Australia (Econsearch 2016). Mussels and abalone production is expected are to grow around 10% per year while that of oysters is neutral (Econsearch 2016).

3.3.7 Primary producers

Phytoplankton biomass estimates for EwE and Atlantis models

In the eastern GAB, coastal upwelling processes that occur during summer enhance primary production and lead to higher phytoplankton biomasses (Section 4.1.1, GABRP Theme 2.2 Report). This process is enabled by the ability of large phytoplankton to effectively utilise the nutrient enrichment resulting from upwelling processes and to outcompete small phytoplankton. In other words, in the eastern GAB, the classical food web pathway via diatoms and zooplankton, dominates during these periods. In contrast, the central GAB is not subject to upwellings and instead is predominated by year-round downwelling conditions. The central GAB communities are dominated by small phytoplankton, bacteria and viruses, leading to a slightly longer energy pathway known as the microbial loop.

Overall, monthly and climatological means indicated that periodically primary productivity in the eastern GAB may be much higher than that in the central GAB, where it is sporadic and more variable, more moderate but constant (Section 4.2.3, GABRP Theme 2.2).

The data we used to estimate phytoplankton biomasses in the GAB were collected during hydrographic surveys in the eastern and central areas of the GAB during the 2015 *RV Investigator* voyage between November 30 and December 15. The eastern GAB transect was sampled during November 30 - December 4 and the central GAB was sampled during December 10 -15. On each transect 4 stations were occupied: on the shelf (~90-100 m), upper slope (~400 m), mid-slope (~800 m) and offshore (3000-5000 m). The water column was sampled to 800 m in depths greater than 800 m or to near the bottom in shallower depths. Vertical profiles of temperature, salinity, fluorescence

and dissolved oxygen were taken at each station and seawater samples were collected at 3 depths for pigments, phytoplankton, zooplankton, and dissolved nutrients.

To estimate the standing biomasses of phytoplankton, we first converted the fluorescence profiles at each station to biomass using a fluorescence: chlorophyll$_a$ conversion determined for each profile and then integrated the values (for each m) to the depth at which fluorescence became negative; we then transformed these into phytoplankton biomass using chlorophyll$_a$: C ratio of 65 and a C: wet weight of phytoplankton (mg) of 20, i.e.:

B phytoplankton g/m^{-2} = Sum (fluorescence * profile conversion – offset) * 65 * 20 / 1000

Aggregate chlorophyll$_a$ profiles for different regions in the GAB are given in Figure 3.2 for reference purposes.

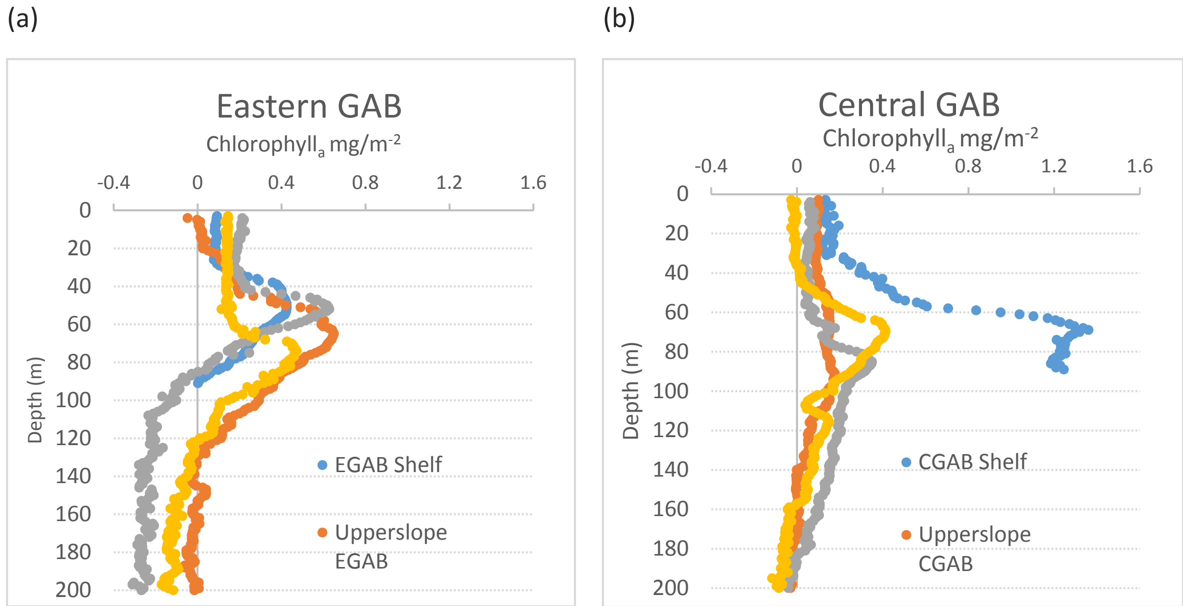


Figure 3.2. a) Eastern GAB (eGAB) chlorophyll profiles from fluorescence data, b) Central GAB (cGAB) chlorophyll profiles from fluorescence data.

We also compared an estimate from the *in situ* chlorophyll data to these calculated values to check for plausibility. These *in situ* chlorophyll values were taken at 3 depths of the vertical profile of each station. For each station, the total chlorophyll was estimated by assuming the value at the middle depth was the peak, and summing the integration of two triangles, one from the surface to the peak depth and one from the peak depth to the maximum depth sampled. This crude estimate of total water column chlorophyll was converted to phytoplankton biomass using chlorophyll$_a$: C ratio of 65 and a C: wet weight of phytoplankton (mg) conversion ratio of 20. The resulting estimates were largely consistent with those obtained by fluorescence except for the eastern GAB upper slope value, which was significantly higher using this method. Neither method was flawless, but the fluorescence curves were considered to be a more accurate representation of the water column chlorophyll$_a$ distribution.

The total phytoplankton determined by the fluorescence method at each of the 8 stations was then apportioned to small and large sizes using the *in situ* chlorophyll$_a$ data i.e. < or > 5 μm. The large

phytoplankton component from the central GAB shelf station was far greater than at any other site on either transect. The proportion of small to large phytoplankton was about 1:2 compared to a range of 3:1 to 1:0 at the other stations, i.e., large phytoplankton were never observed to be the dominant component of the phytoplankton except at the shelf central GAB station. Furthermore, annual primary productivity by size fraction shows that the vast majority of productivity, 100-300 mg C $m^{-2}d^{-1}$, occurred in the < 5 µm autotrophic fraction (small phytoplankton) from shelf to offshore, whereas the only significant contribution from the > 5 µm autotrophic fraction (large phytoplankton) of ~100 mg C $m^{-2}d^{-1}$ occurred on the shelf in the central GAB (Figure 4.2-4, GABRP Theme 2.2). The current hypothesis for the anomalous central GAB shelf is that it is a result of a "hybrid" foodweb in action where recycled nitrogen from an unknown origin but could be atmospheric, on the central GAB shelf is contributing to a higher productivity in the diatoms (GABRP Theme 2.2). The average of small phytoplankton biomasses at each station, except the shelf central GAB value, was 25.08 t.km^{-2} and that of large phytoplankton was 3.20 t.km^{-2} (Table 3.11). If the central GAB shelf phytoplankton is included in the calculation, the results are 25.21 and 8.03 t.km^{-2} for small and large phytoplankton biomass respectively (Table 3.11).

Table 3.11. Estimates of total water column phytoplankton biomass at each station on the central and eastern GAB transects and apportioned into small and large fractions according to fluorescence data.

Transect	Site	Integrated phytoplankton biomass (tkm^{-2})	Small	Large
Central GAB	Shelf	67.96	26.12	41.84
	Upper slope	18.27	17.65	0.62
	Mid slope	30.09	22.81	7.27
	Offshore	20.71	20.10	0.60
Eastern GAB	Shelf	24.50	24.50	0
	Upper slope	45.37	44.88	0.48
	Mid slope	28.66	21.21	7.45
	Offshore	30.37	24.40	5.97
	Average (excluding CGAB shelf)	28.28	25.08	3.20
	Average of all stations	33.24	25.21	8.03

Group 69. Large phytoplankton

The estimate of large phytoplankton biomass in the GAB ecosystem across all stations was 8.02 or 3.2 tkm^{-2} if the anomalous central GAB shelf station was excluded (Table 3.10). A P/B of large phytoplankton production was calculated from the average daily integral primary productivities in the Great Australian Bight in the euphotic zone across all stations from the shelf to offshore stations (Figure 4.2-4 in Theme 2 report) of ~25 mg C m^{-2} d^{-1}. The annual production was estimated to be 182.5 g/m^{-2}. Therefore, the P/B was estimated to be 57.04 assuming an average biomass of 3.2 or 22.7 assuming biomass of 8.02 tkm^{-2}.

Group 70. Small phytoplankton

Small phytoplankton comprised the fraction of phytoplankton <5 µm and included autotrophic picophytoplankton and small nanophytoplantkon. An estimate of the small phytoplankton biomass was made from the data collected during surveys in early summer of 2015 (GABRP Theme 2.2

Report). The estimate from across all stations occupied of 25.21 tkm^{-2} was little different from 25.08 tkm^{-2} the value if the anomalous central GAB shelf station was excluded (Table 3.10). Total production was estimated from the average daily integral primary productivities in the Great Australian Bight in the euphotic zone across all stations from the shelf to offshore stations (Figure 4.2-4 in Theme 2 report) of 226 mg C m^{-2}y-^{1}. Using an average of the biomass estimates, P/B was therefore estimated to be 65.61.

Group 71. Microphytobenthos

Microphytobenthos comprised benthic bacteria and benthic heterotrophic microflagellates. Estimates of 0.5 t km^{-2} were used from the Spencer Gulf EWE Model M. Doubell (SARDI). Biomass was estimated only in the gulf areas which accounted for 1% of the total GAB model domain. We used the P/B estimates of 706.5 for microphytobenthos from the Jurien Bay model of Lozano *et al.* (2011). Other estimates of P/B and Q/B estimates were 541 and 700 from an enclosed sea model in the Chilean North Patagonian ecosystem (Pavés *et al.* 2013) and 9470 and 18940 in the North Sea model of Mackinson and Daskalov (2007). The latter considered that a growth efficiency around 50% and respiration around 30% was reasonable. Diet was based on that of benthic microflora in the North Sea model of Mackinson and Daskalov (2007): their diet was 20% cannibalistic i.e. microflagellates that consume bacteria and 80% from particulate or dissolved organic matter (POM, DOM) Mackinson and Daskalov (2007) included POM and DOM in the water column detritus and sediment detritus groups respectively. In GAB model, we had only one detrital functional group and considered DOM and POM to be included implicitly, therefore this group was deemed to consume detritus rather than explicitly POM and DOM.

Group 72. Seagrass

Seagrass communities in the study area are comprised of members of the families Zosteraceae, Posidoniaceae, Hydrocharitaceae, and Magnoliophyta and dominated by *Posidonia* species (Kirkman 1997). Estimated biomass of seagrass per unit of habitat area was 12,749 t km^{-2}, and production per unit was 31,000 t km^{-2} yr^{-1} (Gillanders *et al.* 2015) therefore P/B was estimated to be 2.43.

Group 73. Macroalgae

Biomass and productivity estimates for macroalgae were derived from studies of *Ecklonia radiata*, a habitat-forming macrophyte in Spencer Gulf (Gillanders *et al.* 2015). Using the mean depth of surveyed macroalgae habitat (10 m), a density of ~13 *E. radiata* m^{-2} was assumed based on Kirkman's (1989) depth-density relationship. The mean dry weight of a single plant is 99 g (Larkum 1986), leading to an estimated biomass of 1.29 kg dry wt m^{-2} (or 1 290 t dry wt km^{-2}). A review of productivity estimates for *E. radiata* provided an average value of 3.58 kg dry wt m^{-2} (or 3 586 t dry wt km^{-2}) (Novaczek 1984, Larkum 1986, Kirkman 1989). Using these estimates of biomass density and productivity for seagrass and macroalgae, and assuming that dry weight for these groups equates to 10 % of wet weight (Duarte & Kirkman 2001) , total biomass for seagrasses and macroalgae within Spencer Gulf was estimated to be 12915.13 t km-2 . A ratio of annual productivity to biomass was derived for both groups to inform the ecosystem modelling. Production was assumed to be 35,862 t km^{-2} yr^{-1}, and therefore P/B was calculated to be 2.78.

Group 74. Discards

This group accounts for discarded fish from fisheries in the model area. Fate of the discarded components of landings varies between fisheries. The total of discards across all fisheries calculated from the fisheries catch statistics and estimates was 0.4 t km^{-2}.

Group 75. Detritus

No biomass estimates of detritus were available for the GAB and so a nominal value of 200 t km^{-2} was used based on 100 tkm^{-2} in the East Bass Strait model (Bulman *et al.* 2006), 390 t km^{-2} in the West Florida Shelf (Okey & Mahmoudi 2002) and a similar value off Newfoundland (Bundy 2001).

3.1 Balanced model

The basic parameters used to inform the 75 functional groups within the *Ecopath* model are presented in Table 3.12. Balancing the model required adjustment to parameters or diets of groups where ecotrophic efficiencies (EE) were initially >1. EE is the proportion of production that is used in the system i.e. either passed up the food web via predation, used for biomass accumulation, migration or exported (Christensen and Walters 2004). Ecotrophic efficiency varies between 0 and 1. It will approach 1 for groups with high predation pressure and 0 for groups with no predation, fishing pressure or migration. If it exceeds 1 for one or more groups, the model is unbalanced because more production is leaving the system than is being produced. To balance the GAB model, many iterative adjustments were made: most were slight changes to dietary proportions, while others were changes to biomass (B), production (P/B) or consumption rates (Q/B) and are indicated in Table 3.12. Some changes particularly to biomass estimates were quite large but given that few of the biomass estimates were targeted for this model domain, it was considered justifiable if within reasonable bounds for current knowledge of this or similar ecosystems.

Table 3.12 Final balanced GAB model parameters. Where parameters were changed, initial values are in parentheses. Model–estimated values are in red.

Group name	Trophic level	Habitat area (fraction)	Biomass in habitat area tkm^{-2}	Biomass tkm^{-2}	P/B y^{-1}	Q/B	EE	P/Q
Baleen whales	4.28	0.99	0.0076	0.0076	0.020	5.10	0.00	0.00
Toothed whales	5.42	0.98	0.1353	0.1331	0.020	5.65	0.00	0.00
Bottlenose dolphins	5.01	0.25	0.0142	0.0035	0.080	18.99	0.47	0.00
Common dolphins	5.05	0.20	0.0434	0.0087	0.090	20.58	0.56	0.00
Long-nosed fur seal	4.83	0.63	0.0023	0.0015	1.184	47.53	0.14	0.02
Australian fur seal	4.77	0.02	0.0800	0.0015	1.157	34.93	0.01	0.03
Australian sea lion	4.88	0.16	0.0042	0.00065	(0.79) 0.892	29.44	0.23	0.03
Albatross	5.25	1.00	0.00011	0.00011	1.000	70.54	0.07	0.01
Shearwaters	4.91	1.00	0.00218	0.00218	1.000	150.96	0.02	0.01
Small petrels	4.37	1.00	0.00003	0.00003	1.000	639.97	0.34	0.00
Gannets	5.05	0.19	0.000010	0.000002	1.000	138.95	0.68	0.01
Terns	4.84	0.19	0.000007	0.000001	0.050	86.75	0.97	0.00
Shags and cormorants	4.34	0.19	0.000014	0.000003	1.000	77.40	0.07	0.01
Gulls	4.00	0.14	0.000014	0.000002	1.000	80.36	0.56	0.01
Little Penguins	4.93	0.12	0.00009	0.00001	1.290	85.64	0.96	0.02

Group name	Trophic level	Habitat area (fraction)	Biomass in habitat area tkm^{-2}	Biomass tkm^{-2}	P/B y^{-1}	Q/B	EE	P/Q
Shelf pelagic sharks	5.32	0.40	0.021	0.0084	0.130	2.61	0.99	0.05
Offshore pelagic sharks	5.58	0.80	0.003	0.0024	0.200	1.20	0.05	0.17
Shelf demersal piscivorous shark	5.27	0.20	0.3508	0.0702	0.470	2.60	0.11	0.18
Shelf demersal sharks	4.14	0.30	0.024	0.0072	(0.17) 0.188	1.32	0.15	0.14
Deep demersal sharks	5.19	0.80	0.78	0.624	0.160	3.30	0.00	0.05
Skates and rays	3.69	0.30	0.2196	0.0659	0.418	1.76	0.06	0.24
Southern Bluefin Tuna	5.03	0.70	0.012	0.0084	0.485	3.65	0.93	0.13
Tunas and billfish	5.59	0.60	0.05	0.03	0.600	6.20	0.40	0.10
Offshore pelagic piscivores	5.15	0.80	1.098	0.878	0.184	2.33	0.90	0.08
Offshore pelagic invertivore large	4.97	0.80	0.545	0.436	0.205	2.03	0.90	0.10
Shelf large pelagic piscivores	4.64	0.30	0.29	0.087	0.271	3.10	0.98	0.09
Sardine	3.63	0.20	1.717	0.343	1.6	5.04	0.87	0.32
Shelf pelagic planktivore small	4.15	0.20	1.67	0.334	(1.01) 1.560	(7.3) 10.50	0.82	0.15
Mackerels	4.08	0.30	9.239	2.772	(0.33) 0.420	(3.10) 3.18	0.95	0.13
Redbait	3.82	0.30	1.957	0.587	0.360	3.90	0.95	0.09
Shelf small demersal piscivores	3.39	0.30	1.017	0.305	0.552	4.46	0.95	0.12
Shelf small demersal omnivores	3.43	0.30	9.3	2.79	0.662	5.72	0.95	0.12
Shelf large demersal piscivores	4.33	0.30	2.564	0.769	0.325	3.11	0.95	0.10
Shelf large demersal omnivores	3.09	0.30	0.803	0.241	0.389	3.57	0.95	0.11
King George whiting	3.81	0.20	0.073	0.015	0.548	2.29	0.92	0.24
Garfish	2.70	0.20	0.343	0.069	0.329	4.73	0.98	0.07
Snapper	3.84	0.30	0.208	0.063	0.150	2.90	0.29	0.05
Deepwater flathead	4.46	0.30	0.277	0.083	0.200	2.80	0.95	0.07
Bight redfish	4.20	0.30	0.617	0.186	0.370	2.90	0.95	0.13
Migratory mesopelagics	3.82	0.80	11.150	8.920	(0.68) 1.65	6.00	0.98	0.28
Non-migrating mesopelagics	4.66	0.70	2.331	1.631	(1.01) 1.65	6.67	0.99	0.25
Slope small demersal invertivores	3.84	0.80	1.827	1.462	0.570	4.28	0.95	0.13
Slope small demersal piscivores	4.41	0.80	0.370	0.296	0.420	3.50	0.95	0.12
Slope large demersal piscivores	5.07	0.80	0.687	0.55	0.242	2.54	0.95	0.10
Slope large demersal invertivores	4.66	0.80	0.342	0.273	0.340	3.55	0.95	0.10
Benthic grazers	2.18	0.30	2.82	0.846	(6.0) 0.39	(4) 1.3	0.98	0.30
Abalone	2.00	0.04	0.125	0.005	0.73	(12.41) 2.5	0.89	0.29
Benthic detritivore	2.66	1.00	35.086	35.086	(5.00) 0.9	(32) 3	0.95	0.30
Benthic carnivores	3.01	1.00	6.281	6.281	(2.00) 1.0	(22) 3	0.97	0.33
Meiobenthos	2.00	1.00	6.137	6.137	35	125	0.19	0.28
Shelf filter feeders	2.00	0.20	112.836	22.567	(1.6) 0.260	(6) 1.50	0.95	0.17
Deep filter feeders	2.00	0.80	5.931	4.745	(2.8) 0.260	(5) 1.50	0.05	0.17
Shelf macrozoobenthos	3.00	0.20	161.0	32.20	(2.8) 0.400	(14) 2.67	1.00	0.15
Squid & cuttlefish shelf	4.55	0.20	0.387	0.0774	1.825	18.25	0.99	0.10
Octopus shelf	4.06	0.20	0.199	0.0398	2.370	7.90	0.96	0.30
Rock lobster	2.93	0.10	0.0872	0.0087	0.730	12.41	0.31	0.06
Western king prawn	2.38	0.20	0.5706	0.1141	7.570	37.90	0.58	0.20
Crabs & bugs	2.88	0.20	0.686	0.137	2.800	8.50	0.42	0.33
Deep macrozoobenthos	2.92	0.80	16.955	13.564	2.800	8.50	0.40	0.33
Deep squid	4.78	0.80	0.967	0.773	(1.8) 2.240	(10) 8.00	0.98	0.28
Gelatinous zooplankton	3.40	1.00	1.5	1.5	(64.9) 4.858	(218.5) 13.88	0.89	0.35

Group name	Trophic level	Habitat area (fraction)	Biomass in habitat area tkm^{-2}	Biomass tkm^{-2}	P/B y^{-1}	Q/B	EE	P/Q
Large zooplankton	3.28	1.00	9.948	9.948	(5.37) 6.5	(17.58) 17.00	0.98	0.38
Mesozooplankton	2.58	1.00	4.386	4.386	28.840	82.00	0.72	0.35
Microzooplankton	2.49	1.00	21.346	21.346	46.030	(131.37) 121.3	0.25	0.38
Nanozooplankton	2.60	1.00	0.881	0.881	(658) 570	1441.00	0.85	0.40
Pelagic bacteria	2.00	1.00	2.42	2.42	(570) 600	(1142) 975	0.98	0.62
Microphytobenthos	2.11	0.01	0.5	0.005	(541) 706	1412	0.98	0.50
Farmed finfish	1.00	0.00	400.7	0.006]	(1.61) 1.18	(11.74) 7.84	0.00	0.15
Farmed oysters	2.16	0.00	0.01]	0.00001	0.650	6.00	0.00	0.11
Large phytoplankton	1.00	1.00	3.2	(3.2) 6.4	(570) 124		0.40	
Small phytoplankton	1.00	1.00	25.08	25.08	73.000		0.96	
Seagrass	1.00	0.01	12748.82	165.735	2.430		0.00	
Macroalgae	1.00	0.00	12915.13	7.75	2.780		0.14	
Discards	1.00	0.40	0.4	0.160			0.00	
Detritus	1.00	1.00	200	200			1.00	

The foodweb of the GAB ecosystem model showing trophic flows between the functional groups and the trophic levels as estimated by *Ecopath* is depicted in Figure 3.3. The GAB ecosystem supports many iconic and high trophic level species such as sharks, marine mammals and birds, and whales. It is also home to a range of commercially important species ranging throughout the trophic levels such as a proportion of the global SBT population and other tunas and billfishes at the highest level; deepwater flathead, orange roughy and oreo dories, bight redfish, and mackerels at trophic level 4; King George whiting, snapper, small pelagics such as sardines and redbait at trophic level 3; rock lobster, prawns and abalone at trophic level 2. The GAB ecosystem also contains the two gulfs which largely support aquaculture and the inshore fisheries targeting some of the species previously mentioned. The gulfs are dominated in terms of biomass by macroalgae and seagrass and which account for the large overall biomasses in the model. However, these producers are not the dominant drivers in the system: small and large phytoplankton tend to drive the dynamics of this system.

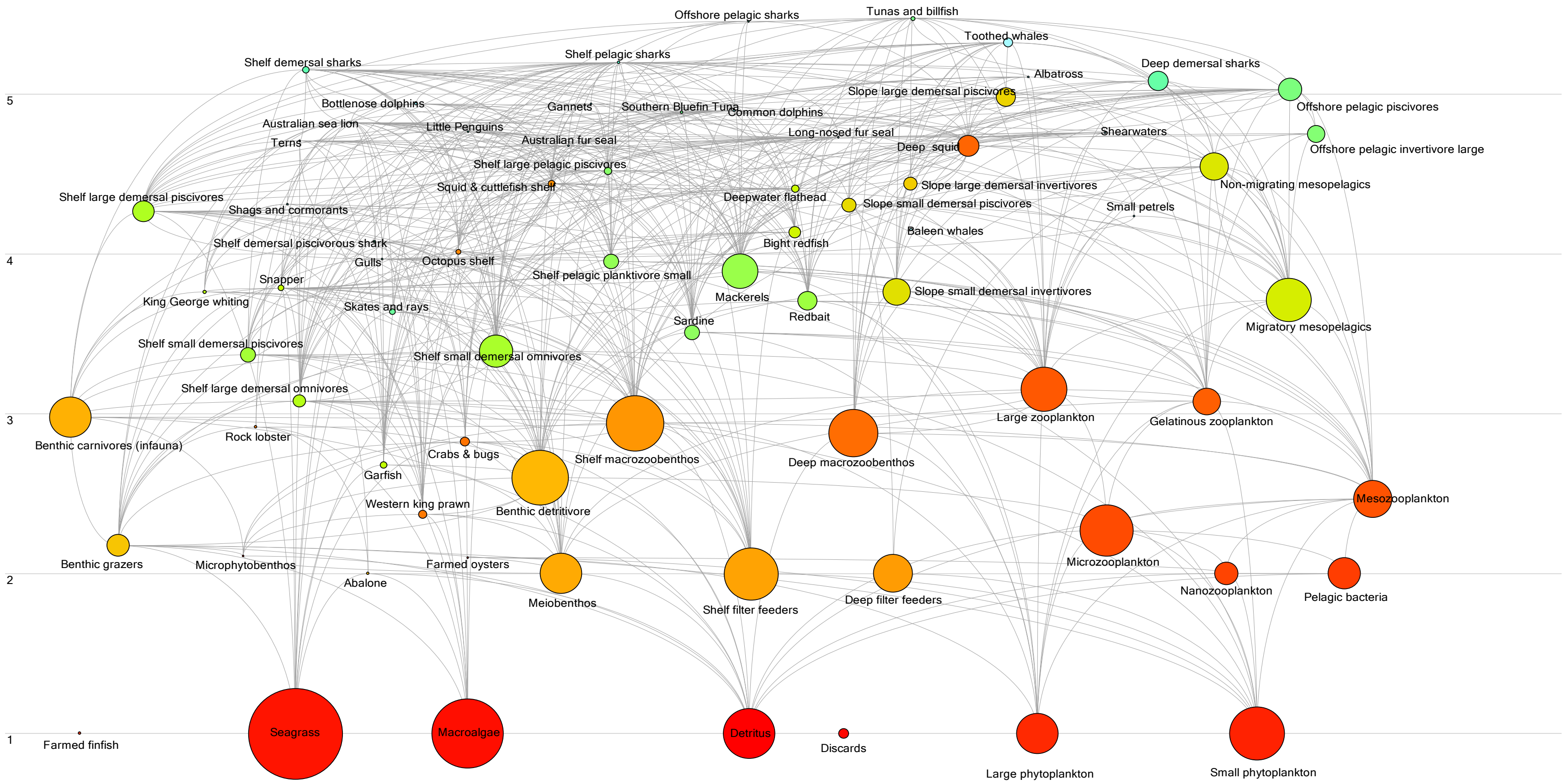


Figure 3.3. Flow diagram expression of the trophic flows between functional groups in the GAB ecosystem. Trophic levels are on the y axis, the x-axis groups are arranged to allow the best visual representation of the foodweb. Functional groups are represented by a circle; the size of the circle is proportional to its biomass and the colour of circles is unrelated to any parameter.

3.2 Model fitting to time series (Ecosim)

Time series of annual catch and catch per unit-effort (CPUE) derived from fishery logbook data were calculated for commercially fished groups, and estimates of biomass (stock assessments or modelled fishable biomass) and/or fishing mortality (F) were also included where available. The only non-fishery related times series included were for three pinniped species where trends in pup production were used to estimate change in population biomass within the GAB region over time. Further details on the time series used in the GAB ecosystem model are presented in Appendix 7.

Time-series of biomasses and catches were loaded into Ecosim and an optimisation (fitting procedure) was run to modify the Ecosim predator vulnerability parameters to achieve the best model fit possible (based on model sum of squares (SS)). The vulnerability parameters change the degree to which a predator in the model can impact its prey by setting the exchange rate of between vulnerable and invulnerable proportions of the prey population. This concept is based on the foraging arena theory (Walters *et al.* 1997) and represents the "trophic control" of the predator-prey dynamics. For example, if an increase in biomass of a predator has a large influence on the predation mortality of its prey then it is considered to be "top-down" controlling and the vulnerability parameter would be high. On the other hand, if predator abundance increases had little influence on predation mortality of its prey, and in fact prey abundance has greater influence on the predator, then control is "bottom –up" and the vulnerability parameter on the prey would be low (<1). Vulnerabilities are one of the key parameters to determine based on observed data. Sensitivities were searched for groups with time series only and optimised, resulting in vulnerabilities that resulted in a better fit of the model predictions to the observed data. Following this procedure, some of the default Ecosim parameters were also adjusted to further improve model fit (decreasing the model SS).

In this version of the model, we adjusted the relative feeding time of marine mammals to 0.5 (0 for all other groups), to account for modifications to their search feeding times in response to changes in prey availability (Christensen *et al.* 2008). There are other factors such as density-dependent predator-prey switching power of the dolphin and seal groups in response to changes in prey availability and density-dependent changes in catchability for pelagic schooling fish such as sardines (Christensen *et al.* 2008, Piroddi *et al.* 2010) which we were unable to explore fully.

Examples of the final model fits are provided in Figure 3.4. While the model was unable to fit to some of the short timescale variability in CPUE or biomass, e.g. for the commercial species such as bight redfish, deepwater flathead and snapper, it usually reproduced the general trends in the catches well. While the model could be forced to fit some of the environmental stochasticity more closely via the use of forcing time series (similar to fitting recruitment time series in stock assessments) this would not greatly benefit its use for exploring broad scale scenarios where those forcing time series are unknown. In terms of the use of the model as a basis for scenario exploration, some components of the model would benefit from calibration to longer time series for the reasons discussed immediately below. Nevertheless, even without further calibration, the model's capacity to reproduce observed time series for the majority of species where such information is available means it is fit for purpose – i.e. it is appropriate to use it as a basis for exploring broad scenarios.

The three species for which some explanation of the fit is required are snapper, bight redfish and deepwater flathead. In each case the failure is due to the short time series used to calibrate the model, along with the variability and uncertainty in the time series. For snapper, the biomass time series was derived as an aggregate of a complicated suite of estimates from stock assessment

models across several stocks (Fowler *et al.* 2016). The stock assessment-derived series of increasing biomasses were in direct contrast to the declining trend in the empirical data e.g. Spencer Gulf/West coast, while the trends for stocks reliant on recruitment from Port Philip Bay , e.g. South East coast and the Gulf St Vincent stocks, were sustainable but recently declining (Fowler *et al.* 2016). Therefore, the lack of fit of the EwE model biomass estimates to the time series was considered misleading. Furthermore, the model-predicted catches fitted the empirical catch data quite well (Fig 3.4) suggesting that the predicted slight decline in biomass of snapper, might be a better overall representation of the stock.

The difficulty of the model to capture bight redfish dynamics is less obvious until the history of the stock depletion since the late 1980s is taken into account. Around the mid-2000s the fishery peaked with 10 vessels operating and nearly 1000 t per year taken, but by the start of the model period this had declined quite quickly to about one-third of the peak effort and catch (Haddon 2015). Not accounting for higher initial biomasses by fore-shortening the time series hampered the ability of the model to fit to the declining trend.

Similarly, for deepwater flathead the historical period of the fishery – from the late 1980s and through its peak in the 2000s – is not being accounted for in the model fitting and dynamics with only the input of the short time series from the Fishery Independent Surveys (FIS) (Knuckey *et al.* 2015). The FIS trend showed a large decline (Fig 3.4) but the EwE model predicted a small increase in biomass. However, Haddon (2016) compared the FIS time series with standardised CPUE data from Sporcic and Haddon (2016) and found that the initial FIS estimate for 2006 was greater than the CPUE-predicted spawning biomass while the final FIS estimate (interspersed with missing data) was highly uncertain and much lower. In fact, the CPUE predicted female spawning biomass for the time period of our model parameterisation rose slightly from 2006 to a peak at 2012 before a slight decline (Haddon 2016). While EwE model doesn't exactly capture the shape of Haddon's trend either, the overall trend of a slight increase is the best statistical fit and results in a fairly good fit for catch time series.

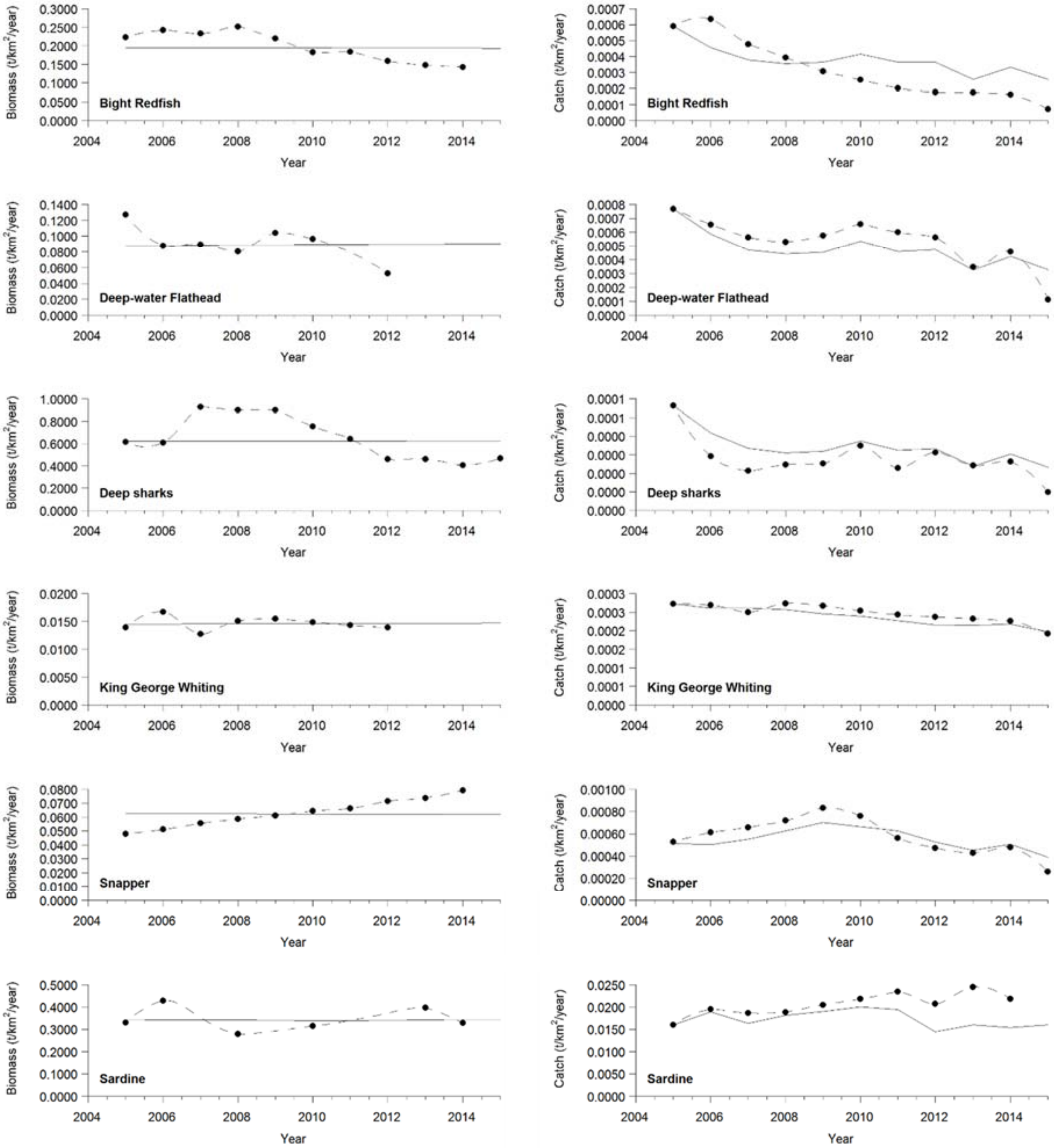


Figure 3.4. Example of time series fits of the GAB ecosystem model (thin line) to observed biomass (CPUE) and catch (dots and dashed trend line) data for six key commercial groups between 2005 and 2015).

3.3 Temporal changes in GAB ecosystem

3.3.1 Trends in biomass-*Status Quo*

The *Status Quo* scenario was the base or key run where the simulation for the first ten years was driven by actual effort in the fisheries followed by 40 years of projection at the constant exploitation rate (as of 2016). This Status Quo scenario was the simulation against which we could compare outcomes of the various scenarios undertaken in Section 5. The relative change in functional group biomasses between 2006 and 2015, estimated by the GAB ecosystem *Ecosim* model, are presented in Figure 3.5. The greatest changes were a near doubling of SBT, and increases of between 60% and 30% of two slope demersal groups, demersal sharks and abalone (Fig 3.5a). There were more large declines, i.e. >30%, observed than increases: on the shelf large pelagic piscivores, demersal sharks, garfish, snapper, rock lobster and gannets declined, and in the deeper habitats, offshore pelagic sharks and large demersal piscivores declined. Amongst the invertebrates, abalone increased the most (Fig 3.5b).

The overall trends in absolute biomass of the entire system were somewhat variable, but resulted in an overall but small decline. But more than half of the biomass of the system is invested in lower trophic groups, e.g. plankton, detritus, so by excluding those groups and the aquaculture species and discards, there was a very small overall increase of the remaining species (~5%)(Fig 3.6). There is relatively little change and low overall variability.

Absolute biomasses of species were often very small, and consequently small changes at an ecosystem-level perspective appeared large from the species-level perspective. Variations in catch follow the variation in biomass as expected given a constant fishery effort.

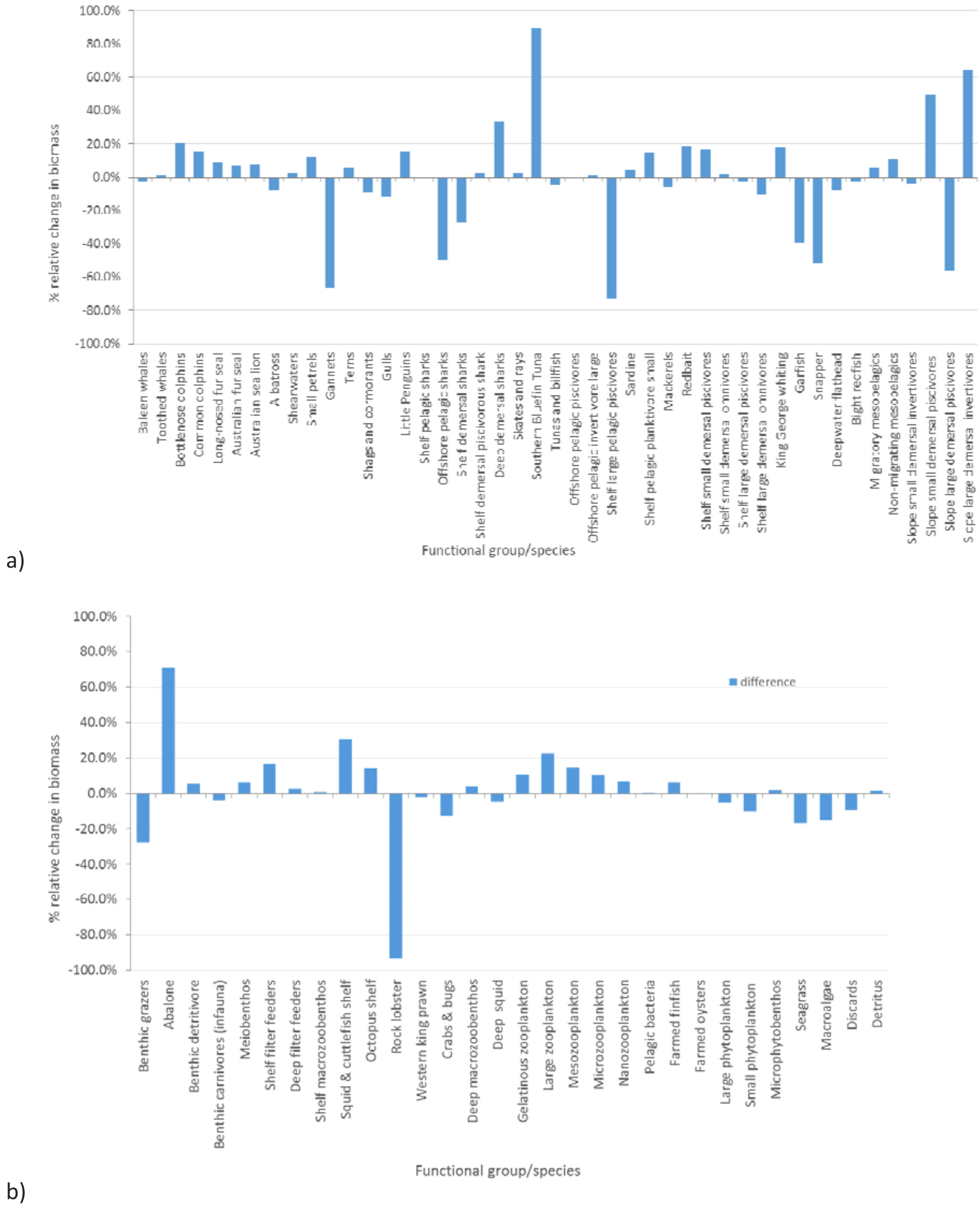


Fig 3.5. Relative changes (%) in biomass of a) vertebrates and b) invertebrates - the Status Quo scenario.

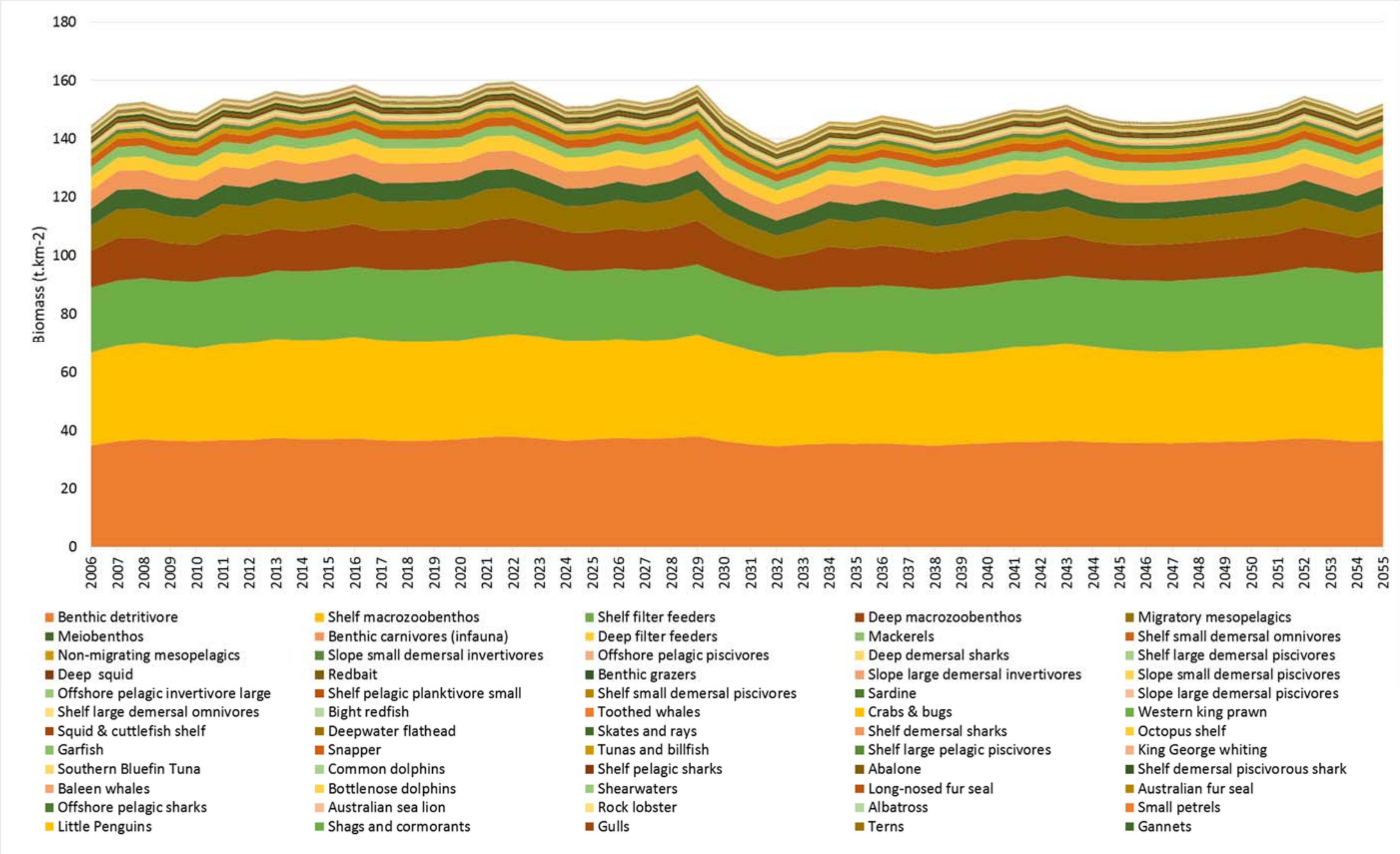


Figure 3.6. Changes in Status Quo scenario biomasses (t.km-2) of all functional groups and species (excluding plankton, detritus and aquaculture groups) from 2006 to end of projection period 2055. Status Quo scenario: actual exploitation rates were used until 2016 beyond which the 2016 rate was fixed for the rest of the projection. The plot is ordered from the greatest overall biomass (benthic detritivores) to the smallest (gannets) (t.km-2).

3.3.1 Trends in catch-*Status Quo*

The *Status Quo* scenario was driven by actual effort in the fisheries initially, followed by 40 years of projection at the constant exploitation rate (as of 2016). The fleets whose catches declined the most were the rock lobster fleets followed by nearly all other fleets (Fig 3.7). The fleets that had the biggest increased catches by the end of the 50-year scenario assuming a constant effort into the future were the Commonwealth Danish seine, Victorian scalefish and Victorian pot fisheries (Fig 3.7), but, all had very small values of catch in 2006 and so very little extra catch by weight would appear as a large relative change.

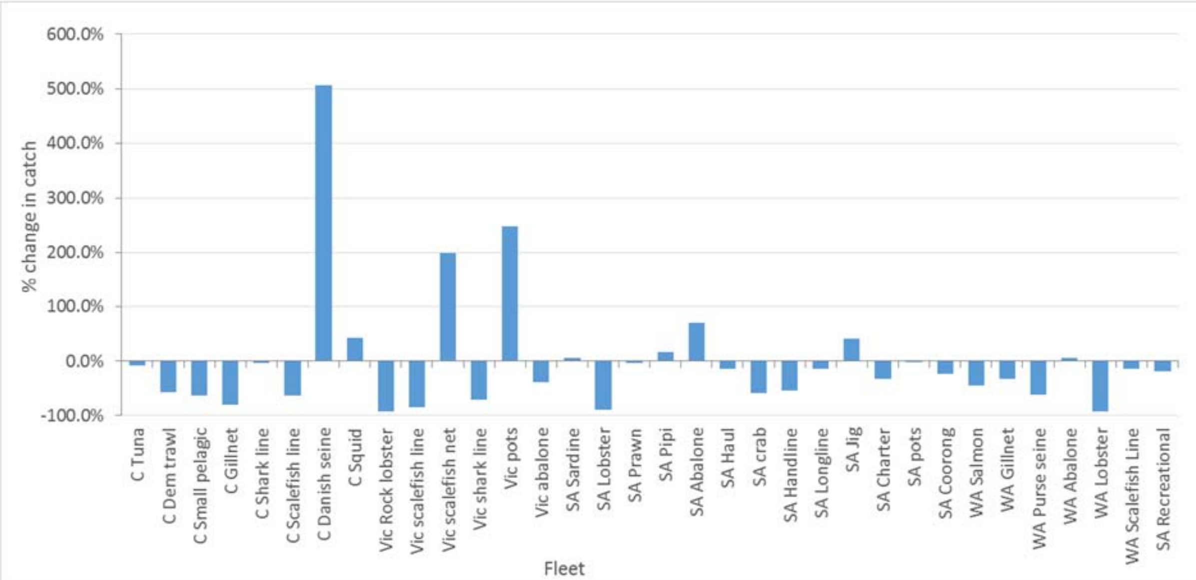


Figure 3.7 Relative changes (%) in catches for fleets calculated over the period 2006-2016 (Status Quo scenario).

Consequently, the catches per functional group or species also reflected these fleet changes. Overall, there was a decline of about 16% in catches across all species over the whole projection period, but most of that decline occurred during the first decade for which we used the historical fishery effort, with only a few per cent difference by the end of the fore-cast period (Fig 3.8). In other words, given this scenario's assumption of constant fishing efforts in the forecast period, the decline in catches must be as a result of changes in biomasses of species.

Catches of species groups from rock lobster through crabs and bugs (depicted in Fig 3.8 as the 27 groups on the bottom of the graph and top of legend), declined by more than 20% over the entire simulation period. Decreases of 95% were predicted for rock lobster catches while catches of other species targeted by the majority of the fleets decreased overall by 26% to 82%. Most of these decreases occurred during the first decade of the model simulation when actual fleet efforts were being used and the catches were as observed (Fig 3.8). During the forecast period, however, rock lobster, catches remained stable for another decade before declining to a low level at the end of the projection period, and appears to be a result of fishing mortality rather than a consequence of predation or other food-web interaction effects.

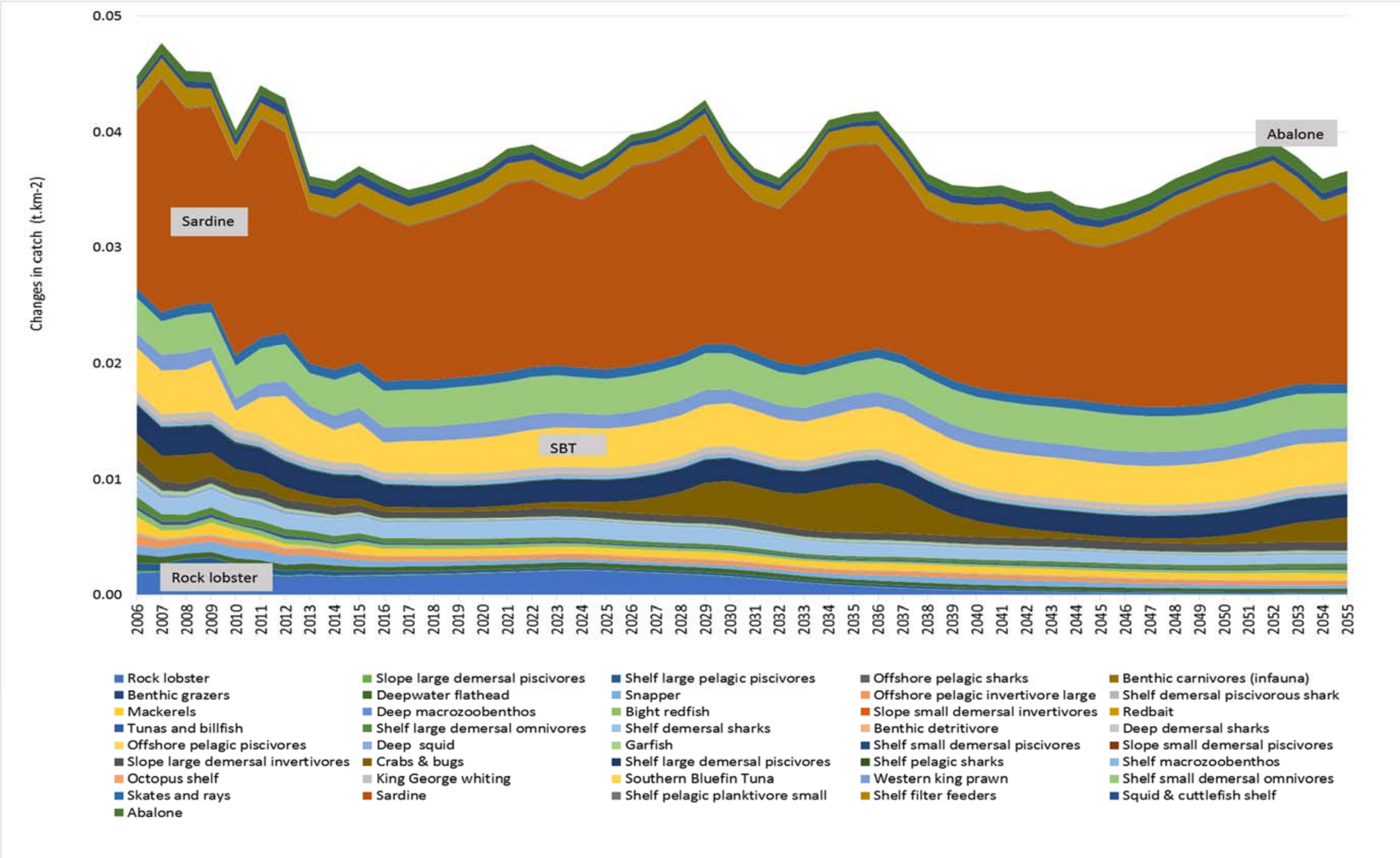


Figure 3.8. Changes in EwE Status Quo scenario catches (t.km-2) of all species across all fleets from 2006 to end of projection period 2055. Status Quo scenario: actual exploitation rates were used until 2016 beyond which the 2016 rate was fixed for the rest of the projection. The plot is ordered from the greatest overall negative change (rock lobster) through to the greatest positive change overall (abalone) reading legend from left to right across columns.

At the time where rock lobster catch began to decline, crabs and bugs catches began to increase and their catches fluctuated more noticeably than any other groups throughout the whole period, but resulting in an overall 20% increase.

Catches of several of the most important commercial species such as sardine and SBT did not vary greatly, only 4% increase and 4% decrease respectively. Catches of King George whiting and western king prawns were also only a few percent different. While the relative change in catch of some of these species might be small, the absolute catches of sardine and tuna are quite large and represent a significant proportion of the commercial catch in the GAB. However, interpretation of these trends need to be viewed cautiously. Sardine is dependent on seasonal primary productivity of the region although the species can recover from severe setbacks quickly as exhibited by its recovery from the viral pathogen outbreaks (and see Scenarios in Section 5). SBT is entirely dependent on reproduction and recruitment processes, and adult mortality occurring outside the model domain. Our focus was not fully account for SBT stock dynamics external to the model domain and therefore Status Quo scenario results for SBT should be viewed with caution. However, in the scenarios we investigate later in Section 5, we address and incorporate potential effects of variability due to climate-induced changes in seasonality (directly on phytoplankton), sardine response to pathogen and changes in stock recruitment of SBT through forcing functions that approximate hypothetical responses of the relevant species.

3.3.2 Conclusion

While the Status Quo scenario projection of constant 2016 fishing effort, is relatively stable for most species, there are some obvious species whose dynamics are highly uncertain e.g. for rock lobster and other invertebrate groups. To some extent, this uncertainty can be attributed to lack of complete data sets, however, the difficulty of representing spatial attributes of the species such as stock structure and cross-jurisdictional differences across common stocks in this version of the model is also likely contributing to the patterns seen.

Nevertheless, our objective was not to exactly match the nuances of each commercial stock and its management, but to build a model that would provide an overall ecosystem–level perspective of the possible broad-scale consequences of fishing activity, climate changes, and threats to ecosystem function via pathogen or oil exploratory activities in the GAB. This was to be done as faithfully as possible to the standard EwE implementation procedures so as to provide a robust contrasting view to that provided by the Atlantis ecosystem model. Comparison of scenario outcomes across a variety of model platforms as a way of cross-checking information that ultimately might be used to inform management decision-making (in a strategic broad scale sense not in a tactical annual quota-setting sense), is becoming more common in natural resource management and planning (e.g. Smith *et al.* 2011, Tittensor *et al.* 2017).

4. AN ATLANTIS ECOSYSTEM MODEL FOR THE GREAT AUSTRALIAN BIGHT: DEVELOPMENT AND PARAMETERISATION

4.1 Atlantis Introduction

Whole-of-system, or end-to-end, ecosystem models such as Atlantis incorporate both higher and lower trophic levels as well as biological parameters, hydrodynamic features and fisheries and socioeconomic components (Fulton 2010). They typically include environmental drivers, habitats, the food web, and major human uses. Because of this they can allow more comprehensive investigations into the functioning of marine ecosystems under various environmental conditions or resource management regimes. They also provide insight into the linkages and processes that occur in both natural and perturbed marine systems, beyond that which can be gained from studying a single species or impact.

Atlantis is a whole-of-system model commonly developed by marine scientists to increase understanding of system dynamics and strategically inform resource managers (Fulton *et al.* 2011). It has been recognised as one of the best whole-of-system models in the world (by the UN FAO) for considering the ecosystem implications of exploitation of marine resources. This recognition is largely because it is spatially explicit, age and size structured and comprised of sub-models that explicitly simulate biogeochemical cycling at one end or the ecosystem and human impacts and management at the other. At the time of its initial development it was one of very few models with this degree of ecosystem process coverage. It has been used to model more than 30 systems round the world, spanning polar, temperate and tropical and from small estuaries to large ocean regions (Weijerman *et al.* 2016b, Audzijonyte *et al.* 2017). While Atlantis should not be used for tactical short-term advice, such as setting quotas, it is well suited to consideration of broader scale strategic and exploratory analyses. That is, “what if” scenarios, general evaluation of management strategies, and other questions that draw on its ability to simulate multiple interactions between environmental factors, different marine species and humans (Fulton *et al.* 2011).

The Atlantis modelling approach has provided important insights for managers when making natural resource management decisions particularly in context of ecosystem-based management (EBM). In Australia, the Atlantis modelling framework has been used to explore ecosystem complexity (Fulton *et al.* 2007b), fisheries management (Smith *et al.* 2011), nutrient loading in catchment areas (Savina *et al.* 2008) and multiple use issues for commercial harbours (Fulton *et al.* 2017). Atlantis continues to be used to complete system level Management Strategy Evaluation (MSE) for the Australian Commonwealth Fisheries (e.g. the Small Pelagic Fishery and the Southern and Eastern Scalefish and Shark Fishery); where it has helped consider trade-offs inherent in alternative management scenarios (Fulton *et al.* 2007b, Fulton *et al.* 2014, Smith *et al.* 2017) and the efficacy of tiered harvest control rules (Fulton *et al.* 2016, Dichmont *et al.* 2017). More recently the modelling framework has been used to examine the sustainable multiple use of coastal systems (e.g. Gladstone Harbour) – including the effects of coastal development, nutrient and contaminant loading and bioaccumulation, shipping, dredging, port development and coastal land use (Fulton *et al.* 2017). More broadly, Atlantis has also been used to help consider the ecological impacts of climate change (Fulton & Gorton 2014, Weijerman *et al.* 2015) and evaluate socio-economic responses to alternative management strategies (Weijerman *et al.* 2016a).

In this study, we developed an Atlantis model for the Great Australian Bight (GAB), including coastal and open ocean regions. As a demonstration of the utility of the model (which is available now for

use by planners and other people interested in the management and use of the GAB and its resources), we used the model to explore the ecological consequences (changes in trophic linkages and biomass flow) of increased fishing pressure, shipping, ocean warming, and spatial reserves. In the process we aimed to provide strategic insight into the importance and function of specific trophic groups in the ecosystems in the GAB and which groups would be most impacted by a series of natural and human-induced changes.

4.2 Methods

4.2.1 Atlantis framework

Atlantis is a deterministic biogeochemical whole-of-system modelling framework that is spatially-resolved in three dimensions (Fulton *et al.* 2004). It includes several sub-models to track nutrient flows through the main biological and detritus groups within marine ecosystems. The primary ecological processes considered in Atlantis are consumption, production, migration, recruitment, waste production, habitat dependency, predation and other (natural and fishing) mortality. The outputs of the model consist of deterministic spatial time series for each biological and human dimension in the modelled ecosystem.

Details of the ecological theory, operational aspects, and the mathematical equations that underpin the key functions of Atlantis have been extensively detailed elsewhere (Fulton *et al.* 2007b, Link *et al.* 2010, Kaplan *et al.* 2012, Audzijonyte *et al.* 2017). A schematic of the model's content is given in Figure 4.1.

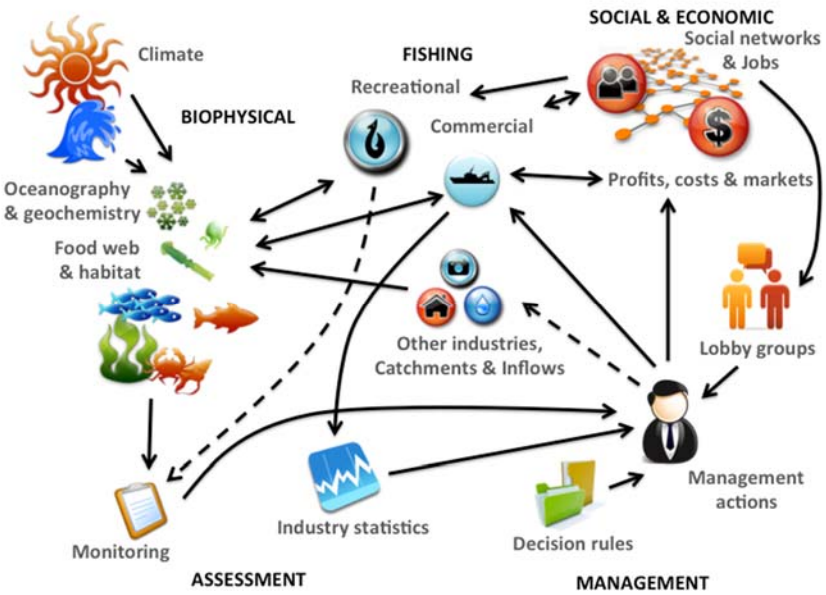


Figure 4.1 Schematic of the Atlantis modelling framework including the hydrodynamic forcing and the biophysical and exploitation sub-models.

4.2.2 Geography, model extent and design

The GAB model domain covers a region of about 1,329,953 km^2 (including boundary boxes), extending from the Head of Bight, South Australia to Portland, Victoria between 132.0° and 139.7° E longitude (Figure 4.2). The model area is spatially defined both vertically and horizontally and divided into 47 irregular polygons. Within each box there are up to 7 depth layers, depending on the total

depth of the box – shallower boxes have fewer layers with the nominal potential layer depth shown in Figure 4.2. In the open ocean boxes the maximum depth represented was 3000 m; waters below this depth were omitted and the bottom explicit layer was treated as having an open boundary with regard to exchanges.

This Atlantis model domain was created based on bioregionalisation and information used to create previous South East Australian (SE) Atlantis models (Johnson *et al.* 2011). This meant that the boxes are defined based on depth, geological features and ecological community boundaries. In comparison to the earlier Atlantis models in the region, this GAB focused model includes greater spatial resolution of oceanic boundary boxes and in the Spencer Gulf.

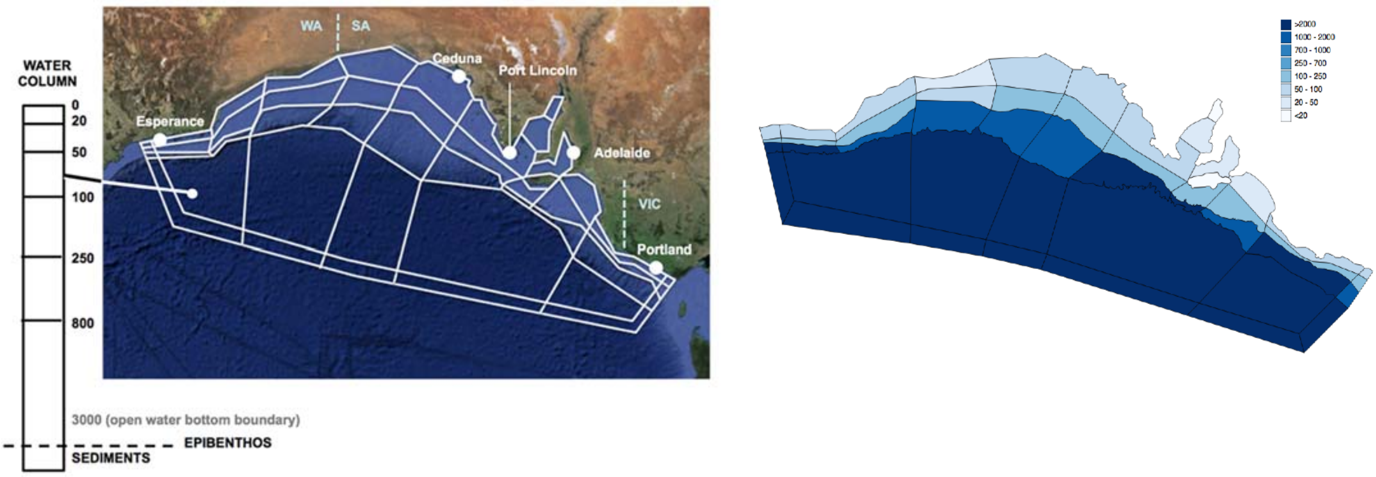


Figure 4.2. Map area of the model domain covering 1,329,953 km2. Purple boxes are boundary condition boxes, while others are dynamic boxes with different maximum depths.

4.2.3 Physical model

Atlantis uses hydrodynamic forcing files to represent the physical environment and oceanic transports. These files were created using data derived from two hydrodynamic models developed in GABRP Theme 1. Both of these models provided physical inputs for temperature, salinity and physical horizontal and vertical exchange (i.e. advection-diffusion water movement). The oceanographic conditions provided by the GABRP Theme 1 models were only for a limited time period and so were recycled through the course of any individual Atlantis run to create longer time periods. This meant that the physical forcing captured strong seasonal patterns, rather than interannual variability. Static maps and example time series for temperature and salinity are given in Figure 4.3 and 4.4.

As it is well established that pelagic primary productivity in the region is highly influenced by seasonal coastal upwelling, particularly in the eastern GAB (Ward *et al.* 2006), mean monthly upwelling anomalies were also used as a physical driver in the model.

Each spatial cell of the model (i.e. one depth layer of one spatial box) is considered uniform in its environmental variables and hydrodynamic processes. The conditions of these variables can change at each time step (usually every 12 h) depending on the water fluxes between cells.

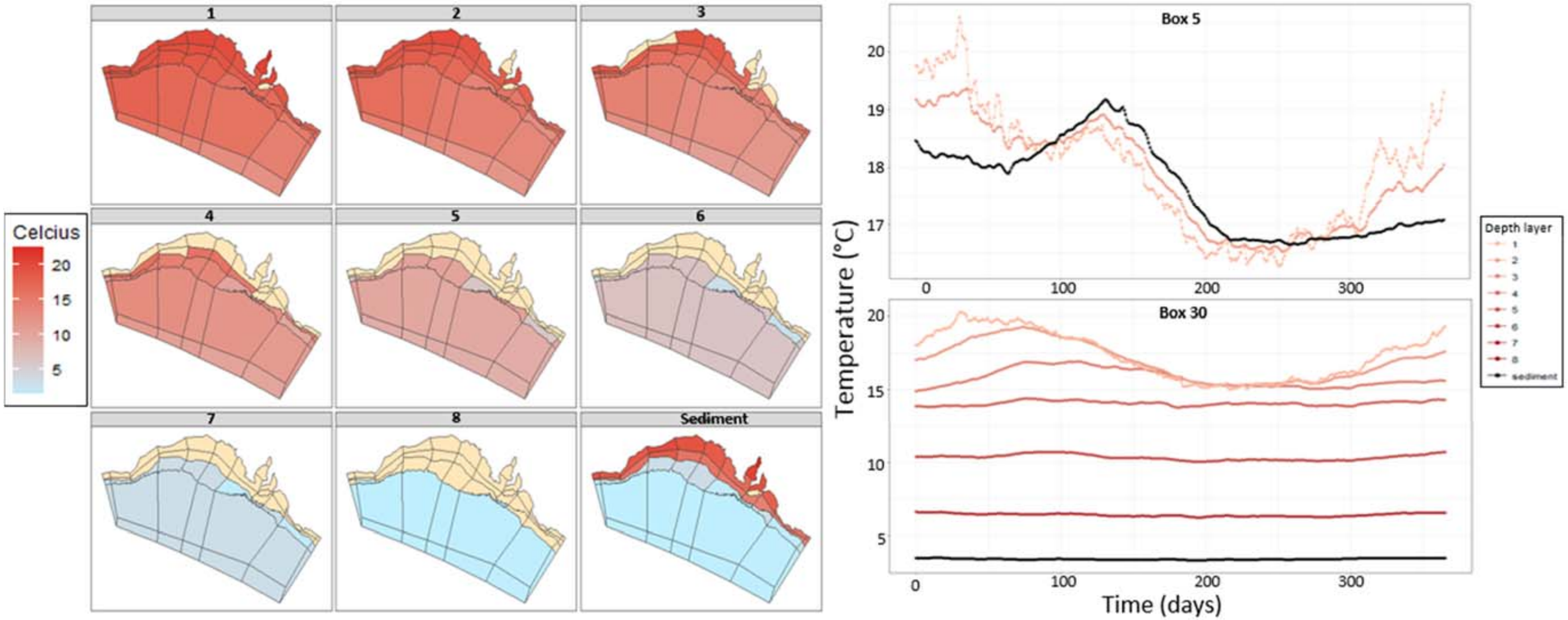


Figure 4.3. (A) Temperature (in °C) map and static depth profile, and (B) time-series for coastal box 5 (coastal) and slope box 30 (slope/open ocean), based on BlueLink hydrodynamic model output. Layer 1 is the surface layer. Bottom and sediment layers may have the same temperature.

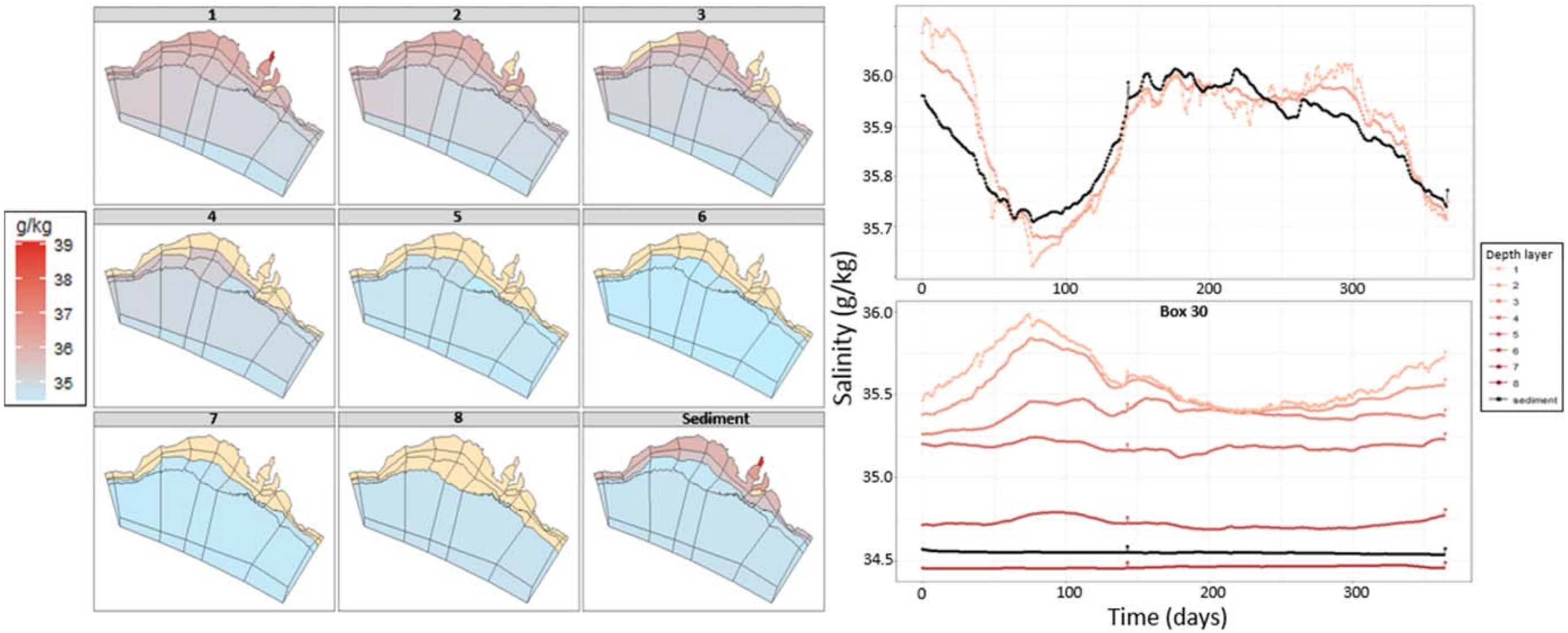


Figure 4.4. (A) Salinity (in g/kg) map and static depth profile, and (B) time-series for coastal box 5 (coastal) and slope box 30 (slope/open ocean), based on by the BlueLink model output. Layer 1 is the surface layer. Bottom and sediment layers may have the same salinity.

4.2.4 Biological model

The GAB Atlantis tracks nitrogen and silica through the food web (with the base currency being mg N m^{-3}, with the exception of epibenthic groups which are tracked in terms of mg N m^{-2}.

The biological groups included in the GAB Atlantis model consisted of 64 functional groups in which species were aggregated based on similar size, diets, habitat preferences, migratory patterns, metabolic rates, and life history strategies (Table 4.1, Appendix 8.1). The biological components provide a representation of the entire food web, inshore and offshore, pelagic and demersal and from bacteria and phytoplankton up to top predators. Aquaculture groups representing juvenile southern bluefin tuna and (bivalve) molluscs were included separately. The list of groups and species broadly matches the list identified for the GAB EwE model discussed in Section 3.

Primary producers included phytoplankton, macroalgae, and seagrass, and two bacteria groups (pelagic and sediment). Nineteen invertebrate groups were included in the model, most of which were treated as aggregate biomass pools. Rock lobster, urchins and abalone were treated as linked represented using a fully age and size-structured model, similar to the one employed for vertebrates, which tracks average size, condition, growth and mortality of each age class in each spatial cell.

All 34 vertebrate groups in the model were modelled using an age and size structured model – with typically 7-10 age classes (with each age class representing 1-8 years depending on the species[1]). This representation tracks the abundance and weight-at-age (based on structural and reserve nitrogen) for each cohort of each group in each spatial cell. Of the vertebrate groups, 16 were teleosts, 6 chondrichythans, 7 marine mammals and 4 seabirds.

Parameters for initial abundance estimates of all groups in the model were obtained from published sources or were model-derived (i.e. what biomass could be supported by the system in a stable state) where published data were unavailable (Table 4.1). Data for other biological parameters – such as seasonal distribution, reproduction, growth and habitat preference – were obtained from a variety of sources (e.g. other GABRP themes and regional experts), the literature used for the corresponding groups in the GAB EwE model discussed above, FISHBASE (www.fishbase.org) and SEALIFEBASE, or re-parameterised from ecosystem models that encompassed the study domain (Fulton *et al.* 2007a, 2007b).

Table 4.1. List and initial biomasses of functional groups in the GAB Atlantis model. For details of groups compositions see Appendix 1. Biomass values in tkm^{-2} are provided for reference - so that values can be compared with the GAB EwE model parameterisation

Code	Common name	Initial Biomass		Source
		Tonnes (t)	t km^{-2}	
AQT	Aquaculture tuna	508	0.000	Fulton and Gorton 2014
AQM	Aquaculture mollusc	563	0.000	Fulton and Gorton 2014
FKG	King George whiting	4,996	0.004	Fowler *et al.* 2014
FPM	Mackerel	12,493	0.010	Bulman *et al.* 2006
FPA	Anchovy	22,273	0.018	Bulman *et al.* 2006
FPS	Sardine	31,853	0.026	Bulman *et al.* 2006
FPB	Redbait	26,926	0.022	Bulman *et al.* 2006
FVS	Piscivorous shallow fish	5,072	0.004	Edgar & Barrett 1999, Bulman *et al.* 2006
FVT	Tuna and Billfish	31,664	0.026	Young *et al.* 1996, Bulman *et al.* 2006
FVB	Southern Bluefin tuna	63,258	0.051	Everson *et al.* 2014

[1] Note that for the purposes of reproduction and aging annual age cohorts are tracked so that interannual variability in cohort strength is explicitly incorporated, but for all other ecological processes (e.g. feeding, growth, movement etc.) the aggregated age classes are used.

Code	Common name	Initial Biomass Tonnes (t)	t km-2	Source
FFH	Flathead	21,318	0.017	Klaer 2013
FMM	Mesopelagic migratory fish	669,297	0.544	Bulman *et al.* 2006
FMN	Mesopelagic non-migratory fish	348,433	0.283	Bulman *et al.* 2006
FDD	Deep-demersal fish	19,882	0.016	
FDH	Herbivorous demersal fish	71,222	0.058	Edgar & Barrett 1999
FDS	Shallow demersal fish	82,053	0.067	Edgar & Barrett 1999
FSG	Garfish	2,882	0.002	
FRD	Redfish	23,437	0.019	
FSN	Pink snapper	107,197	0.087	
SDG	Green eye dogfish	939	0.001	Daley *et al.* 2015
SHD	Shark demersal	109,867	0.089	Fulton *et al.* 2007a
SHP	Shark pelagic	279,024	0.227	
SHS	School Shark	17,786	0.014	
SHG	Gummy shark	29,291	0.024	
SSK	Skates and rays	141,560	0.115	Fulton *et al.* 2007
SBG	Gulls	1,309	0.001	Reid *et al.* 2002
SBA	Petrels	3,314	0.003	
SBP	Penguin	40	0.000	
SBD	Diving seabirds (petrels)	68	0.000	
SFA	Australian fur seal	4,388	0.004	Goldsworthy *et al.* 2003
SFL	Longnose fur seal	4,104	0.003	Goldsworthy *et al.* 2003
SL	Australian sea lion	1,369	0.001	Goldsworthy *et al.* 2003
WHB	Baleen whale	4,468	0.004	Fulton *et al.* 2007a
DOB	Bottlenose dolphin	8,228	0.007	Fulton *et al.* 2007a
DOC	Common dolphin	2,674	0.002	Fulton *et al.* 2007a
WHT	Whale tooth	93,002	0.076	Fulton *et al.* 2007a
BRL	Lobster	22,197	0.018	Fulton *et al.* 2007a
BGA	Abalone	222,178	0.181	Fulton *et al.* 2007a
BGU	Urchins	96,418	0.078	Edgar & Barrett 1999, Bax & Williams 2000
CEP	Squid	346,280	0.282	O'Sullivan & Cullen 1983, Gales *et al.* 1993, Lynch 2004
BFS	Filter-feeders (shallow)	54,630	0.044	Edgar & Barrett 1999, Bax & Williams 2000
BFD	Filter-feeders (deep)	2,605,116	2.118	Bax & Williams 2000
BG	Benthic grazer	1,363,898	1.109	Edgar & Barrett 1999, Bax & Williams 2000
BMS	Macrobenthos	2,998,760	2.438	Edgar & Barrett 1999, Barrett *et al.* 2007
BMC	Commercial crustacea	179,994	0.146	Edgar & Barrett 1999
PWN	Prawn	70,130	0.057	Fulton *et al.* 2007a
BD	Deposit feeders	277,917,293	225.958	Bax & Williams 2000
BC	Benthic carnivores	37,760,502	30.701	Bax & Williams 2000
MA	Macroalgae	272,856	0.222	Barrett *et al.* 2001
SG	Seagrass	198,140	0.161	Barrett *et al.* 2001
ZG	Gelatinous zooplankton	44,611,950	36.271	Bulman *et al.* 2006
PL	Diatoms	3,203,913	2.605	Harris *et al.* 1987, Bax & Williams 2001
PS	Pico-phytoplankton	20,456,137	16.632	Harris *et al.* 1987, Dandonneau *et al.* 2004
ZL	Carnivorous zooplankton	74,923,955	60.916	Young *et al.* 1996
ZM	mesozooplankton	86,622,961	70.428	Young *et al.* 1996
ZS	Microzooplankton	187,688,338	152.598	Model derived
PB	Pelagic bacteria	5,331,585	4.335	Model derived
BB	Sediment bacteria	75,521,004	61.402	Model derived
BO	Meiobenthos	15,104,201	12.280	Fulton *et al.* 2007a
DL	Labile detritus	120,833,606	98.242	Model derived
DR	Refractory detritus	302,084,014	245.606	Model derived

4.2.5 Trophic connections

The potential trophic connections between groups are given in Appendix 8.2. This diet matrix in Atlantis represents the potential availability of a prey item to a predator should all else be in the

predator's favour; this is unlike the EwE diet matrix, which represents proportional diet composition. Whether predation actually occurs depends on whether the predator and prey coincide temporally and spatially (given mobility, habitat preferences and habitat state), relative habitat dependency and the state of habitat refugia, the total amount of forage available (summing across prey groups) and whether the prey is of an appropriate size to be caught and consumed by the predator. Size and age structured groups have their diets split into juvenile and adult interaction matrices to represent the strength and rapidity of ontogenetic diet shifts that occur in these groups. Data on prey-predator interactions were taken from regional studies where possible (e.g. the data sources referred to in the description of the GAB EwE model) or from other published sources – refer to Fulton *et al.* (2007), Fulton and Gorton (2014) and Smith *et al*. (2015) for further details. The final values used were the result of estimates from these sources modified through model calibration so that the realised diet composition and biomass trajectories matched the available data.

4.2.6 Non-trophic interactions, dependencies and processes

Within boxes spatial heterogeneity is also represented, with a fixed proportion of 3 sediment types – soft (muds and silts), reef (emergent reef or rocky ground), and flat (sands and pavements) – defined per box; the sum of which must be 1.0. Layered over this geology are canyon areas (which can enhance productivity locally) and living habitat types – specifically seagrass, macroalgae, shallow filter feeder and deep filter feeders. Each habitat dependent group indicates which of these geological and living habits it prefers (or avoids). These preferences act to restrict the spatial domain of groups that are associated only with particular habitat types. This representation also allows for non-trophic interactions (e.g. competition for space and habitat use).

Other non-trophic processes include movement. Migration patterns that took species outside the (Smith *et al.* 2015)model domain on a seasonal or annual basis were incorporated in the model for 3 functional groups: diving seabirds (petrels), southern bluefin tuna, and baleen whales. Within domain horizontal movement also occurred seasonally or based on the distribution of prey fields. The model also includes vertical movement (i.e. diel vertical migration). By incorporating vertical stratification of physical properties and vertical migrations of certain biological components the interactions of hydrodynamic and biological processes that vary with depth were represented with sufficient detail to reproduce the gross properties of vertical profiles.

4.2.7 Fishing model

The GAB region supports some of Australia's most valuable fisheries, including four main Commonwealth and five main South Australian (State) managed fisheries (Wilson *et al.* 2009, Knight & Tsolos 2010). Annual fisheries landings and discard data from 2005 to 2016 were obtained from various sources (Table 3.2) and broken down into 11 fisheries (fleets) operating within the GAB ecosystem listed in Table 4.2. Commonwealth fishing data were obtained from the Australian Fisheries Management Authority. Fisheries data were also obtained from State fisheries departments for fisheries managed by each of three States encompassed in the GAB-Atlantis model. Recreational fishing (which is based on the dynamically changing human population in the area) was also included based on state and national surveys (Henry & Lyle 2003, Currie *et al.* 2006, Jones 2009, Giri & Hall 2015).

While Atlantis has the capacity to incorporate dynamic fishing fleets, there was insufficient time available to implement the full socio-economic representation of fleet dynamics in Atlantis and this study is a strategic investigation of a series of anthropogenic pressures, therefore a fishing mortality

based representation of fishing pressure was used instead. This is similar in concept to how fisheries are represented in EwE. Compared to the more dynamic effort-based models, this simple representation has the potential effect of increasing the proportion of the population that is landed (as it is less responsive to realised catch rates and other behavioural drivers such as profitability, market price, social connections, etc.) and it removes some of the noise associated with variations in fishers' behaviour that a dynamic fishing model can impose. Fishing mortality (F) per fishery was estimated for each fished group by setting F to the proportion of the total population of each group that was taken as catch by that fishery. Fishing pressure was imposed based on estimates of the current rates of fishing by both federal and state fleets (see above). The final values used were modified to a small degree in the calibration process, in order to allow for a stable biomass (i.e. no evidence of numerical instability) under constant conditions and for biomass trajectories that matched observed trajectories in the system over the past 10 years given observed catches.

4.2.1 Model calibration

We parameterised the model to obtain a stable system state with long run biomasses within approximately 20% of the initial biomass values (Table 4.1). Where available, time-series trajectories of both biomass and abundance of groups, taken from the stock assessments, technical reports and published literature were also used to calibrate the model. As were catch time series. A key difference to EwE was that spatial patterns, habitat coverage, physical forcing, vertical and horizontal spatial distributions, initial abundances (numbers), weights in nitrogen, and vertical and horizontal migration were also checked through the calibration process to ensure that the model was as good as possible.

4.3 Status Quo Atlantis run

The GAB-Atlantis model produced realistic ecosystem structure and function, with biomasses of the correct order of magnitude and plausible dynamics. During the entire projection period under the *Status Quo* simulation invertebrates dominate the biomass, as they do in the real system, and show relative stability throughout the projection period. The trophic groups that accounted for the highest proportion of total system biomass were those associated with the microbial loop or detritus fuelled pathways - including micro-zooplankton (23%), deposit feeders (19%), and gelatinous zooplankton (11%). Total biomass of invertebrate groups over the projection period are shown in Figure 4.5. There is a strong seasonal cycle displayed for many of the planktonic groups including pico-phytoplankton, diatoms and micro-zooplankton.

Table 4.2. Summary of annual fishing mortality rates per gear

Name	Aqua-culture	C'wealth trawl fishery	Sardine fishery	Shark fishery	Invertebrate fishery	Coastal fisheries	Prawn trawl	Recreational fishery	Shipping impacts	Land use impacts
Group	**Aquacult**	**trawlFD**	**fleetSARD**	**lineSH**	**diveINV**	**coastFD**	**trawlPWN**	**recFISH**	**SHIP**	**LANDUSE**
Aquaculture tuna	1‡	0	0	0	0	0	0	0	0	0
Aquaculture molluscs	1‡	0	0	0	0	0	0	0	0	0
Sardines	0	0	0.08	0	0	0	0	0	0	0
Anchovy	0	0	0.002	0	0	0	0	0	0	0
King George Whiting	0	0	0	0	0	0.15	0	0.0001	0	0
Mackerel	0	0.01	0	0	0	0	0	7.3E-08	0	0
Shallow piscivores	0	0.09	0	0.005	0	0.03	0	0.03	0	
Tuna and billfish	0	0	0	0	0	0.001	0	0	0	0
Southern bluefin tuna	0	0	0	0	0	0.067	0	0	0	0
Myctophids	0	2.6E-06	0	0	0	0	0	0	0	0
Flatheads	0	0.06	0	0	0	0	0	0.28	0	0
Pink snapper	0	0	0	0	0	0.001	0	9.3E-05	0	0
Redfish	0	0.003	0	0	0	0	0	0	0	0
Deep demersal fish	0	0.07	0	0	0	0	0	0	0	0
Shallow demersal fish	0	0.008	0	0.0002	0	0.02	0	0	0	0
Garfish	0	0	0	0	0	0.10	0	0	7.3E-06*	0
Shallow demersal herbivores	0	0	0	0	0	9.34E-05	0	0	7.3E-06*	0
Demersal sharks	0	2.1E-05	0	0.002	0	0	0	0	0	0
Gummy shark	0	0	0	0.22	0	0	0	6.6E-05	7.3E-06*	0
School sharks	0	0	0	0.04	0	0	0	4.5E-05	7.3E-06*	0
Pelagic sharks	0	0	0	0.0001	0	0	0	1.7E-05	7.3E-06*	0
Green-eye dogfish	0	1.8E-06	0	0.0007	0	0	0	0	0	0
Skates and rays	0	0.0008	0	5.2E-05	0	0	0	0.0003	7.3E-06*	0
Urchins	0	0	0	0	0.002	0	0	0	7.3E-06*	0
Abalone	0	0	0	0	0.001	0	0	0.0002	7.3E-06*	0
Rock lobster	0	0	0	0	0.034	0	0	0.002	7.3E-06*	0
Deep benthic filter feeders	0	0.0002	0	0	0	1.67E-05	0	0	0	0
Shallow benthic filter feeders	0	0	0	0	0	0.0008	0	0	7.3E-06*	0
Deposit feeders	0	5.1E-08	0	0	0	5.1E-06	0	0	7.3E-06*	0
Benthic carnivores	0	1.7E-10	0	0	0	0	0	0	0	0
Benthic grazers	0	0	0	0	9.5E-06	0	0	0	7.3E-06*	0
Commercial crustacea	0	1.6E-05	0	0	0	0.0016	0	6.3E-11	0	0
Macrozoobenthos	0	2.9E-06	0	0	0	8.54E-07	0	0	7.3E-06*	0
Squid	0	0.0006	0	0	0.0007	0.007	0	7.3E-08	0	0
Prawns	0	0	0	0	0	0	0.017	0	0	0
Petrels	0	0	0	7.3E-08	0	0	0	0	0	7.9E-08
Penguins	0	0	0	0	0	0	0	0	7.3E-06*	7.3E-08
Gulls	0	0	0	0	0	0	0	0	7.3E-06*	8.1E-08

Name	Aqua-culture	C'wealth trawl fishery	Sardine fishery	Shark fishery	Invertebrate fishery	Coastal fisheries	Prawn trawl	Recreational fishery	Shipping impacts	Land use impacts
Group	**Aquacult**	**trawlFD**	**fleetSARD**	**lineSH**	**diveINV**	**coastFD**	**trawlPWN**	**recFISH**	**SHIP**	**LANDUSE**
Australian fur seals	0	7.3E-08	0	0	0	0	0	0	7.3E-06	7.3E-08
Longnose fur seals	0	7.3E-08	0	0	0	0	0	0	7.3E-06	7.3E-08
Sea lions	0	7.3E-08	0	0	0	0	0	0	7.3E-06	7.3E-08
Baleen whales	0	0	0	0	0	0	0	0	7.3E-06	0
Orcas	0	0	0	0	0	0	0	0	7.3E-06	0
Bottlenose dolphins	0	7.3E-08	0	0	0	0	0	0	7.3E-06	0
Common dolphins	0	7.3E-08	0	0	0	0	0	0	7.3E-06	0

‡ Only at time of harvest. * Mortality was only imposed for the shipping traffic scenario, it was 0 for all other scenarios including the Status Quo.

(a)

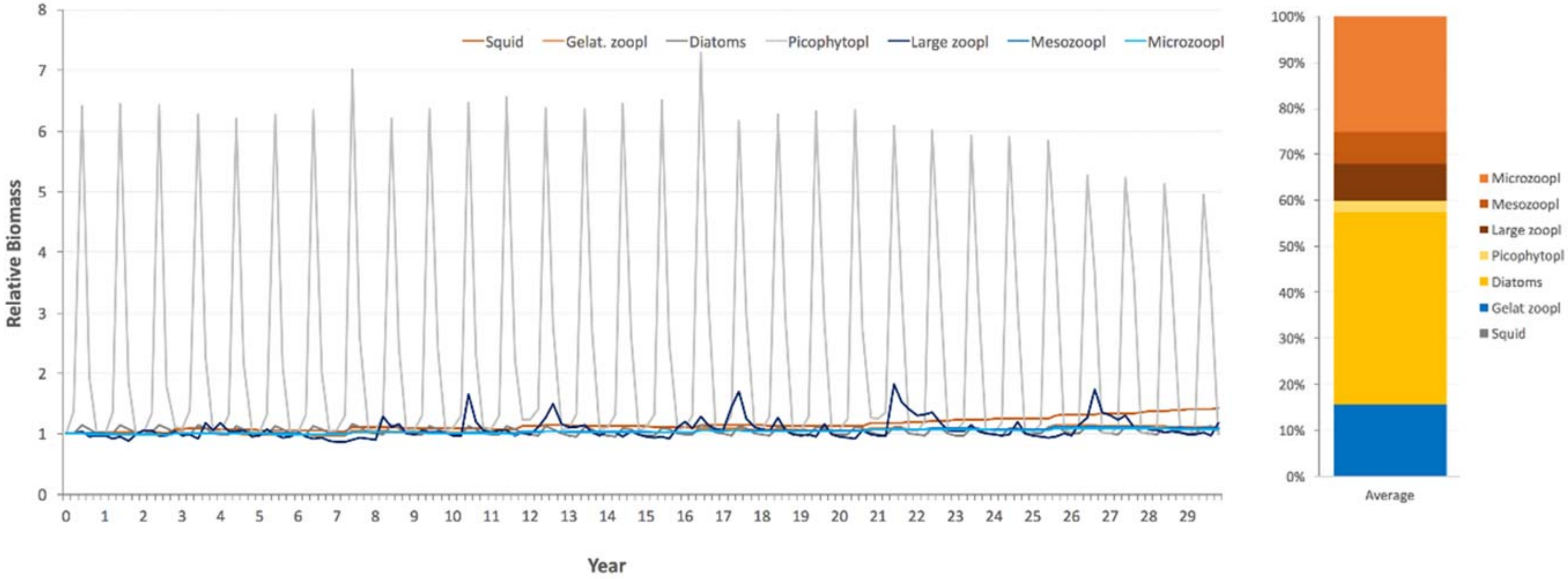


Figure 4.5. Trajectories of relative biomass of the dominant invertebrate functional groups, excluding the detritus and bacteria, (a) in the pelagos and (b) benthos and their average community composition (inserts) over the final 5 years of the Status Quo simulation under constant forcing.

(b)

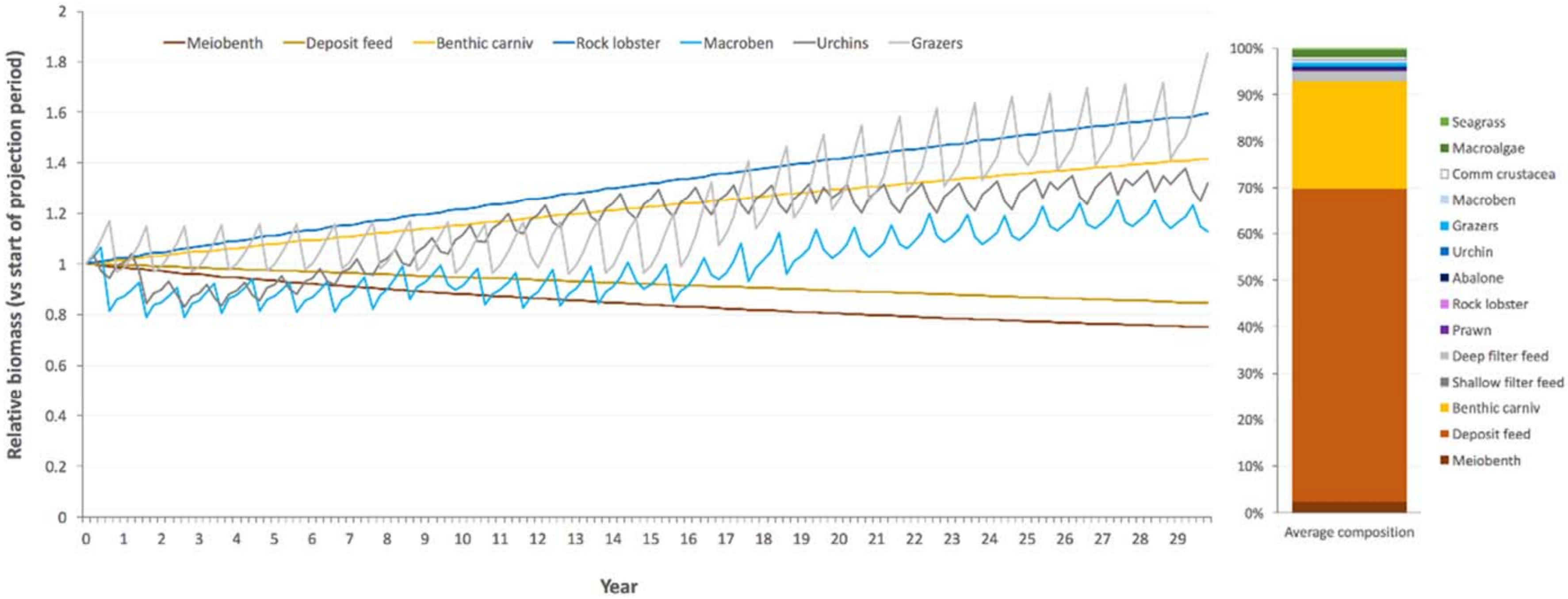


Figure 4.5: Continued

Examples of the relative total biomass and age-class structure for the age-structured (mainly vertebrate) functional groups are given in Figures 4.6, 4.7 and 4.8. Of all the vertebrate groups the mesopelagic fishes had the highest biomass (0.2% of total system biomass). The biomass of the majority of the vertebrate functional groups remained stable through the projection period of the *Status Quo* model run (there is still annual or multi-year variation, but it is within a stable band of biomasses). Some of the top-predator groups increased in total biomass through the simulation as there is little predatory control on them through time, this may reflect the lack of sufficient density dependent behavioural controls. Instabilities in age structure (and thus biomass trajectories) were shown for shallow piscivores and herbivorous fishes and non-migratory mesopelagic fishes, likely due to interactions between their relative sizes, prey and predator fields. Analysis of output on finer temporal scales than shown here indicates that migratory patterns of the baleen whales, southern bluefin tuna and petrels are as desired.

Importance of classic food web and microbial loop production

Box by box inspection of the plankton community composition indicated that the Atlantis model predicted that diatoms played a larger role than is seen in reality GAB-wide, mainly by: periodically contributing to a subsurface maximum in the central GAB (inshore and offshore); and by being the main primary producer in the upwelling events in the east. The smaller phytoplankton was a significant source of primary production in the west, offshore in the central GAB and periodically over the shelf areas of the central GAB (alternating to some degree with the larger phytoplankton and often being closer to the surface); and while present in the eastern GAB were not as dominant as the diatoms. The zooplankton structure followed the classic pattern in the east, with larger bodied zooplankton feeding on the diatoms and other size classes only at lower levels. In the western and central GAB the smallest zooplankton classes constituted significant proportions of the entire zooplankton biomass and often dominated (though sporadic blooms of diatoms on the shelf and shelf break can support larger zooplankton seasonally).

While informed by the Theme 1 GABRP data, the model is only loosely constrained by those initial conditions and tuning parameters. Consequently, the persistence of the plankton community patterns through the course of the simulations and across scenarios suggests it is likely an emergent property of the oceanographic and food web conditions in the GAB. There is not an exact match for what was observed, but the rough divisions seen in reality between classical webs (based on diatoms and large zooplankton; in the west), the microbial loop dominating in the central GAB and the hybrid community on the shelf in the central GAB seem to all be present. That same general functioning appeared to be maintained regardless of the scenario, even if absolute biomasses varied (e.g. with climate change – where smaller bodied plankton grew in abundance across the entire domain).

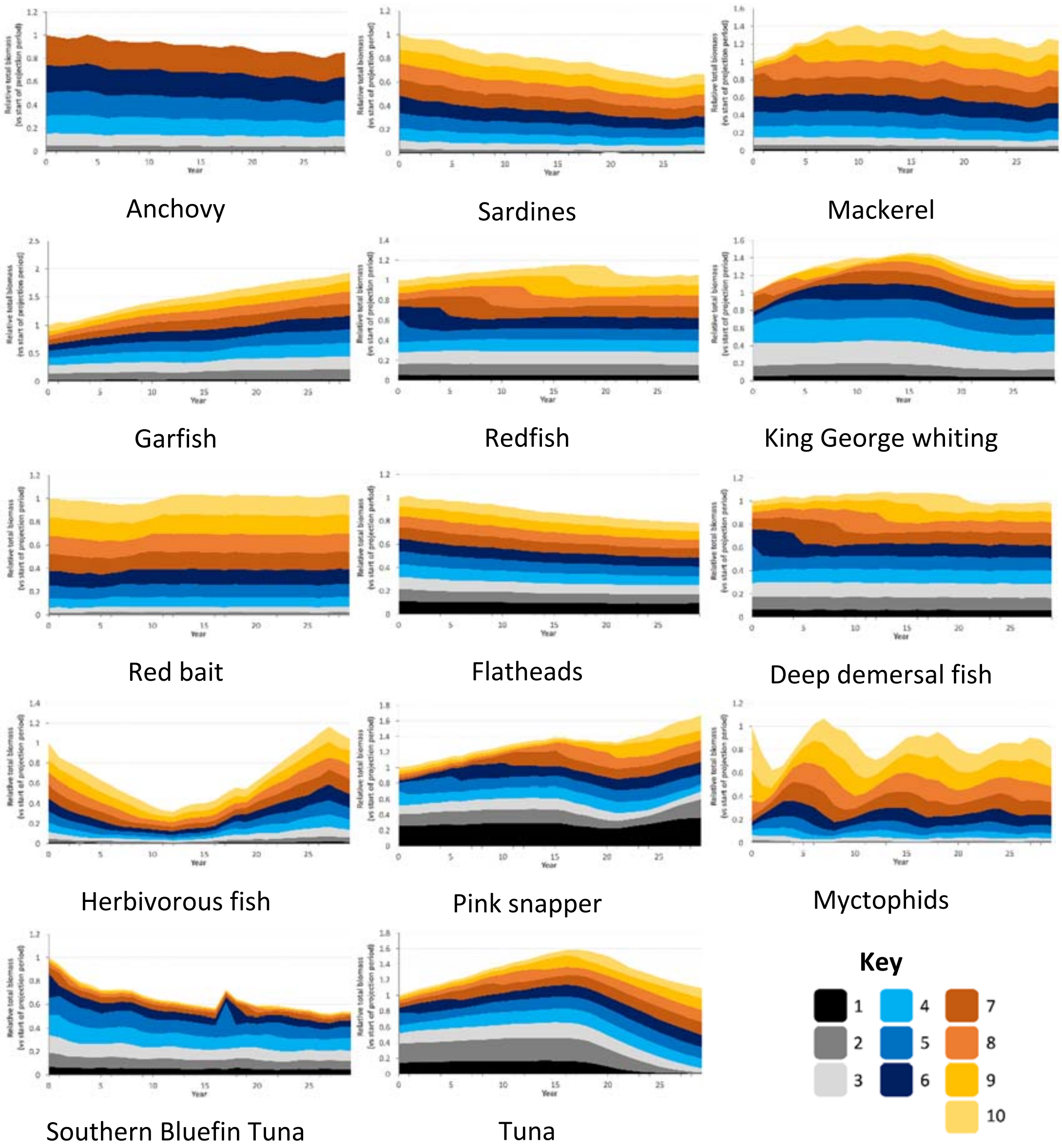


Figure 4.6. Example relative total biomass and age-class distribution for fish functional groups in the Status Quo model run.

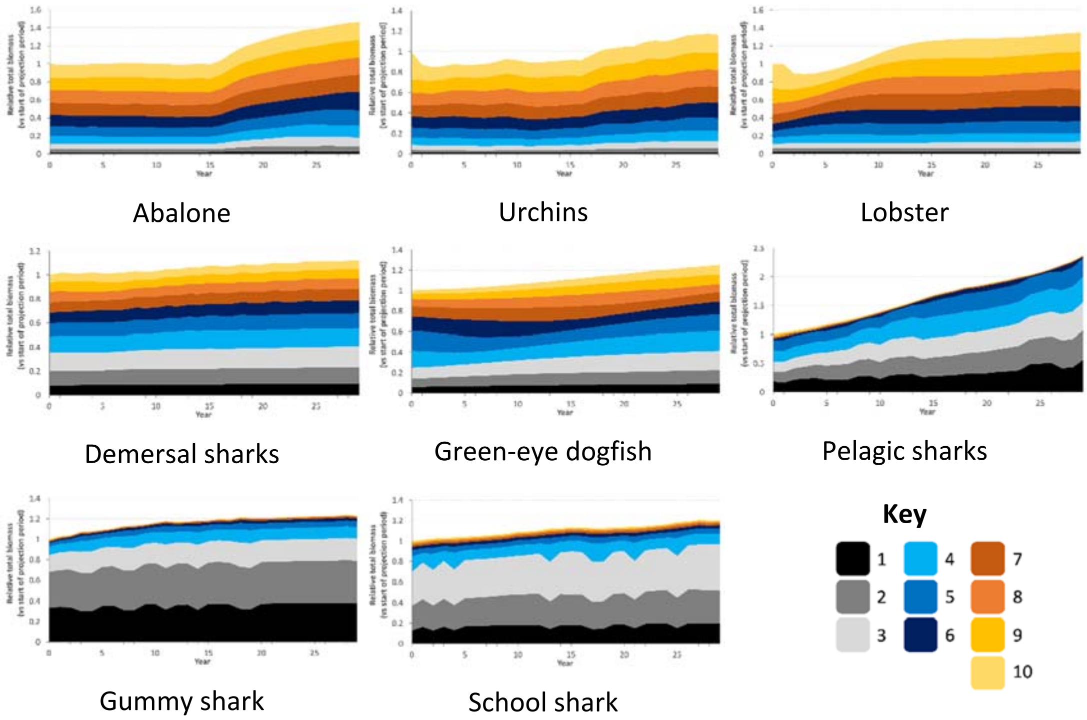
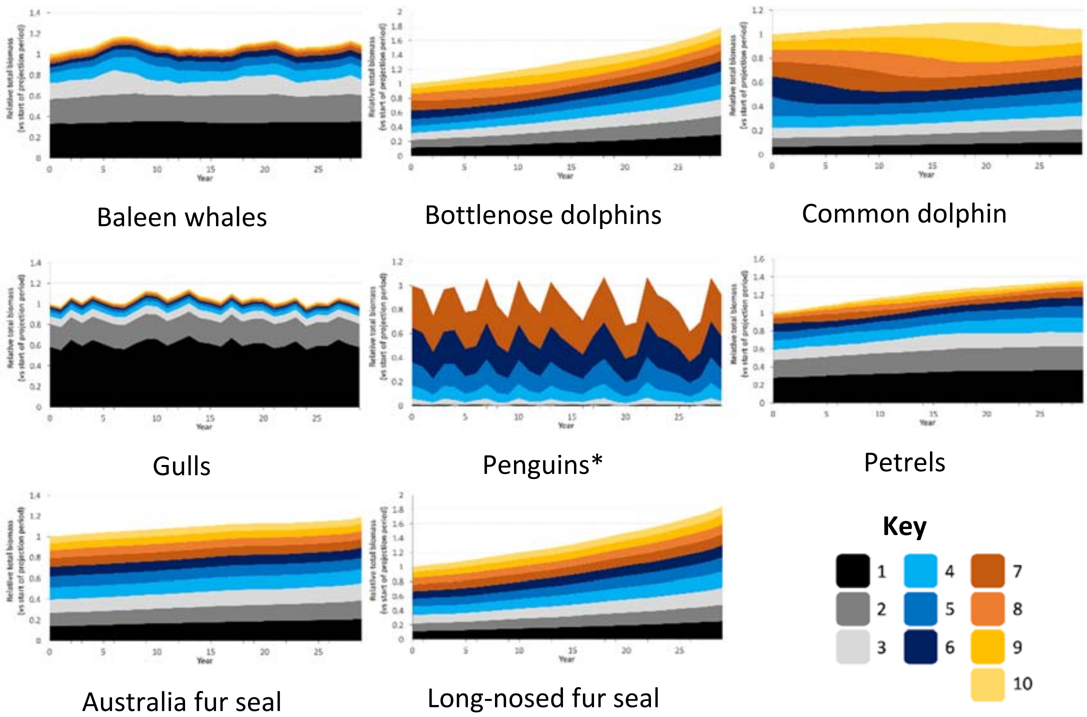


Figure 4.7. Example relative total biomass and age-class distribution for sharks and age-structured invertebrates in in the Status Quo model run.

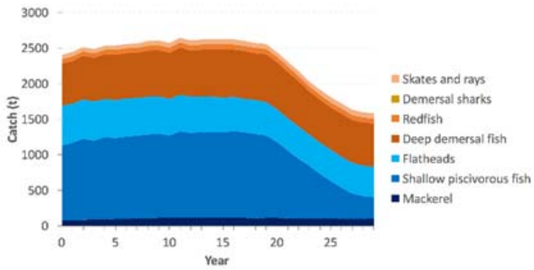


* Note Penguins show erratic patterns inter-annually due to the interaction of seasonal cycles in abundance and condition and the annual reporting cycles.

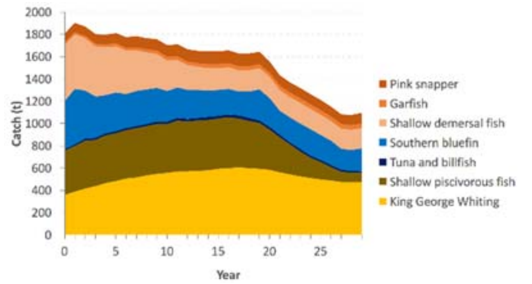
Figure 4.8. Example relative total biomass and age-class distribution of marine mammals and seabirds in the Status Quo model run.

Catches

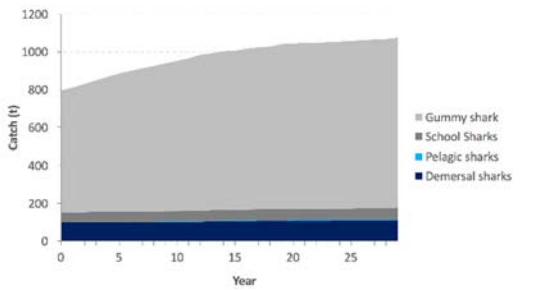
Catches of all fisheries showed temporal trends that mirrored temporal trends in the biomass of the dominant target species (Figure 4.9). Abalone and rock lobster where caught in high relative proportions in the Invertebrate and Recreational fisheries while catches of shallow piscivores, sardine, King George whiting, and gummy sharks dominated the Commonwealth Trawl fishery, Coastal fisheries, and the Shark fishery, respectively.



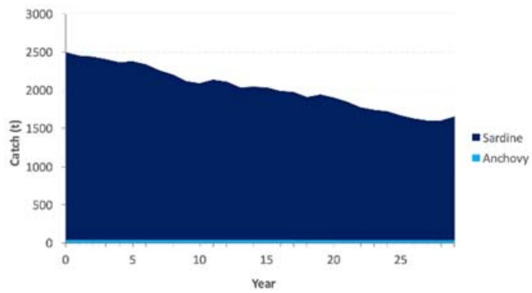
Commonwealth trawl fishery



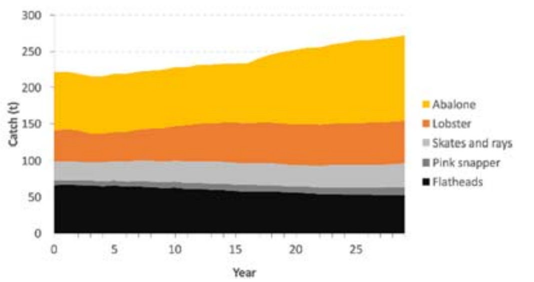
Coastal fisheries



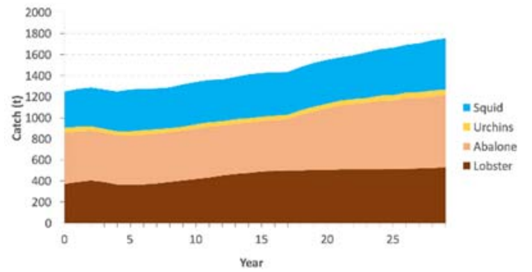
Shark fishery



Sardine fishery



Recreational fisheries



Invertebrate fishery

Figure 4.9. Plots of the fisheries catches for key functional groups in each fishery during the projection period of the *Status Quo* run.

5. SCENARIOS

5.1 Introduction

The principal objective of the final form of the project was to build the ecosystem models to a point where they were scenario-ready, and provide some demonstration examples of the kinds of scenarios that the models could be used to examine. Originally, we proposed that the models would be used to explore the potential effects of climate variability and change, changes in fishing effort, aquaculture and incidents related to oil/gas activities or other changes to the level and mix of industries in the region. The reshaping of the GABRP (especially Theme 6) through the course of the project meant that there was insufficient information available to deliver fully dynamic representations of the human dimensions or very detailed scenarios of change beyond fisheries, aquaculture shipping and oil/gas activities (i.e. much less of the on-land activities could be represented than originally intended).

In addition, the revised timeline for the final synthesis stages of the project meant that the scenarios could not be elicited from the stakeholders in the way initially intended. Instead it was decided by the Management Committee (MC) that the project team in collaboration with the MC and GABRP theme leaders and other key researchers would identify the final set of stressors and scenarios to test in order to demonstrate the capacity of the models. The details of each were checked with relevant experts – for example, those pertaining to shipping and oil/gas activities were checked with the Australian Maritime Safety Authority (AMSA), BP and Statoil.

The final set of stressors and scenarios approved by the MC included:

- Ocean warming: several levels of ocean warming based on IPCC projections;
- Fishing: a range of increased and decreased fishing effort that span plausible historical ranges and are in line with those used nationally and internationally (e.g. by the EU INDISEAS initiative) to check ecosystem dynamics;
- Spatial management: the effects of marine parks and coastal and offshore fishing closures;
- Sardine pathogen: a pathogenic outbreak on sardine stock similar to those seen in the region in the past;
- SBT: various mechanisms for increased SBT biomass; and
- Shipping: increased vessel activity and an accidental oil /fuel spill from a vessel collision (this last event is AMSA's highest rate risk for the region).

Wherever possible, we ran complementary scenarios in each model, but given the different structures of the model the implementation of the scenarios differed in some details from model to model and not all scenarios and all variations could be replicated in each model. For example, scenarios relating to spatial management (of marine parks) and oil spills could only be simulated in Atlantis. In Atlantis, 6 stressors were examined, some with several variations, giving a total of 17 scenarios. In EwE, 4 stressors were examined for a total of 10 scenarios.

5.2 Scenario descriptions

The range of scenarios were developed to explore the impacts on the surrounding ecosystem in addition to the impacts on specific fished stocks (Table 5.1). In each of the scenarios, only those parameters or forcing functions required to represent the specific model conditions applied to represent the scenario were altered, all other parameters and forcing files were held identical to those in the *Status Quo* simulations. For Atlantis simulations, all scenarios ran for the first 20 years without change from the *Status Quo* conditions to allow for consistent model 'burn-in', this is consistent with Atlantis best practice (with the period of burn-in selected empirically based on the results of the calibration to ensure there was no persistent transient effects of the initial conditions in the system, and that by the start of the projection period the model state is stable and follows historical trajectories where known). The scenarios specific imposed perturbations, were then applied for a further 30 years (called the projection period), a total run time of 50 years. The burn-in period is discarded and not included in the analysis of model results. A 30-year time frame was used so that short-medium term outcomes of the scenarios could be considered. While a longer time period could be considered if long term change is the focus of the study, this was not the case here. Instead the 30-year time span was used as this is the typical time span of most interest to regional planners and others with a strategic view of a system.

For EwE, standard model procedures are a little different. As the time dynamic scenarios are initialised from a mass balance (equilibrium) point and there is no age structure or explicit nutrient cycling, the model trajectories do not have the same sensitivity to initial conditions and so no burn-in is required. Instead, the first ten years of simulations used the observed data (i.e. the values used to tune the model) to reproduced the short-term historical trajectories before implementing the scenario conditions for the final 40-year projection period.

Seasonal model output was obtained for all scenario simulations from both models. For evaluation of each scenario the biomasses, fisheries catches and ecological indicators were normalised relative to the *Status Quo* scenario.

Table 5.1. The scenarios that were implemented and which models were used to run them

Scenario Category	Scenario	Model	Atlantis Model change
Status Quo	Status Quo	Atlantis, EwE	
Ocean warming	IPCC low (+0.2°C)	Atlantis	Biological sub-model
	IPPC med (+0.5°C)	Atlantis	"
	IPPC high(+1.0°C)	Atlantis	"
	IPPC very high (+2.0°C)	Atlantis	"
	Primary production forcing (=+2.0°C)	EwE	
Fishing	No Fishing	Atlantis, EwE	Run file (turn fisheries off)
	F X 0.1	Atlantis, EwE	Harvest sub-model
	F X 0.5	Atlantis, EwE	"
	F X 2	Atlantis, EwE	"
	F X 10	Atlantis, EwE	"
Spatial Management	No Marine Reserves	Atlantis	"
	Restricted fishing - coast	Atlantis	"
	Restricted fishing - offshore	Atlantis	"
Sardine pathogen	Mortality - 70% juv. sardines	Atlantis, EwE	Forcing file

Scenario Category	Scenario	Model	Atlantis Model change
Southern bluefin tuna	High recruitment year (static F)	Atlantis	“
	High recruitment year (static catch)	Atlantis	Forcing file and Harvest sub-model
	Biomass accumulation 5% + Immigration	EwE	
	Biomass accumulation 10%	EwE	
	Starting biomass x 2	EwE	
Shipping	Accidental oil spill	Atlantis	Spatially explicit forcing file
	Shipping levels increase	Atlantis	Harvest sub-model

Scenario 1: Ocean warming

Ocean warming has been shown to impact the community composition and abundance of primary producers (Hays *et al.* 2005, Sommer & Lengfellner 2008), including seagrass and microalgae (Beer & Koch 1996, Diaz-Pulido *et al.* 2007). Ocean warming and related changes to the physical and chemical properties of the ocean have also been shown to impact the physiology, life-history and distributions of secondary (Richardson 2008) and tertiary species (Doney *et al.* 2011). Such population-level changes in abundance have flow-on impacts (bottom-up and top-down) through the whole food web (Edwards & Richardson 2004, Winder & Schindler 2004). These dependencies and affects are parameterised into Atlantis explicitly.

The climate scenarios were based on the temperature projections output from the Climate Model Intercomparison Project (CMIP5, Kirtman *et al.* (2013). In that project, global climate models simulated Intergovernmental Panel on Climate Change (IPCC) Representative Carbon Pathways (RCP) scenarios. The resulting temperature projections suggest that the mean annual sea surface temperatures will increase by more than 2.0°C by the mid-century and by >4.0°C by 2100, although total increase is dependent on how the global community addresses (or not) levels of emissions. Given the uncertainty around the RCP projections we simulated four scenarios of ocean warming (at all depth layers) which spanned the range of temperatures seen in the ensemble of RCP mid-century projections – specifically temperature increase of 0.2, 0.5, 1.0, and 2.0°C per decade. The mechanism of change then is via direct effects on metabolic processes and species distributions (which are based on tolerated thermal ranges). We examined resultant impacts on productivity, forage fish and dependent top predators as well as fisheries. As regional downscaling was not available for all RCP scenarios (only the most extreme temperature ranges) we decided not to confound the analysis by using different spatial current patterns in each simulation. Consequently, we assumed current patterns did not shift, only the temperatures. This means there is uncertainty about spatial distributions versus what may be observed in the future as it there is the potential for currents and any upwelling/downwelling to shift in location and magnitude.

In EwE, representing climate change is a more indirect process, with a forcing function applied to the production rates of primary producer groups to reflect shifts in primary productivity that result from the changed conditions. We followed the approach adopted for the Fisheries and Marine Ecosystem Model Intercomparison Project (FISH-MIP) project, a collaboration of global ecosystem modellers which is examining the implications of climate change for fisheries globally as input to the next round of IPCC updates

(https://www.isimip.org/gettingstarted/marine-ecosystems-fisheries/). The FISH-MIP method required calculating a primary production anomaly derived from biogeochemical models driven with physical forcing from general circulation models (i.e. global ocean-atmosphere models). However, the outputs from the global models do not represent the Australian region very accurately, but fortunately we were able to obtain output from a downscaled regionally-based model that did (Feng *et al.* 2016, Zhang *et al.* 2016, 2017). Outputs from a control (*Status Quo)* and RCP 8.5 scenario run with the regional downscaled model were used to derive time series of anomalies for primary production specific to the GAB that were used as forcing functions for EwE. The regional climate model considered phytoplankton as a single grouping whereas we modelled two size classes, small and large. Furthermore, we were attempting to account for the two or three food-web dynamics, classical in the east, microbial in the central and the "hybrid" model, as discussed in Section 3.3.7. Therefore, rather than use the same production anomaly for both small and large phytoplankton, we made a very broad assumption about the rates derived for the two regions. We assumed that the production anomaly for the central GAB was predominantly influenced by the small phytoplankton and reflective of small phytoplankton production in general. We also assumed that in the eastern GAB the large phytoplankton were more influential for the production rates because they were more abundant and present throughout the year, frequently driven by upwellings but very quickly grazed. Therefore, on average, production rates from the climate model for the eastern GAB region would be more reflective of large phytoplankton production. This is conjecture, but does match the mix of species groups seen in satellite estimates of relative phytoplankton productivity per group for the region (e.g. as used in Rosenberg *et al.* 2014).

We calculated the forcing function anomalies for both the eastern GAB and the central GAB regions, centred on the eight locations at which primary production observations were taken during the field surveys of Theme 2. An area was defined around each of those locations, for which the data were extracted from the regional model output and averaged. These averages were then used in calculating the production anomaly series (Figure 5.1 a, b). In addition to those two locations, we derived another production anomaly for the Spencer Gulf area to represent climate effects specifically on the seagrasses and macroalgae occurring in the gulfs and coastal areas of the GAB (Figure 5.1c).

In summary, we derived six sets of forcing functions i.e. *Status Quo* and RCP 8.5 series for each of the eastern GAB, the central GAB and the coastal/gulf regions. The anomalies were consistently larger (~10%) in amplitude for the central GAB control series than for the eastern GAB (Figure 5.1a), which we considered consistent with our hypothesis of a higher production rate for small phytoplankton compared to large phytoplankton. Interestingly, for the RCP8.5 series, the situation reversed with eastern GAB series more often resulting in higher maximums than the central GAB projections (as the downscaled model suggests shifting intensity of upwelling events), but both were more variable and on average lower than the control (Figure 5.1b).

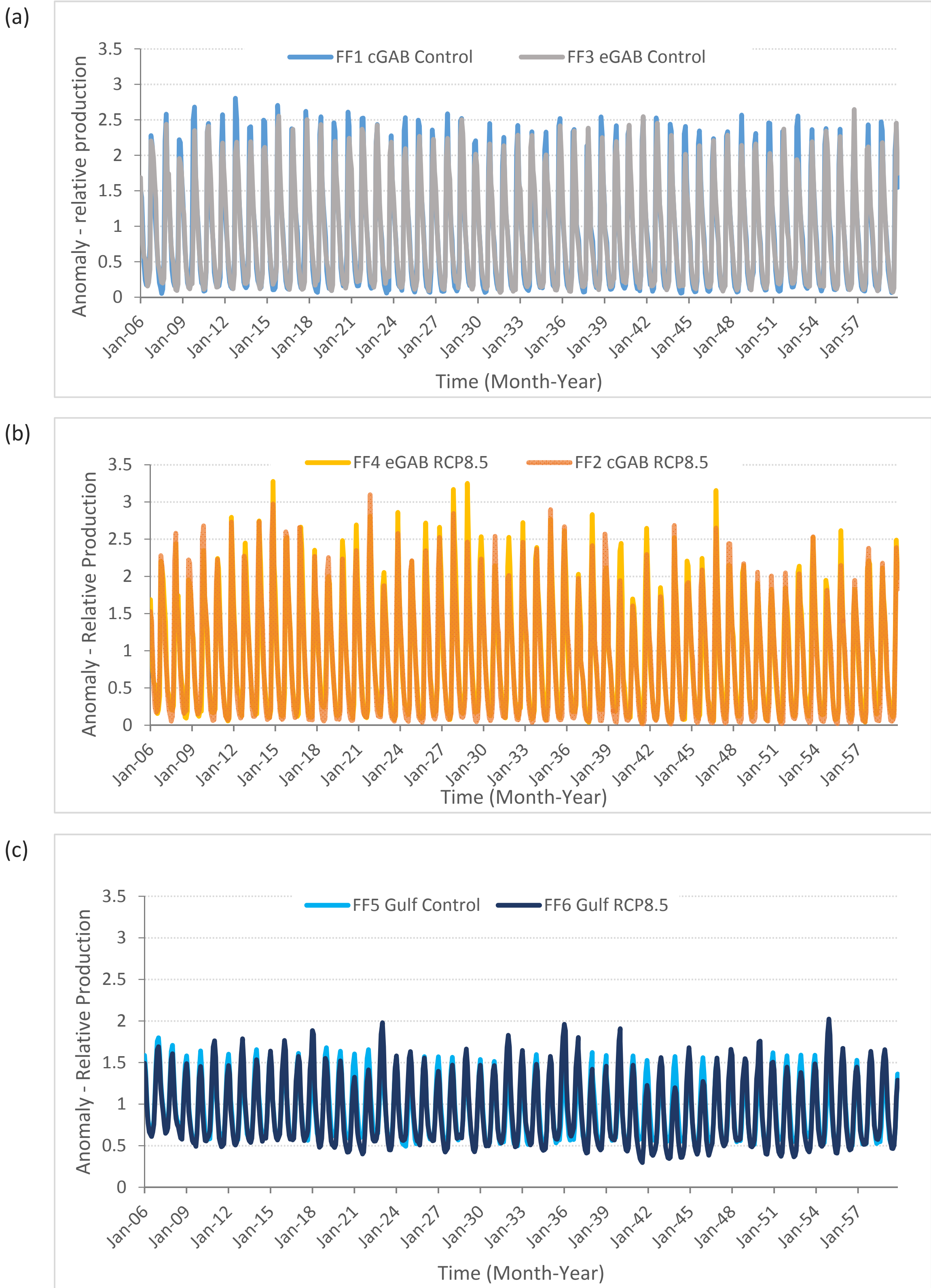


Figure 5.1. The production anomaly series derived from climate model projections that were implemented as forcing functions (FF) for a) the control (Status Quo) scenario comparing central GAB (FF 1) and central GAB (FF3); b) the RCP8.5 scenario comparing central (FF2) and central GAB (FF4) and c) the Gulfs projections comparing the Control (FF5) and RCP 8.5 (FF6) projections.

The six production anomaly series were applied as forcing functions on the large phytoplankton (eGAB (FF3 & 4) small phytoplankton (cGAB 1& 2), and seagrasses and macroalgae (FF5 &6) functional groups according to the appropriate scenario (*Status Quo* or RCP 8.5).

Scenario 2: Variation in fishing

The fishing scenarios use an ecosystem modelling convention regarding scenarios designed to gauge effects of fairly coarse variations in fishing effort; from no fishing, and from low to high fishing rates. This selection is in line with the magnitude of fishing pressure seen historically and with the gross levels of change typically needed to explore effects of fishing on ecosystems around the world.

The global trend in world fisheries is that we are fishing both down (Pauly *et al.* 1998), and through (Essington *et al.* 2006) the food web. While Australian fisheries are considered fairly well managed, through output controls such as quota management of species and stocks, overfishing has occurred in the past as a result of intensive and selective fishing (Flood *et al.* 2016) and continues for a small fraction of species due to the multispecies nature of a number of fishing gears. Consequently, the scenarios focusing on the variation in fishing pressure were particularly interested in exploring how increased and decreased fishing pressure on all fished groups could influence the GAB ecosystem.

Both ecosystem models used fishing mortality (F, exploitation) rates to represent the fisheries and so used time series of relative fishing pressure to represent the fishing scenarios. Five fishing scenarios were considered: no fishing (and no shipping) to look at how large the current anthropogenic footprint is on the GAB; as well as Fx0.1, Fx0.5, Fx2 and Fx10 where F is the 2016 fishing mortality rates (i.e. the F applied in the *Status* Quo simulations). These fairly gross changes in F were chosen so that gross responses could be considered. Much more nuanced scenarios – with different changes in F per fishing gear or stock could be implemented, but at present there was no guidance on what that mix should be so the simple gross changes in F were used as an illustrative example here.

Scenario 3: Spatial management

The spatial management scenarios looked at the broad ecological effects of zoning areas where no commercial activities occur, such as Marine Protected Areas (MPAs) and fishing closures. In the GAB there are several zones recognised in the Australia's Marine Reserve Network (Beeton *et al.* 2015, Buxton & Cochrane 2015) in addition to a number of state and federal fisheries closures, such as those imposed by AFMA for trawling and gillnetting (http://www.afma.gov.au/sustainability-environment/fishing-closures/closure-direction-maps/). Such spatial closures provide refuge for species and their habitat. They assist in the conservation of protected species, retaining biodiversity, and reducing the potential for species to become overfished (Claudet *et al.* 2008).

As this is a spatial scenario, explicit representation of this scenario was only implemented in Atlantis. To do this the proportions of each model box closed to fishing activities were estimated by overlaying authority-derived maps (Figure 5.2) on the shape file of the GAB model domain using QGIS. The nuanced zoning present in 2016 were implemented in the *Status Quo* scenario, which represented the pattern of zones by closing the estimated proportion of each box within a zone but only for those fisheries or activities affected by

the regulations. In the spatial management scenarios we then set up contrasting scenarios to explore the implications of a removal of spatial management or its extension to greater areas, specifically:

- A case with no fisheries or other closures, i.e. 100% full access to all commercial activities over the whole model domain.
- Cases with large-scale spatial closures of fisheries managed either by the states (70% of all coastal boxes were closed) or the Commonwealth (70% of all shelf and oceanic boxes were closed).

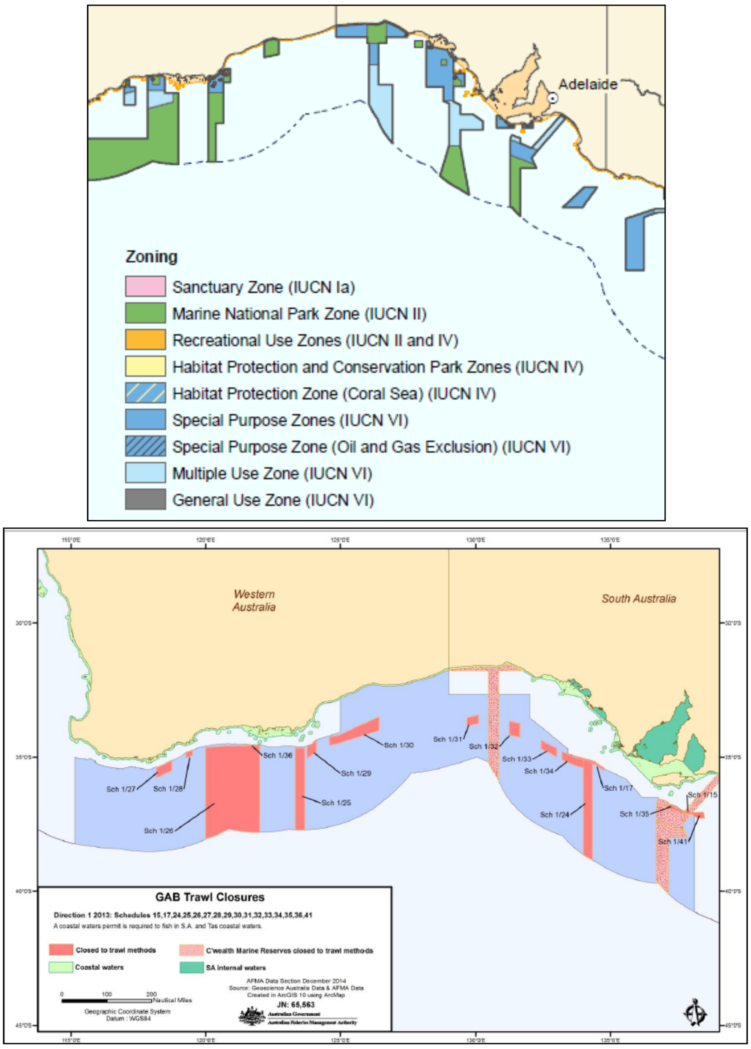


Figure 5.2 Maps of (A) the Commonwealth Marine Reserves Networks operating in the GAB model domain, and (B) the GAB Trawl Fishery closures.

Scenario 4: Sardine pathogen outbreak

The pathogen scenario was based on the mass mortality event that afflicted the spawning biomass of sardine in South Australian waters in the 1990s (Ward *et al.* 2001). The widespread mortality was shown to be unrelated to physical or biological oceanographic factors (Griffin *et al.* 1997), but was due to an introduced pathogen. The historical

mortality event lasted for several months and occurred in two separate years. The ecological implications of this event remain largely unknown.

The Australian sardine (*Sardinops sagax*) is the dominant small pelagic fish species in the GAB (Rogers *et al.* 2013a), where it is harvested to feed southern bluefin tuna in sea-cages near Port Lincoln. While small pelagic fishes have a significant trophic role worldwide, playing a pivotal ecological role in transferring nutrients from lower to higher order predators in marine upwelling ecosystems (Cury *et al.* 2000, Palomera *et al.* 2007), the situation is a little different in Australia. Previous modelling studies suggest that at large scales forage fish are not as central to the functioning of marine ecosystems in south east Australia as they are in other ecosystems around the world (Smith *et al.* 2015), as the forage species are a small part of total ecosystem biomass and predators switch to other prey species. Although observational data suggests that forage fish can form a sizeable part of the diet of seabirds and other iconic species, at least in some locations and seasons and for some species more than others (Expert Panel on a Declared Fishing Activity 2015). As the Smith *et al.* (2015) model covered a much larger area 4 million km^2 from the Western Australian border, around the southern and eastern coasts of Australia to the Lord Howe Rise) it was judged that a scenario looking specifically at the GAB region and the trophic dependency on forage fish would be insightful.

To replicate the widespread mortality in Atlantis we imposed a one-off mortality event where the linear mortality on juvenile sardines (<2 years old) was increased during the whole spawning period over the entire model domain in a single year at the beginning of the projection period (all other conditions were as for *Status Quo*). This event caused the mortality of approximately 70% of juvenile sardines.

In the EwE model, the mortality effect on sardine was mimicked by spiking fishing mortality (x4) over 8 months from October 2020 to May 2021, this timing matched the months and duration of the mortality event in 1999. Since the sardine population was not age-structured in EwE, mortality was attributed across the whole fishable population. While this means the scenario has the potential to have quite different consequences in EwE and Atlantis (as one reflects age specific mortality factors and one does not) both models were reflecting the event as faithfully as possible given their different structural configurations (which is the whole idea of a multi-model comparison).

Scenario 5: Southern bluefin tuna recovery

Southern bluefin tuna (SBT) (*Thunnus maccoyii)* is an extremely valuable fish species but is classified as Critically Endangered by the IUNC Red List of Threatened Species and is listed as Conservation Dependent under the EPBC Act. In the GAB, juvenile SBT are mainly caught by purse seine fishing where they are then transferred to inshore floating pontoons and raised for several months until they are big enough to be sold (Ellis & Kiessling 2015). SBT are highly migratory, with mostly juveniles coming into the GAB during the summer months (November to May)(Patterson *et al.* 2008).

The scenarios focusing on SBT were interested in examining the separate ecological and commercial implications of a high recruitment event; specifically, is a single event sufficient for supporting recovery or is a longer term increase required? And are the results different if management agencies hold F or catch constant (i.e. decreasing F with increasing biomass)?

In Atlantis the recruitment event was represented by forcing an increasing recruitment by approximately 30% in the first year of the projection period (all other conditions were as for *Status Quo*). Two management scenarios were then run with this recruitment forcing (i) with F as of *Status Quo* (i.e. F held constant) and (ii) where catch was held constant (the F time series needed to achieve this was calculated iteratively).

In EwE, a recruitment event was not directly modelled because the SBT population was not represented as an age-class structured group. Instead, we modelled a higher biomass of SBT via several methods: (i) a biomass accumulation of 10%; (ii) an immigration rate of 5% and a biomass accumulation of 5%; and (iii) a doubled SBT starting biomass. Biomass accumulation essentially "protects" biomass from unexplained mortality, predation or fishing mortality and that proportion of biomass is added to the population growth. The biomass accumulation term employed was to proxy both improved recruitment rates and lower mortality occurring outside the model domain in the Commonwealth and international fisheries. The first scenario meant that for each year an extra 10% of the biomass was added to the population growth. In the second scenario, we applied a lower accumulation rate of 5% but included an immigration rate of 5% to proxy both the recruitment and the external mortality, respectively. The last scenario was to proxy an event that resulted in a doubled biomass but wasn't sustained, more akin to the Atlantis scenario.

Once again the different model configurations meant that the event had to be represented using different mechanisms in the two models – biomass accumulation in EwE (effectively a constant increase in "recruitment" over the course of the projection) and a one-off recruitment event in Atlantis. Consequently, the results are likely to be different in outcome across the two models and represent alternative hypotheses about what might occur and what this means for SBT recovery patterns.

Scenario 6: Shipping spills and increased shipping traffic

Shipping has been identified as one of the main non-fisheries, non-aquaculture activities influencing the GAB system (Gillanders *et al.* 2016). Australia is the fifth largest user of shipping in the world with levels projected to increase substantially in the GAB. Thus, we included a shipping scenario to allow us to look at the ecological effects of a substantial increase in shipping (up to 1-2 orders of magnitude more compared to current shipping levels), with most traffic assumed to be in and directly adjacent to the Spencer Gulf (in Atlantis model boxes 7, 8, 18, 31 and 38). In the GAB Atlantis model, shipping impacted specific functional groups through assumed mortality from sediment resuspension, noise and strike (collision) interactions with cetaceans. In particular, the increased introduction of loud and complex noise sources into a range of habitats is of growing concern (Codarin *et al.* 2009, Nowacek *et al.* 2015). As shown in a number of studies (e.g. Codarin *et al.* 2009, O'Brien 2009, Todd *et al.* 2014), the main functional groups affected by increased shipping traffic included marine mammals, seabirds and soft-bottom benthic invertebrates such as filter feeders and benthic grazers (see Table 5.2). Macroalgae and seagrass have also shown to be impacted (Erftemeijer & Lewis 2006) and early work is suggesting that it may also influence fish behaviour (Rob Williams Oceans Initiative and Oceans Research and Conservation Association Canada *pers com.*).

A side-effect of increased shipping (whether that stems from increased development onshore or via offshore energy developments) is an increased risk of an accidental spill

due to ship collision (Det Norske Veritas 2011). Shipping is a major source of oil spills, both from normal operations and from accidental incidents, worldwide. The Australia Maritime Safety Authority has rated a spill due to a ship collision as one of the highest risk events in the GAB region – the high traffic along the shipping lanes making it much more likely than any other spill event in the region. Consequently, a collision associated shipping spill scenario was explored in scenarios considering the effects of a spill of 1,000 tonnes of heavy fuel oil in the GAB domain – one in mid shelf and one at the mouth of Spencer Gulf (Figure 5.2).

Historically, there has been only two major oil spill (>1,000 tonnes) incidents within Australian waters since 1970, the Oceanic Grandeur and the Kirki (SoE 1996). However, bulk carriers are increasingly common in the GAB (Flinders Ports Chief Engineer, Mr Doug Dow, pers. comm. 13/7/2017) and exhibit a spill risk that is much larger relative to other ship and accident types in Australia (Det Norske Veritas 2011). While most oil spills result from accidents during fuelling of vessels, AMSA is particularly concerned by a collision at sea between vessels on increasingly congested shipping lanes (compared to the extent of the ocean shipping lanes are quite constrained), especially as the fuel oil released in such an event is likely to release much heavier grade oil (i.e. more persistent and toxic) than the lighter grades of oil extracted in Australian waters. To cover the potential extent of spills in different seasons, January and July event dates were explored.

Oil spills have been shown to have large impacts on seabirds, marine mammals, and pelagic fish and plankton species including physical disturbance, behavioural changes, fouling, and ingestion with additional physiological effects of bioaccumulation (Ellis *et al.* 2013, Fraser 2014, Duke 2016). The acute effects on the modelled biological groups were represented via a forcing file of spatially imposed mortality on all functional groups known to be effected by oil toxicity (Table 5.2). Relative changes in the biomass and ecosystem structure were then observed.

Table 5.2: List of species potentially affected by oil spill and magnitude of that effect. Only mortality impacts have been included in this scenario. Growth, reproduction and other chronic affects may be included in future work.

Common name	Assumptions
Aquaculture tuna	Low (as physical protective boundaries assumed to be deployed)
Aquaculture mollusc	Low (as physical protective boundaries assumed to be deployed)
All finfish groups	Age dependent LC50 required, larvae assumed to be highly sensitive, while sensitivity of small fish is moderate and large fish is low (as defined in French-McCay 2004; Young *et al.*2011) except for SBT where sensitivity is high (Young *et al.*2011)
Shark groups	Low (as most effects are thought to happen through consumption of contaminated prey; Young *et al.* 2011)
Seabirds	High but nonlinear sensitivity (e.g. due to oiling of feathers by direct high concentration contamination)
Seals	Moderate to high sensitivity (as for North American species)
Cetaceans	Low sensitivity
Lobster	Moderate sensitivity
Abalone and urchins	Moderate to high sensitivity (Suchanek 1993)
Bivalves	Moderate sensitivity
Other epifauna	Moderate sensitivity
Infauna	High sensitivity
Zooplankton	Low sensitivity
Phytoplankton	No additional mortality due to exposure, as end point studies typically focus on growth for cold water species (Olsen *et al.*2013)
Macroalgae & seagrass	Smothering only (as of French-McCay 2004)

Modelling oil spills is a complicated process due to processes such as evaporation, weathering and dispersion, and this degree of complexity was not captured here. However, an existing particle tracking model applied in the BRAN modelling framework was used to simulate basic dispersal dynamics of the spills (Figure 5.3). The spill footprints and likelihood of contact with oil was estimated using the Australian Connectivity Interface (CONNIE; Condie *et al.* 2005) forced by the currents from the BRAN2.1 model data (which captures the gross behaviour of the models from GABRP Theme 1 but is not identical; in particular it does not include wave dynamics). The CONNIE model tracked the location of particles on a daily basis, which were aggregated up to a 0.5 degree grid. For each location there were two separate releases (1 January and 1 July) and particles were tracked for 60 days in the surface waters (>5 m depth). Each model run released 1400 particles. Particles had an exponential decay rate of 9 days and were exposed to 3% wind. This was repeated for the same date every year for the 14 years available in the BRAN repository and then the cumulative probabilities were averaged over the 14 years to provide the final footprint. This was done to attempt to account for uncertainty associated with inter-annual variation in dispersal conditions (e.g. specific current directions and strengths etc) between years. This CONNIE output was then translated into an exposure metric for the GAB Atlantis boxes by summing probabilities across grid cells falling into each Atlantis model box. Given the size of Atlantis boxes the end result of this mapping process produces end point distributions quite similar to those that the Theme 1 GABRP models would produce when mapped to the same boxes (particularly given multiple seasons and years were considered – so while wave dynamics can lead to different directions of onshore flow to dynamics based on wind, across the 4 footprints considered the bulk the GAB coastline comes under one footprint or another so any specific spatial differences are already covered, at least in a gross form).

The exposure metric per box was then used to scale spatially-explicit increases in mortality on the potentially impacted functional groups. Base rates of mortality and LC50 (lethal concentration required to kill 50% of the population) were taken from the literature, largely associated with laboratory studies or the Deepwater Horizon and Exxon Valdez spills (Suchanek 1993, French-McCay and Jennings 2002, French-McCay 2004, Shigenaka 2011, Young *et al*. 2011, Eliis *et al*. 2013, Olsen *et al.*2013, Kang *et al.* 2014). LC50 rates were further modified for the exposure time per location and ambient temperature using the methods from (De qi *et al*. 2000; Gin *et al.* 2001, McCay *et al.* 2004).

Note that these scenarios should be considered a simple demonstration of potential rather than definitive statements of spills in the region.

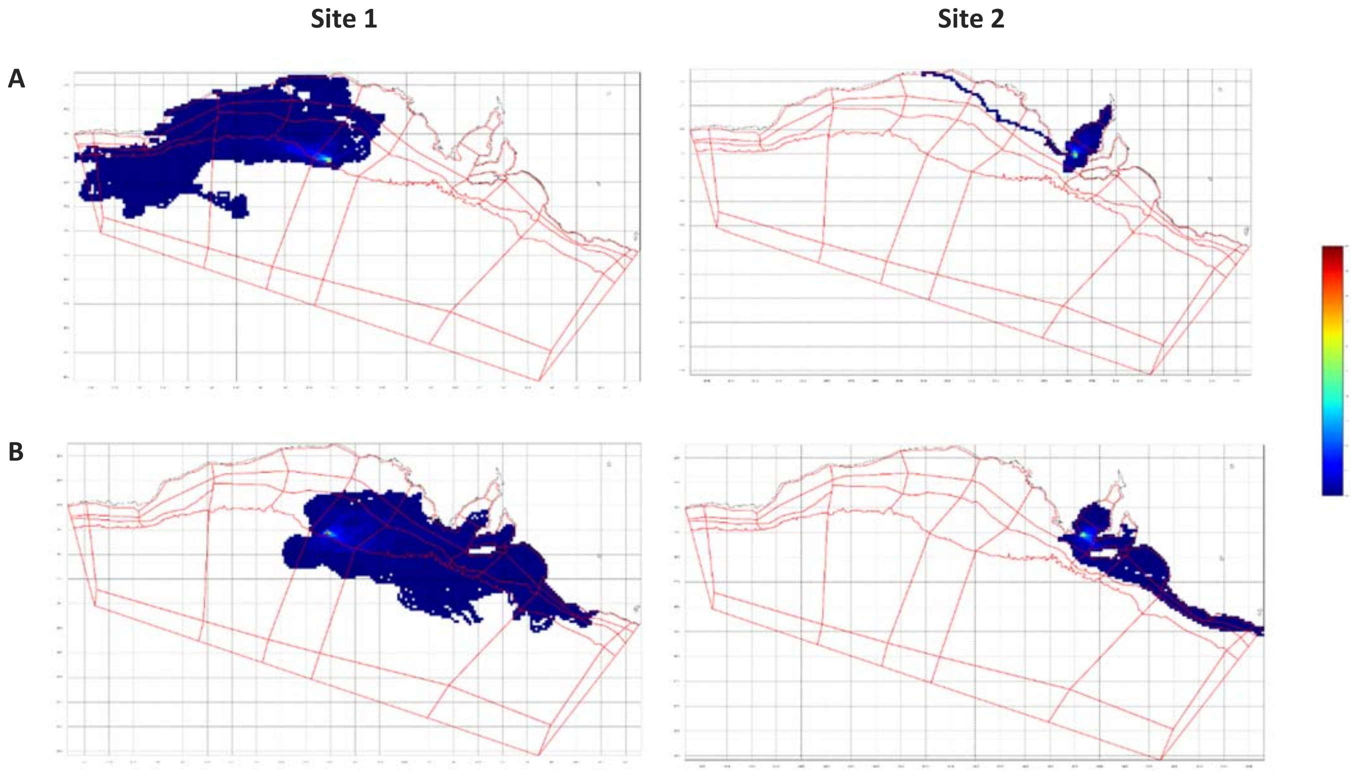


Figure 5.3. Probabilities of exposure to oil from oil spill scenarios at two different locations in (A) January, and (B) July.

5.3 Reporting

5.3.1 Model Trajectories

Change in relative biomass and catch is the main diagnostic used with model output (EwE and Atlantis). The change for variable *x* (Δ_x) is calculated as:

$$\Delta_x = 100 \cdot \left(\frac{\bar{x}_T}{\bar{x}_{SQ}} - 1\right)$$

where $\bar{x}_T$ is the average value over the final 5 years of the scenario (treatment) projection period and $\bar{x}_{SQ}$ is the average value over the final 5 years of the Status Quo simulation.

5.3.2 Ecological Indicators

A number of integrative ecological indicators were also evaluated from the Atlantis simulations to ascertain ecosystem health in the alternative scenarios (Fulton *et al.* 2005). Diversity (Kempton Q) and proportional habitat cover were considered along with the size and compositional indicators recommended by INDISEAS (Shin et al. 2010). Biomass ratios of pelagic and demersal groups, piscivores and planktivores, and infauna and epifauna were also assessed as indices of food web structure and integrity.

5.3.3 Statistics

To help simplify interpretation, a multivariate cluster analysis and principal components analysis was performed (using R version 3.2.2) on the relative biomasses and indicator values.

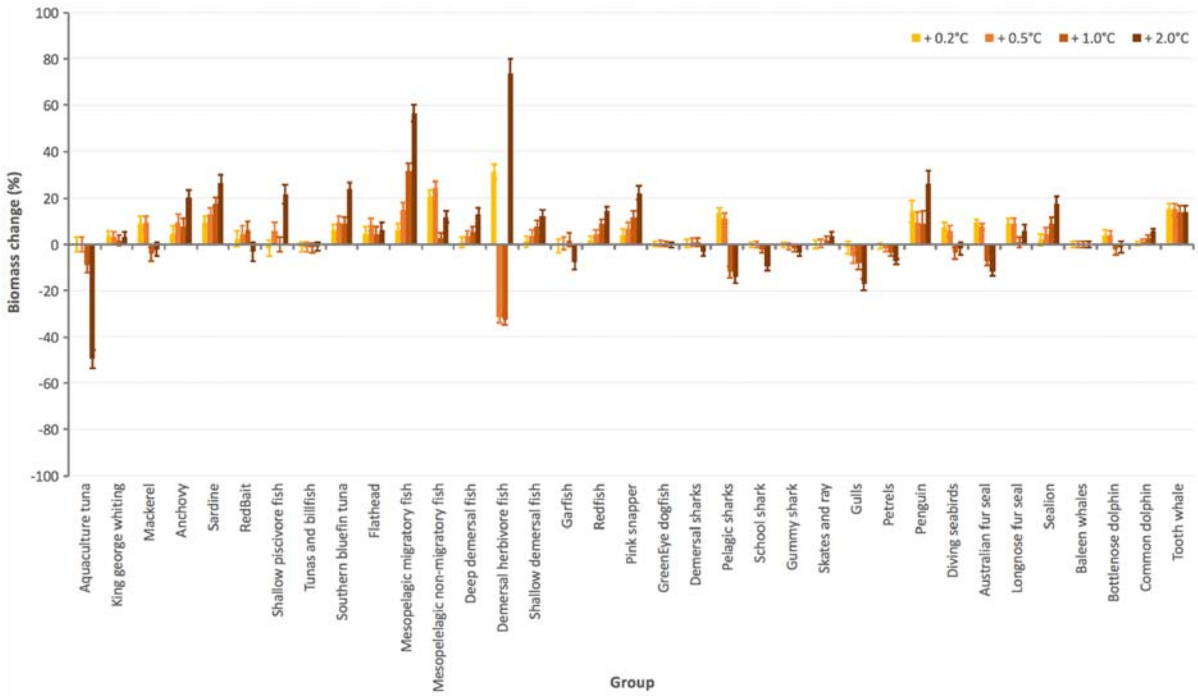
5.4 Results

Variable responses in the relative biomass of individual functional groups were observed for each of the scenarios. We have detailed the impacts of each scenario on the relative biomass and catch of functional groups, before describing scenario driven outcomes in terms of the ecosystem performance indicators. In each case, the biomasses (catches and ecosystem indicators) under the scenario were compared to those of the *Status Quo* simulation to assess the potential influence of the drivers in the scenario on the GAB ecosystem. Note these results only reflect the outcome of a single parameterisation of the model and so do not reflect the degree of uncertainty that exists around the outcomes.

Scenario 1: Ocean warming

The four Atlantis scenarios representing different degrees of warming in the GAB show variable impacts on functional groups (Figure 5.4), but universally indicate that ocean warming has the potential to impact the GAB ecosystem. For many of the teleost groups increasing temperature caused biomass to increase (though often with spatial redistribution), whereas approximately half the invertebrates increase and half decrease. For many of the iconic species (sharks, mammals and birds) there is an increase under the lower temperature rises (due to rising feed levels and enhanced physiological rates), but as the temperature rises further then the populations begin to decline as either forage or individual thermal tolerance is exceeded. Whether an increase or decrease, the hottest climate scenarios (an increase of 1.0 and 2.0°C per decade) had the greatest ecological consequences, particularly on coastal and pelagic groups. Groups that benefited from increasing temperature (or its influence on competitors, predators or prey), with highest increases in relative

(a)



(b)

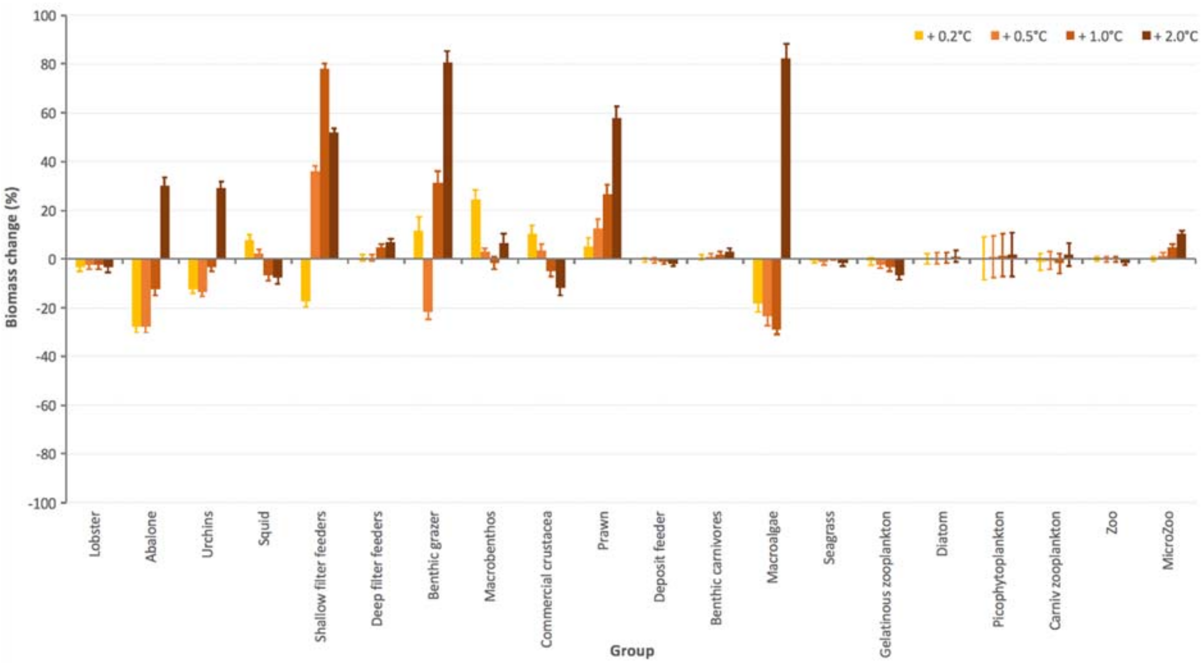


Figure 5.4. Relative changes (%) in the total biomass of (a) vertebrates and (b) invertebrate functional groups under the ocean warming scenarios in Atlantis – calculated relative to the Status Quo simulation.

biomass, were small phytoplankton, aquaculture molluscs, penguins and mesopelagic fishes. The groups most negatively impacted (either directly or via food web or habitat interactions) included macroalgae, abalone, herbivorous fish, commercial crustaceans, seabirds, pelagic sharks (e.g. white sharks) and long-nosed fur seals. Although it should be noted that if algae robust to climate change can become established then grazers on that food source (like abalone) may still tolerate the changes in some spatial locations (potentially at greater density than now). However, this is very uncertain and the results presented should be considered with caution, as the model does not capture explicit evolutionary change or very fine scale dynamics that may be important for some species (e.g. aquaculture molluscs). As the fishery is based on fishing mortality (F), with no changes in the fisheries management rules, the catches reflect the changes in biomass.

The only EwE scenario explored was that for the RCP8.5 scenario equivalent to the most extreme Atlantis scenario of 2.0°C per decade. The peak of the production anomalies under this scenario are lower than under the *Status Quo*, with relative biomasses of oceanic primary producers (except small phytoplankton) dropping by about 10 - 20%, as did coastal macroalgae and seagrasses (Figure 5.5). Consequently, it is unsurprising that biomasses of the majority of groups, either vertebrate or invertebrate, declined; although trophic interactions meant there were some significant exceptions. As predators, particularly top predators declined some of their prey increased – for instance, large pelagic piscivore biomass (representing barracouta, Australian salmon, tailor, gemfish and yellowtail kingfish) more than doubled, snapper increased by over 20% and rock lobster almost doubled. Gannets also increased by nearly half (Figure 5.5). However, in general changes were of lower magnitude and overall, about half of all changes (either positive or negative) were less than 10%. The changes in catches reflected biomass trends, with catches for large pelagic piscivores, snapper and demersal piscivorous sharks and rock lobster increasing by more than 10% (Figure 5.6).

Across the two models 42% of the groups agree in the direction of change under climate forcing (comparing EwE results to the Atlantis scenario with a of 2.0°C increase per decade) – including cultured species, mackerels, red bait, tuna and billfish, shallow demersal fish, garfish, the shark groups, gulls, petrels, Australian fur seals, bottlenose dolphins, squid, prawns and commercial crustaceans, infauna (deposit feeders and benthic carnivores), seagrass, gelatinous zooplankton and mesozooplankton. However, even when direction matches the magnitude typically does not. Only approximately 10% of groups changed in the same way to the same magnitude across models – specifically pink snapper, school sharks, Australian fur seals and gelatinous zooplankton. In most cases the magnitude of change in EwE is much larger than in Atlantis (from 1.5-80x higher). This relative sensitivity of EwE in comparison to Atlantis is well known (Fulton and Smith 2004) and is not unexpected given the fundamental difference in the structure of the models (Johnson *et al.* 2011, Smith *et al.* 2011). Typically, EwE tends to be more reactive than Atlantis, as EwE has little or no size-/age structuring in functional groups or diet interactions and so has little delay processes that buffer change. It is noteworthy that in this case inshore and forage species Atlantis were as reactive as EwE, suggesting the system (or at least key parts of it) is structurally sensitive to drivers through both trophic interactions and the nutrient cycle, and habitat dependencies.

(b)

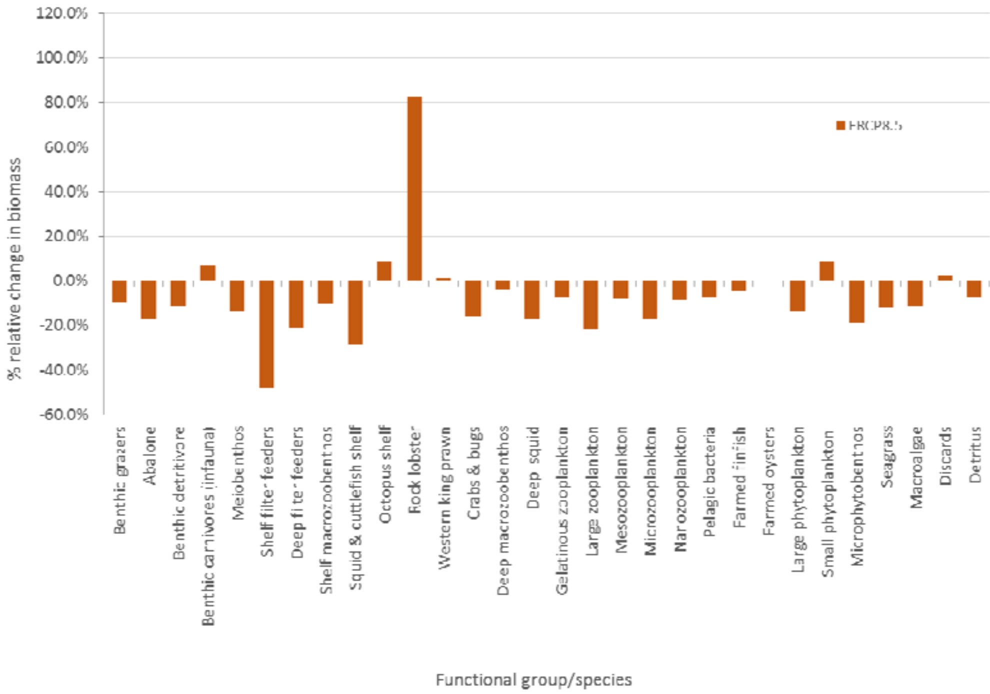
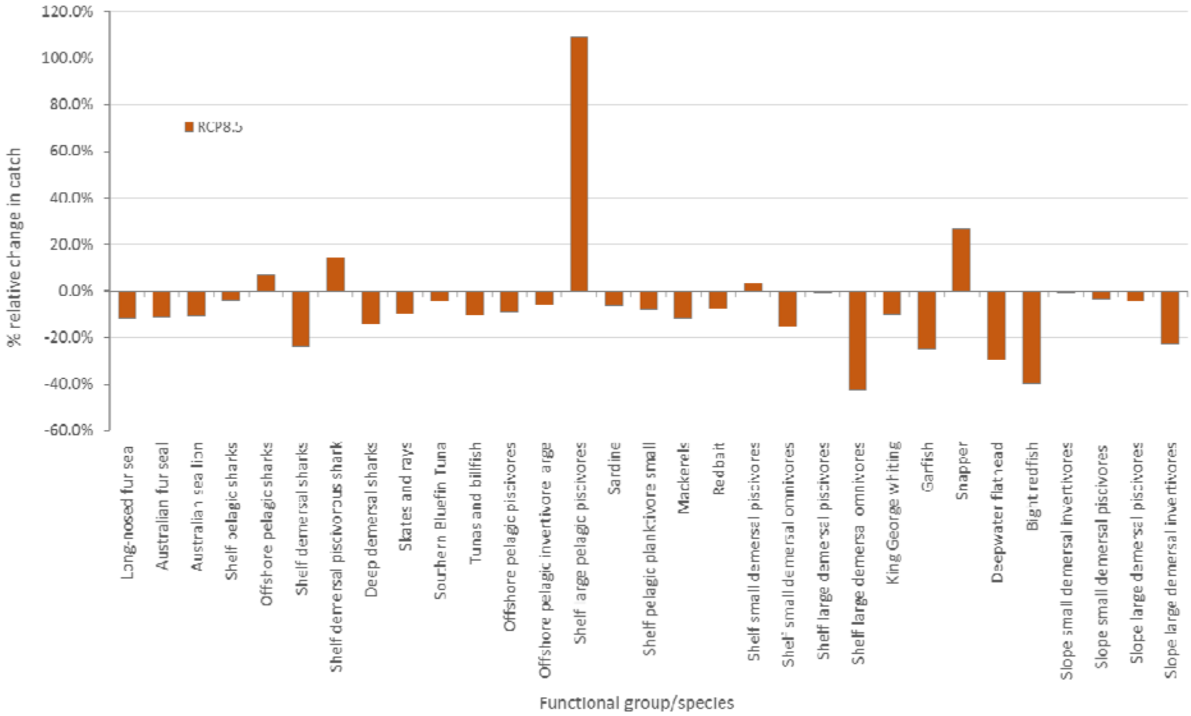


Figure 5.5. Relative changes (%) in the total biomasses of (a) vertebrates and (b) invertebrate functional groups under the ocean warming RCP 8.5 scenario in EwE – calculated relative to the Status Quo simulation.

(a)



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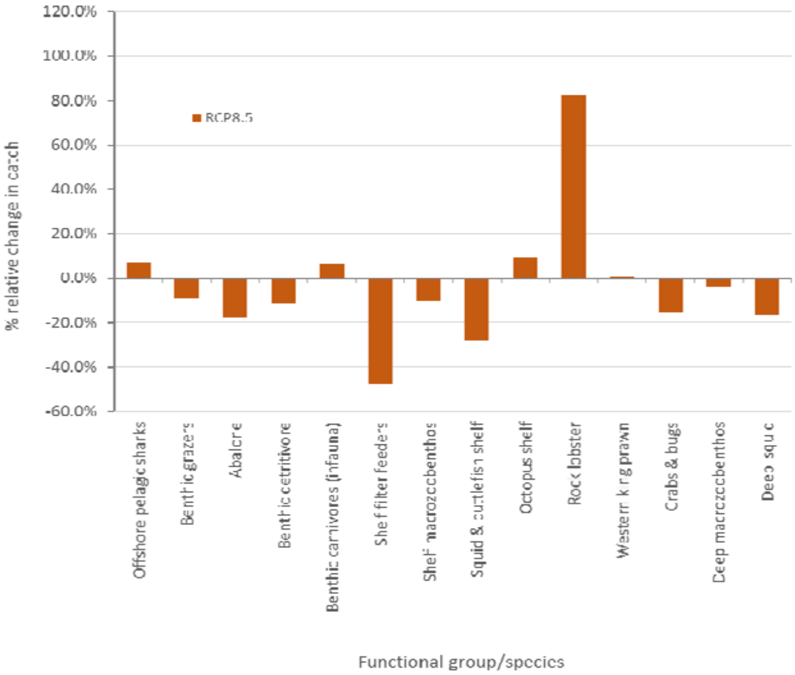


Figure 5.6. EwE relative changes (%) in the total catches of (a) vertebrates and (b) invertebrate functional groups under the ocean warming RCP 8.5 scenario– calculated relative to the Status Quo simulation.

Scenario 2: Variations to fishing levels

Amongst the Atlantis fishing scenarios, the scenario with the greatest negative impact on the relative biomass of functional groups, and on the overall ecosystem structure and integrity, was the

high fishing scenario (where levels of fishing pressure where ten times the *Status Quo*). Indeed, the ten-fold increase in F scenario had the biggest impact on all of the fished groups in Atlantis, driving many to extirpation.

Most functional groups targeted by fishing in Atlantis were sensitive to the level of change in fishing regimes (Figure 5.7). No, or reduced, fishing saw the relative biomass increase substantially (>50%) for King George whiting, piscivorous fish, garfish, flathead, demersal fishes (deep and shallow) and gummy and school sharks. The same teleosts showed major declines (of >50% relative biomass or more) when fishing was increased by a factor of 10, as did sardines, prawns, benthic grazers and rock lobsters. Sharks followed a similar pattern to the fish, but did not decline by as much with increased fishing pressure.

Flow-on effects of changes in fishing pressure were also observed in the un-fished groups in Atlantis, but were small. For example, small (<2%) increases in relative biomass were observed in small and large phytoplankton under a drop in fishing pressure, whereas similarly small decreases in biomass occurred at high levels of fishing pressure. Shifts in the levels of competition or predation pressure also saw shifts in the biomasses of the unfished mesopelagic fish groups.

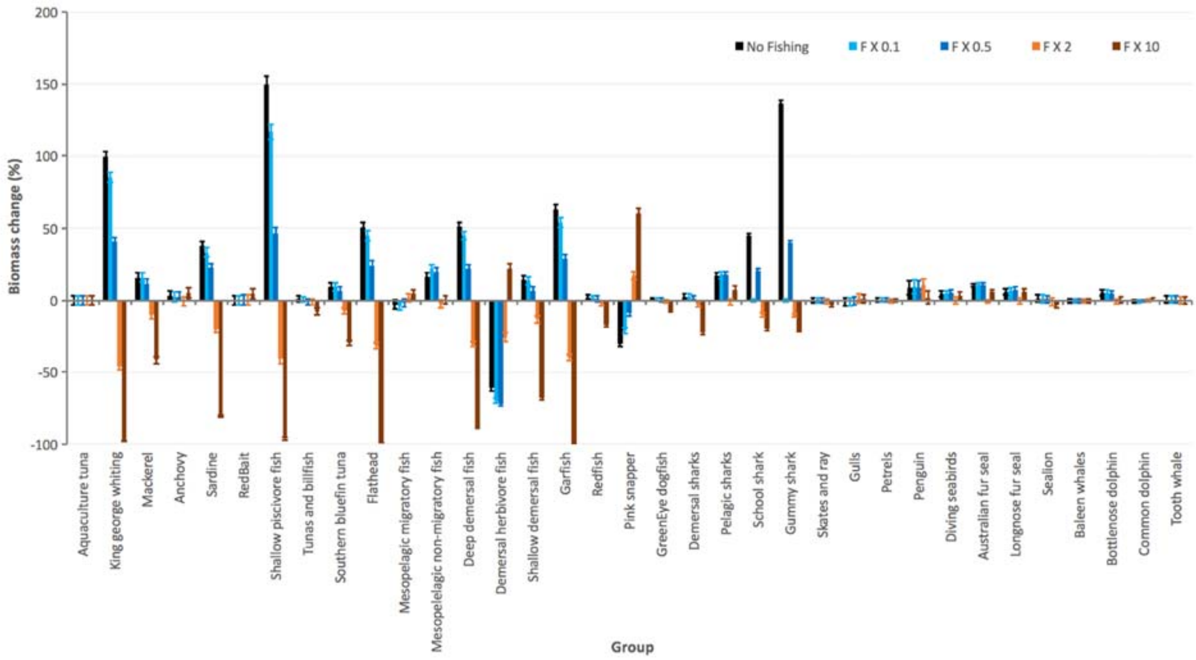
Projected catches in Atlantis typically rose with increasing fishing pressure and dropped with decreasing pressure (Figure 5.8). Some stocks were so depressed, however, that total catch actually fell under the tenfold increase in fishing mortality rates (e.g. shallow piscivorous fish, King George whiting, flathead, garfish, school shark and prawns).

Similar to Atlantis results, the EwE scenario with the greatest negative impact on the biomass of fished species was the ten-fold increase in fishing pressure. A total of 25 functional groups decreased in biomass by more than 20%. The most notable decreases (>50%) occurred in rock lobster, snapper, shark groups, SBT, garfish, shelf pelagic piscivores, deepwater flathead, bight redfish (all fished groups) (Figure 5.9). Indeed, rock lobster declined by 100% i.e. it was extirpated, while the rest were close to a 90% decrease. Not all groups decreased however, with seven functional groups increasing in biomass by 20%. Most notable increases occurred in the large demersal invertivores on both the shelf and the slope and the crabs and bugs, all increased >200%, followed by bight redfish (82%) and cormorants (92%). These responses were the direct result of the removal of predation pressure on the invertebrates, with knock-on benefits to some of their predators (e.g. cormorants). In the case of bight redfish the increased fishing pressure was not sufficient to overwhelm the benefits of the removal of predation pressure as predators such as demersal sharks were removed.

With reduced fishing pressures (e.g. no fishing), rock lobster and SBT biomasses improved the most in EwE: by as much as 800% and 400%, respectively. On the other hand, benthic grazers, crabs and bugs and bight redfish declined at the lower fishing pressures (as their predators increased in biomass).

As expected for these scenarios, EwE catches varied in accordance with the imposed fishing effort (Figure 5.10), with the exception of exceptionally large increases (>3000%) in the catches of large demersal insectivores on the shelf, large demersal piscivores on the slope and crabs and bugs under a ten-fold increase in fishing pressure. This is because of very large increases in the biomass of these groups under heavy fishing pressure (due to a release of predation and competition pressure as predators and competitors are being removed by the fishery) as well as increased direct fishing pressure (with these highly productive groups easily able to absorb that additional pressure given the biomass increases). While these changes are relatively large, they are being compared to very low initial values.

(a)



(b)

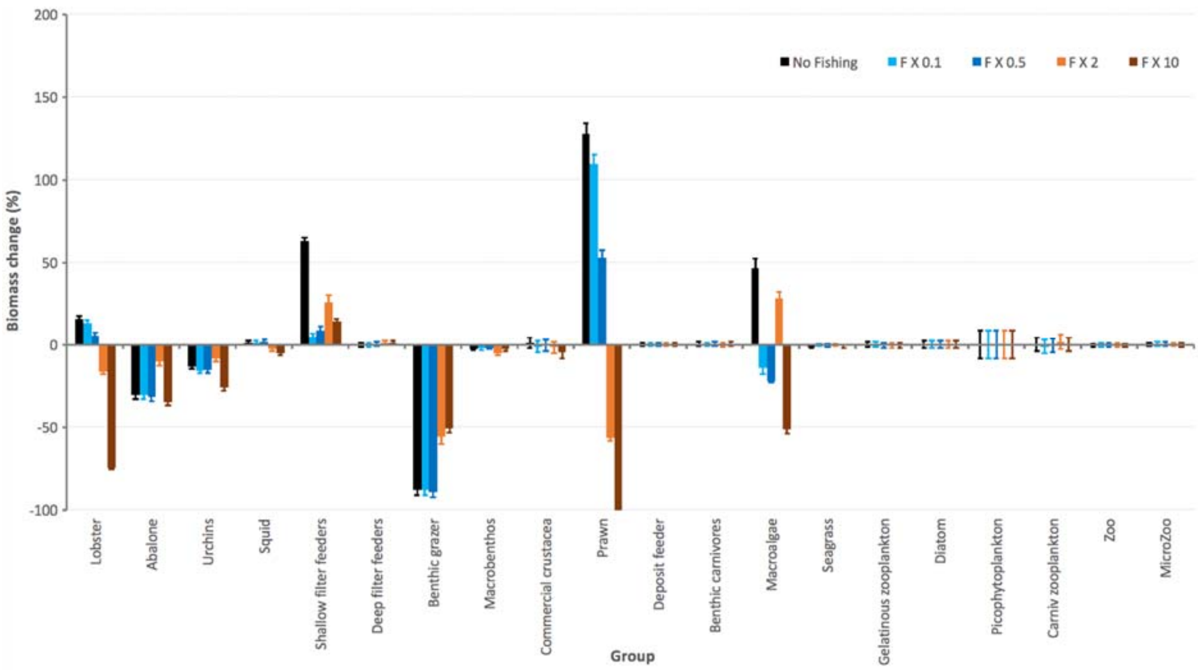
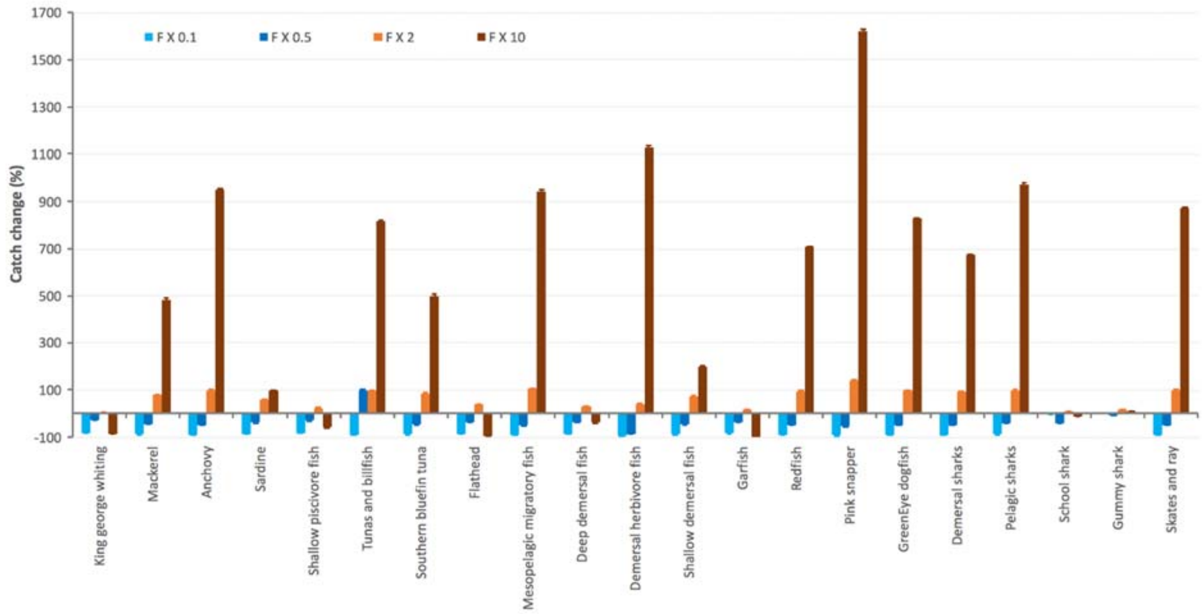


Figure 5.7. Relative changes (%) in the total biomass of (a) vertebrates and (b) invertebrate functional groups under the fishing scenarios in Atlantis – calculated relative to the Status Quo. Note that the biomass change axis is to a different scale to the fishing and shipping related scenarios.

(a)



(b)

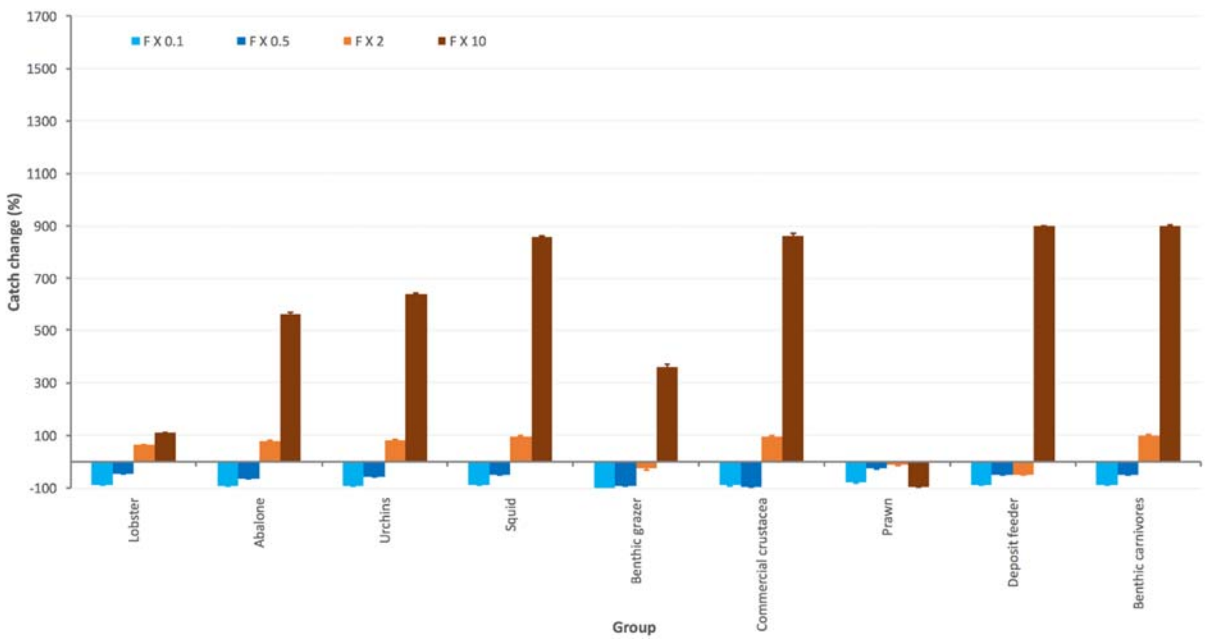


Figure 5.8. Relative changes (%) in the total catch of (a) vertebrates and (b) invertebrate functional groups under the fishing scenarios in Atlantis – calculated relative to the Status Quo simulation.

(a)

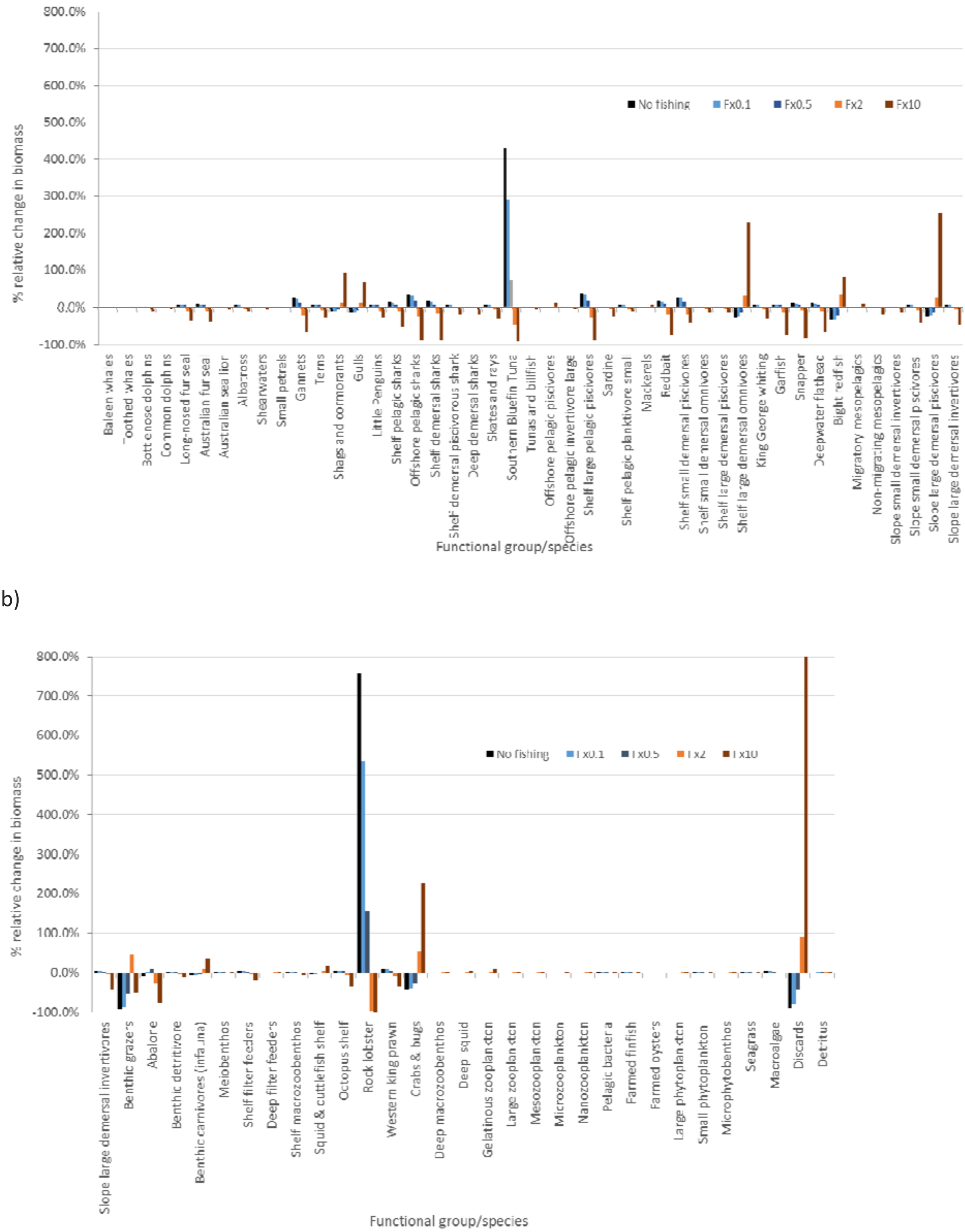
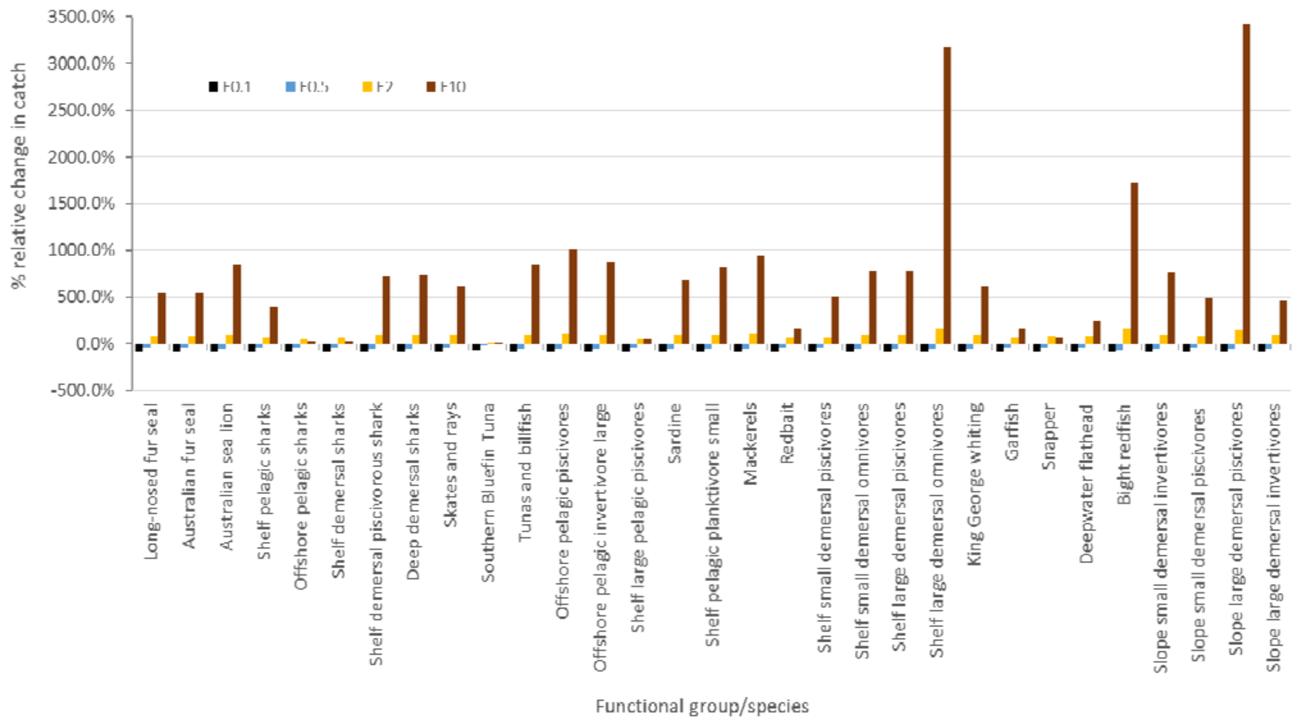


Figure 5.9. Relative changes (%) in the biomasses of (a) vertebrates and (b) invertebrate functional groups under the fishing scenarios in EwE – calculated relative to the Status Quo scenario.

(a)



(b)

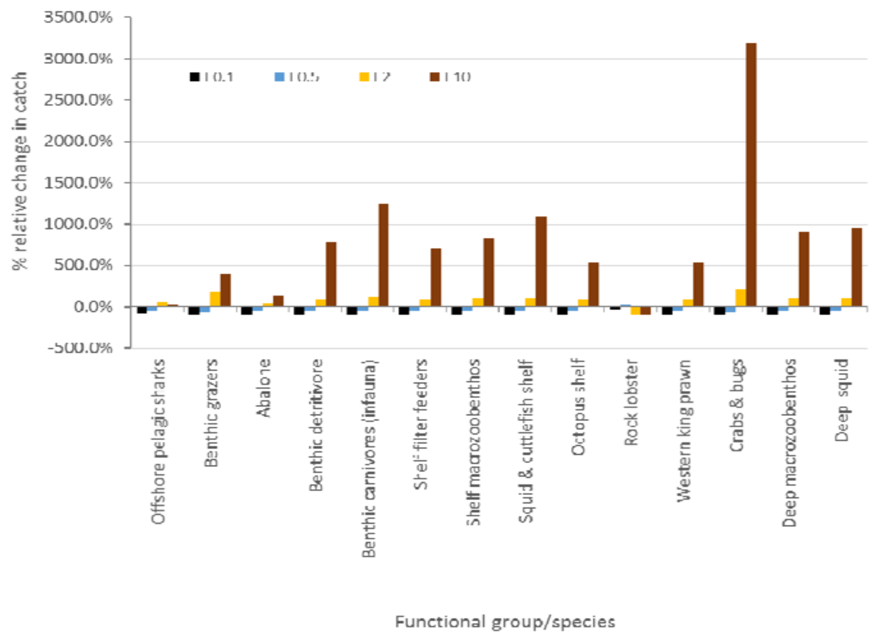


Figure 5.10. EwE relative changes (%) in the catches of (a) vertebrates and (b) invertebrate functional groups under the fishing scenarios in EwE – calculated relative to the Status Quo scenario.

Despite the direction of change differing for half the groups in the models, both models have 70-75% of groups with change of less than 20% versus Status Quo. Again this is not unusual when comparing the output of Atlantis and EwE for similar scenarios (e.g. in an analysis of fishing effects of lower trophic levels both models had the majority of effects at <20% but the specific direction of change for individual groups could be in opposite directions (Smith et al. 2011). These behavioural differences were also compounded by the different way in which the warming was implemented in the two models – with the EwE scenario taking into account regional down-scaled projections, whereas this was not possible for Atlantis, which had to be based on global climate model projections instead. Global projections do not yet represent coastal processes at all well and this may account for at least some of the differences noted in the response of primary producers between the models (primary production drops for EwE but increases slightly for Atlantis), which in turn affects higher trophic levels. As suitable regional down-scaled physical forcing has now become available future Atlantis projections could use this for RCP 8.5, which might lead to more convergent projections.

Extremes of fishing pressure such as we have modelled here were expected to perturb the system significantly and were chosen to demonstrate precisely that. Atlantis effects were often much greater in magnitude than for EwE model, this has been observed in other inter-model comparisons (Fulton and Smith 2004) and is partly due to the age-structured representations in Atlantis (which prevent the rapid responses of EwE which can buffer fishing effects) as well as the explicit spatial representations and habitat dependency – species requiring biogenic habitats in Atlantis are not only directly affected by fishing, but also by any impacts on the habitat forming groups. Nonetheless, comparing across the models they were in agreement regarding the direction of change for the majority 70-80% of groups when fishing pressure was lowered (Fx0, Fx0.1, Fx0.5) or under a doubling of fishing pressure, but the projected direction of change only agreed for 50% of groups if fishing pressure increased by tenfold. The greatest disagreement was around the direction of change of primary producers and their grazers – with Atlantis projecting small decreases whereas EwE saw moderate increases. The two models also disagreed over the effects on top predators, with Atlantis projecting relatively small changes, while EwE predicted quite strong falls.

Scenario 3: Spatial management

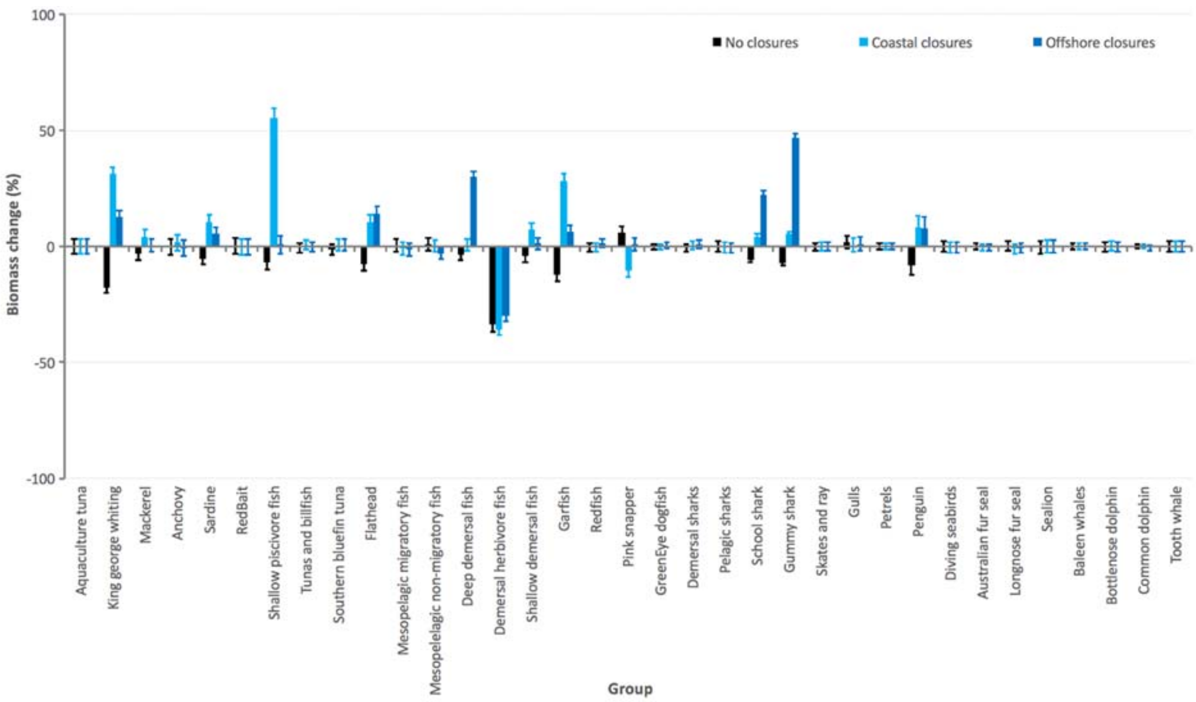
Changes to the current spatial management regime (as defined in the *Status Quo* scenario) saw relative biomasses change by as much as 50% or more (Figure 5.11). Removing all current State and Commonwealth Marine Reserves and fishery closures saw substantial reduction in the biomass of coastal fishes – such as King George whiting, garfish and demersal herbivorous fish – as well as forage species such as small pelagics (anchovy and sardines), prawns, benthic grazers, urchins, abalone and macroalgae. There were also declines amongst penguins and the smaller sharks – such as school and gummy shark. The mammals (at one extreme) and the plankton (at the other) showed no real change, as did many of the seabirds – although this may be because the potential levels of bycatch might be under represented, as the parameterisation currently depends on a period where the rates were lower than at other points in the past.

Closing 70% of all coastal boxes to commercial activities increased the biomass of most coastal fish groups that were fished (e.g. King George whiting, garfish and demersal shelf fishes), though many invertebrates dropped as their predators increase. For a similar (70%) closure of all offshore boxes (Commonwealth fisheries), the groups that showed the greatest benefit (with >10-20% relative biomass) were the target of the offshore fisheries – such as deep demersal fish, gummy and school sharks. More moderate increases were observed in flatheads and sardines, as well as some of the

coastal fishes that benefited incidentally. Zone closures also saw the relative biomass of other groups, such as non-migratory mesopelagic fishes, herbivorous fishes, pink snapper and many of the invertebrate groups decrease.

All fishing fleets were impacted by changes in spatial management. A reduction in closures almost universally led to an increase in catch, whereas the imposition of 70% closure on coastal or offshore boxes saw a drop in catch (Figure 5.12), in many cases quite substantial drops in catch that were far beyond what might have been expected based solely on shifts in biomass.

(a)



(b)

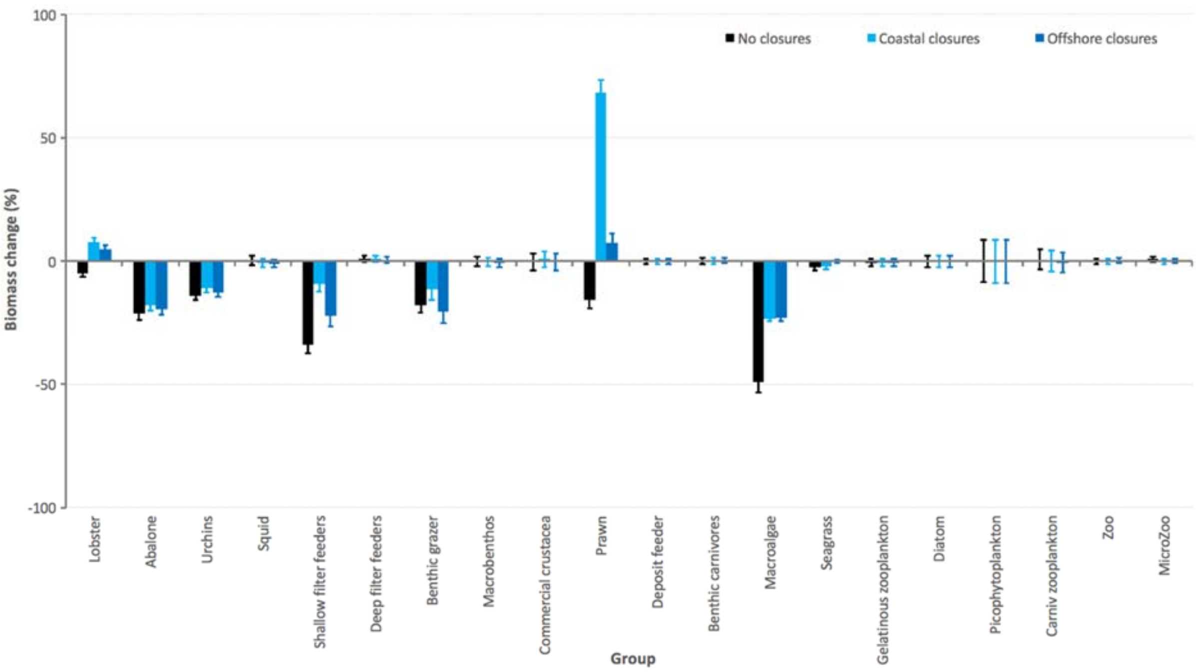
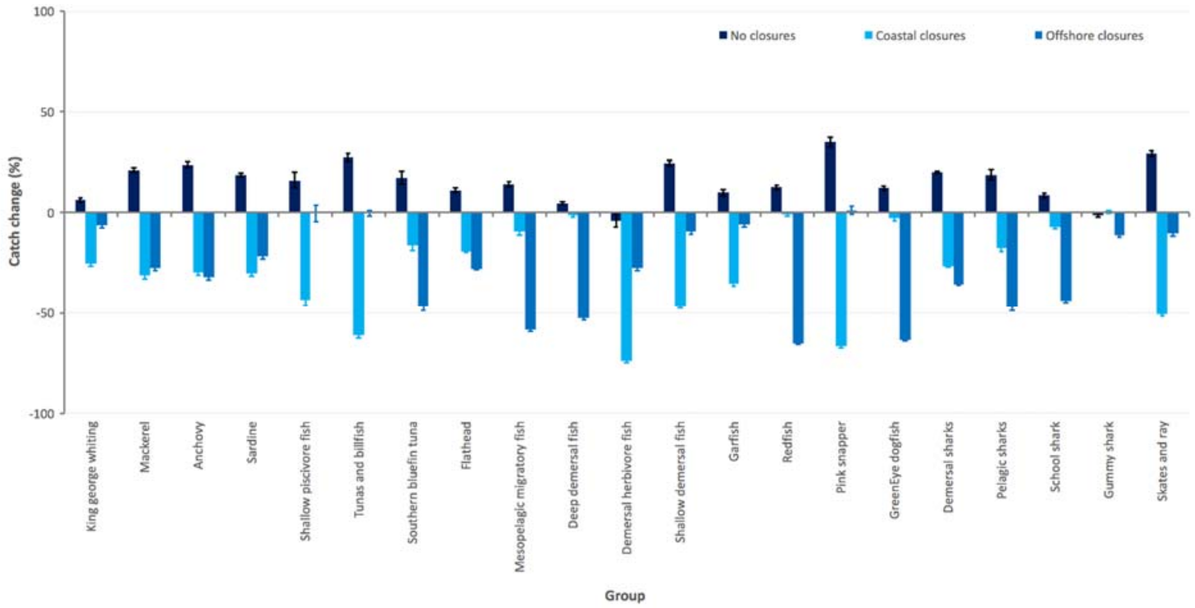


Figure 5.11. Relative changes (%) in the total biomass of (a) vertebrates and (b) invertebrate functional groups under the spatial management scenarios – calculated relative to the Status Quo.

(a)



(b)

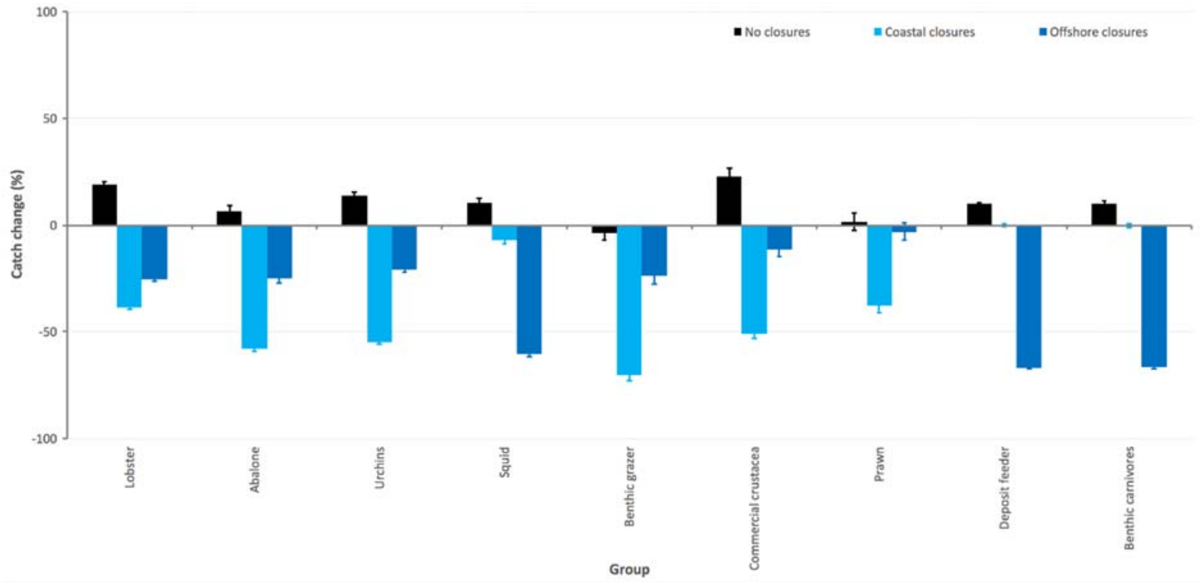


Figure 5.12. Relative changes (%) in total fishing catches of (a) vertebrates, and (b) invertebrates under the spatial management scenarios – calculated in comparison to the Status Quo scenario.

Scenario 4: Sardine pathogen outbreak

The imposed mass mortality on juvenile sardine saw the total biomass of the stock drop by as much as 40% in the short term, but returned to about *Status Quo* levels within a decade (Figure 5.13). Ultimately the stock recovered to within 1% of the *Status Quo* by the end of the projection period.

During the period of stock depression, the ecological consequences of the mass mortality event were evident in the main predators of sardine (including SBT, seabirds and marine mammals), though their biomass varied by < 5%. The major exception was penguins, which declined 20% in abundance, though they rebuilt as sardines did; eventually (rather unexpectedly) ending at higher biomasses than under *Status Quo*. This is the result of interactions mediated by zooplankton, which had an increase and then mild oscillations even after the sardines recovered (due to subtle changes introduced into benthic food webs via interactions mediated by filter feeders and gulls).

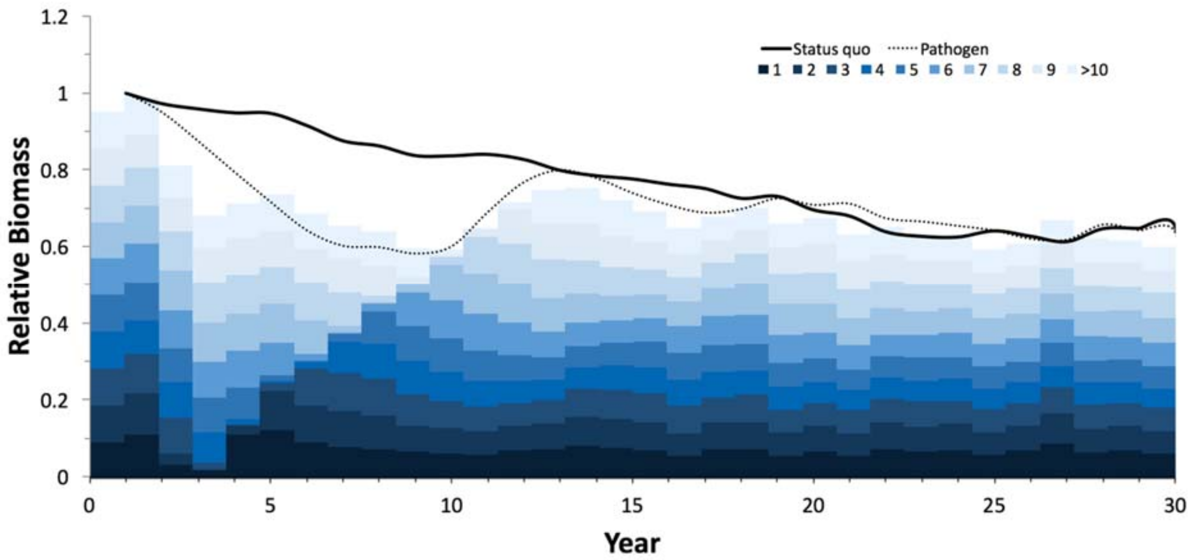
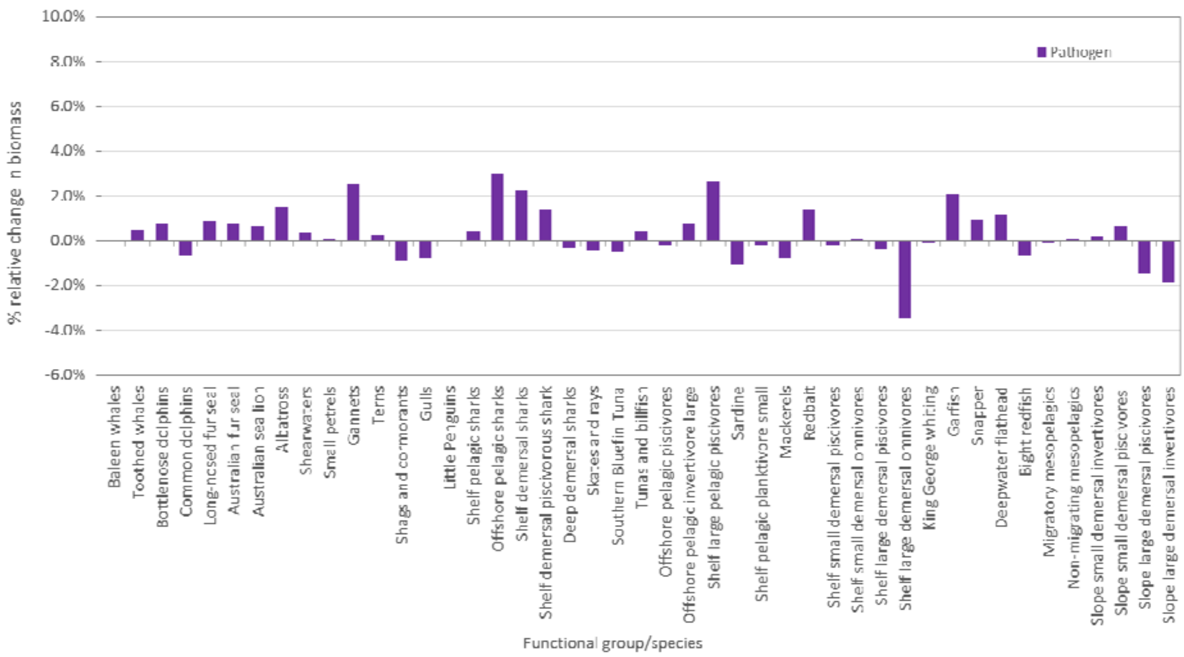


Figure 5.13. Biomass of sardine per age-class through time, showing the response and recovery of the sardine population to the mass mortality event imposed at year 10 of the projection period. The dotted line shows the overall population biomass for the pathogen run, the overall biomass of the Status Quo projection is given for reference (solid line).

As with Atlantis, the EwE scenario for a pathogen attack on the sardine population (represented as a once off event lasting 8 months) had no major long-term effects – i.e. there were no substantial changes in biomass at the end of the simulation (Figure 5.14). The greatest differences, either positive or negative, were all less than 8%: rock lobster declined about 5%, while crabs and bugs increased by 8%. Catches were similarly unaffected: rock lobster catches declined 5% and crabs and bugs catches increased by 4% (Figure 5.15).

a)



b)

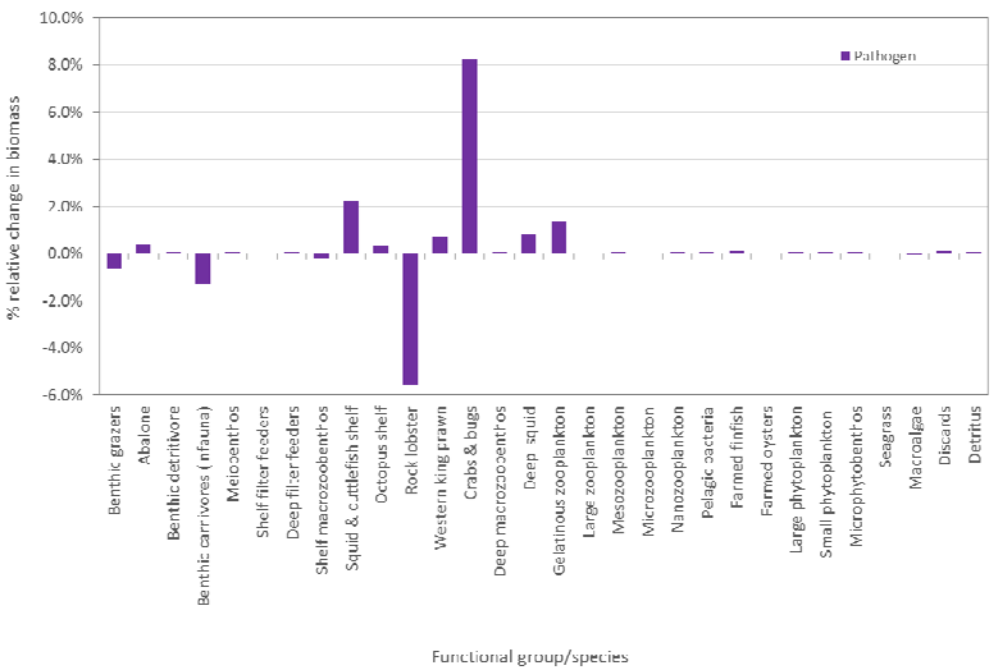
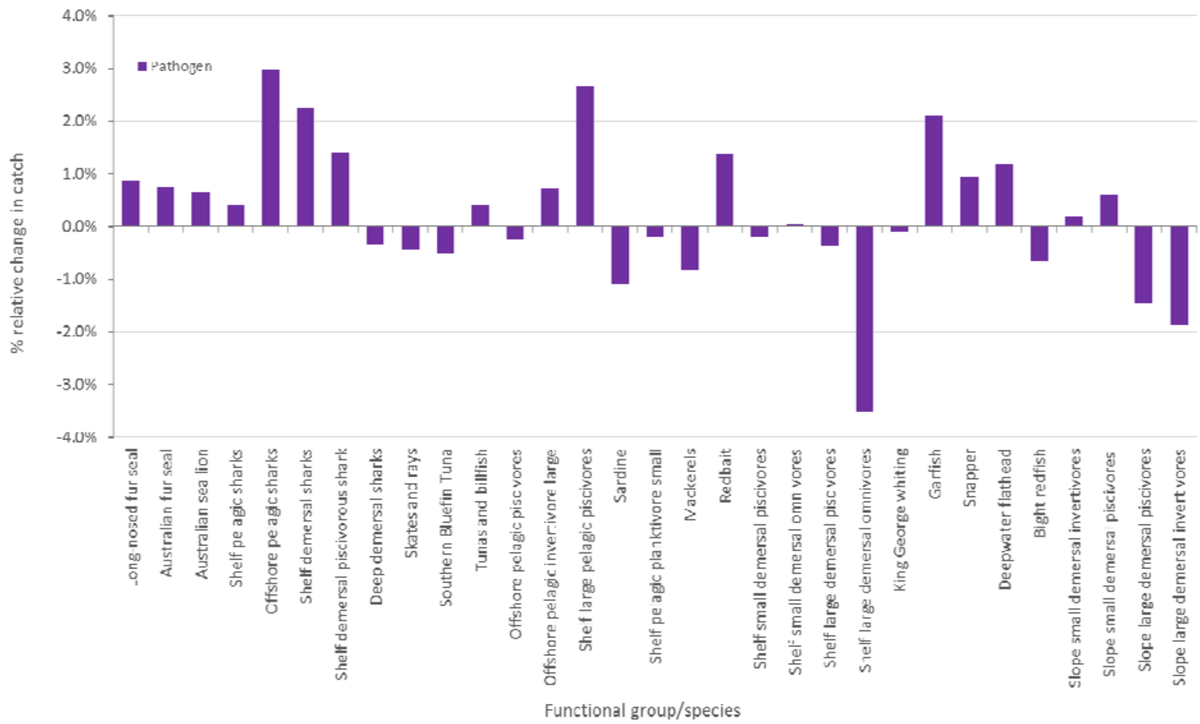


Figure 5.14. EwE relative changes (%) in the total biomasses of a) vertebrate and b) invertebrates - calculated in comparison to the Status Quo scenario.

a)



b)

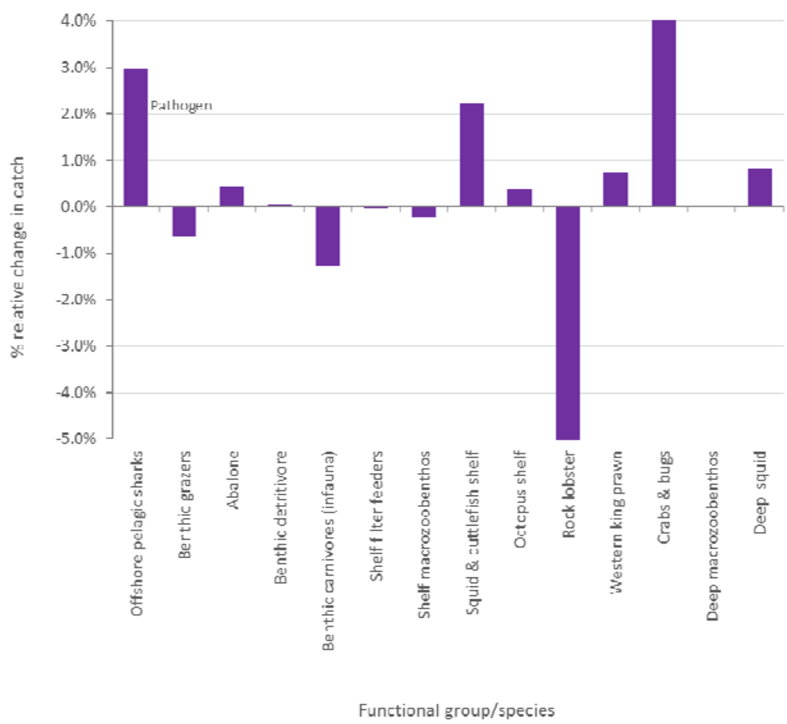


Figure 5.15. EwE relative changes (%) in catches of a) vertebrate and b) invertebrates - calculated in comparison to the Status Quo scenario.

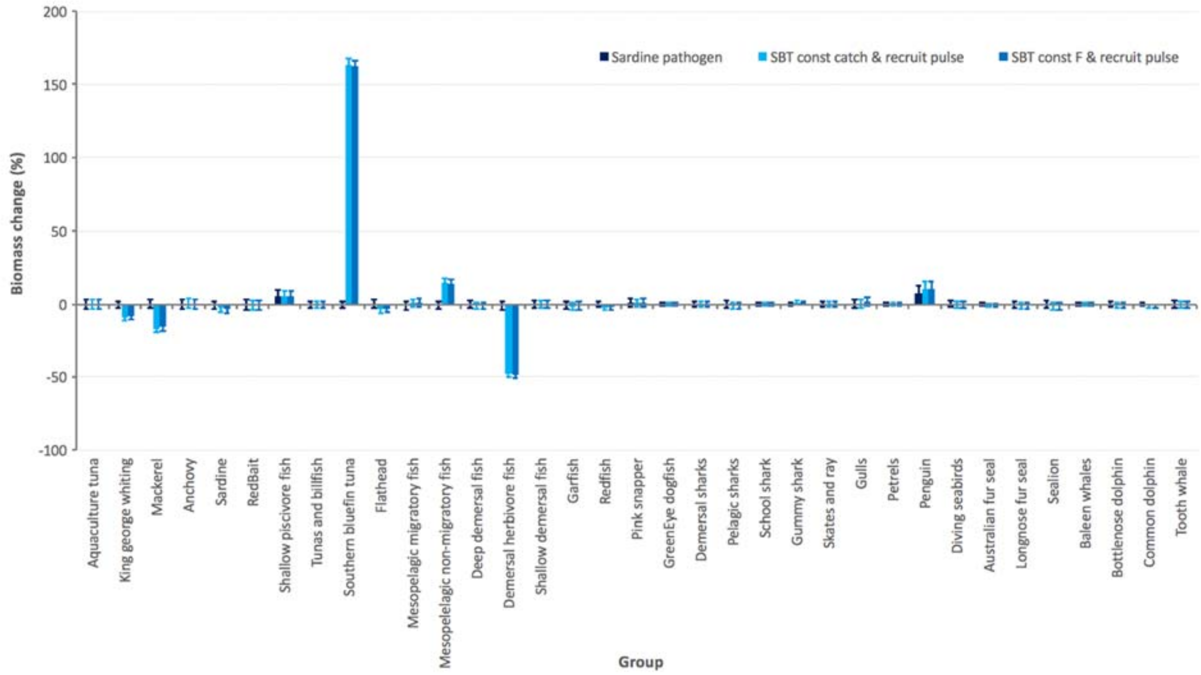
Scenario 5: Southern bluefin tuna

The imposed high recruitment saw the total biomass of the stock increase by as much as five-fold, with the largest effect taking place within five years after the imposed event (Figure 5.16). The stock dropped again relatively quickly, within a decade, though it remained at about twice the *Status Quo* biomasses for the rest of the simulation (regardless of the fishing rules employed). During the period of peak biomass of SBT, the ecological consequences of this event were evident in the main prey of SBT with large decreases (>20% or more) in the relative biomass of redbait, sardine, anchovy, mackerel and migratory mesopelagic fishes. Although, the majority had returned to close to *Status Quo* levels by the end of the projection period, though mackerel remained at levels 10-20% lower (Figure 5.17). As with the sardine event, this one also caused short term changes in predatory pressures that then evolved into ongoing changes in the benthic food webs, which had flow on effects on plankton groups, macroalgae, demersal fish, benthic grazers and seabirds. Catches reflected the biomass changes – even the constant catch case did see lower catches for SBT than the constant F, but this had little material effect on the overall simulation.

Imposing a 10% biomass accumulation rate in EwE (to mimic a long-term recovery trajectory in SBT) resulted in a nearly 50% increase in biomass of SBT and an 18% increase in catch. The EwE scenario using a 5% accumulation rate (to proxy the recruitment) and an immigration rate of 5% (to proxy lower external mortality) also saw substantial increase in SBT biomass and a 16% increase in catch. Doubling the starting biomass had a smaller effect on biomass, leading to a 15% increase in final biomasses (Figure 5.18). The negative net effect on SBT catches (Figure 5.19), which declined more than 30% was caused by the effective halving of the fishing mortality when the starting biomass was doubled. There were no other knock-on effects on the rest of the ecosystem, with any other changes less than 1% in magnitude.

In this instance, it wasn't possible to compare across models as they tackled the SBT scenario in different ways. However, it is safe to say from Atlantis that a single recruitment pulse is insufficient to recover the stock and that longer term shifts in recruitment (or survival outside the model domain) would be required for substantial long-term shifts in the biomass of SBT and the GAB system. This is backed up by the pattern of results produced by the re-parametrisation of EwE. The transient effects within Atlantis suggest, however, that effects of a recovery on the rest of the system might be larger than suggested by EwE.

(a)



(b)

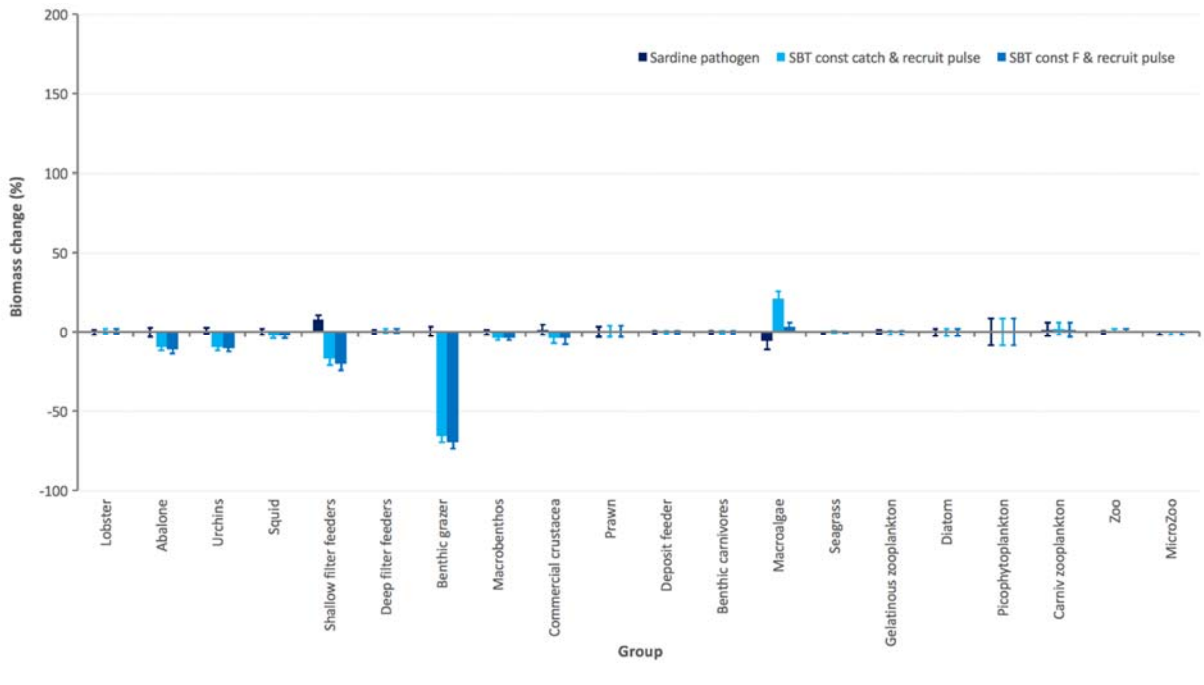


Figure 5.16. Relative changes (%) in the total biomass of (a) vertebrates and (b) invertebrates under the sardine pathogen scenario and the Bluefin tuna scenarios – calculated relative to the Status Quo.

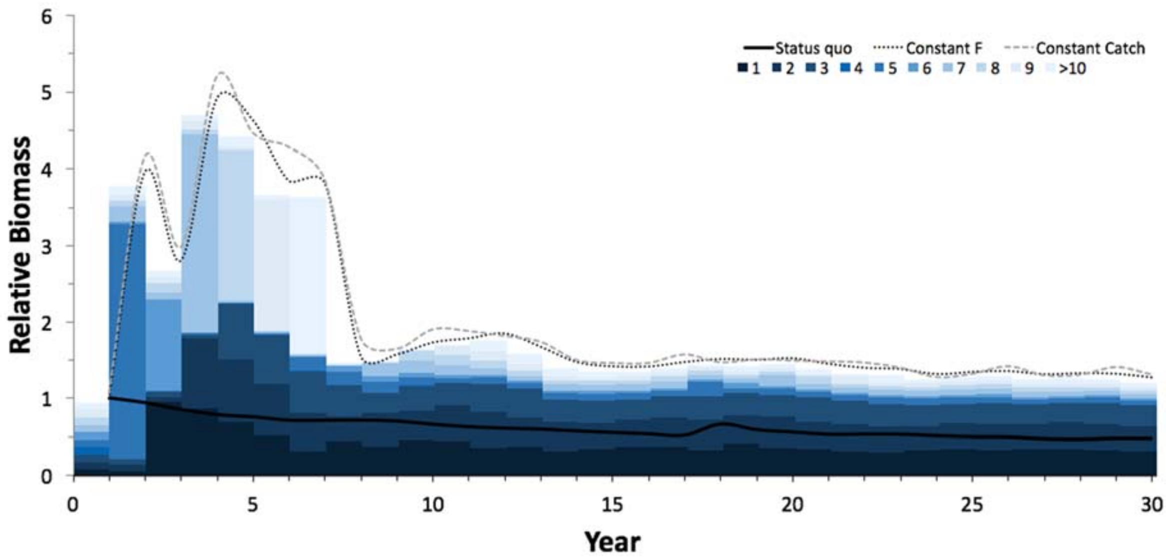


Figure 5.17. Biomass of Southern Bluefin Tuna (SBT) per age-class through time, showing the response of Southern Bluefin to a very high recruitment event. The black dotted line gives the total biomass of SBT in the model domain with the recruitment event and a constant F fishing scenario, while the grey dashed line is when there is a constant catch scenario instead and the solid black line is the Status Quo scenario (given for reference).

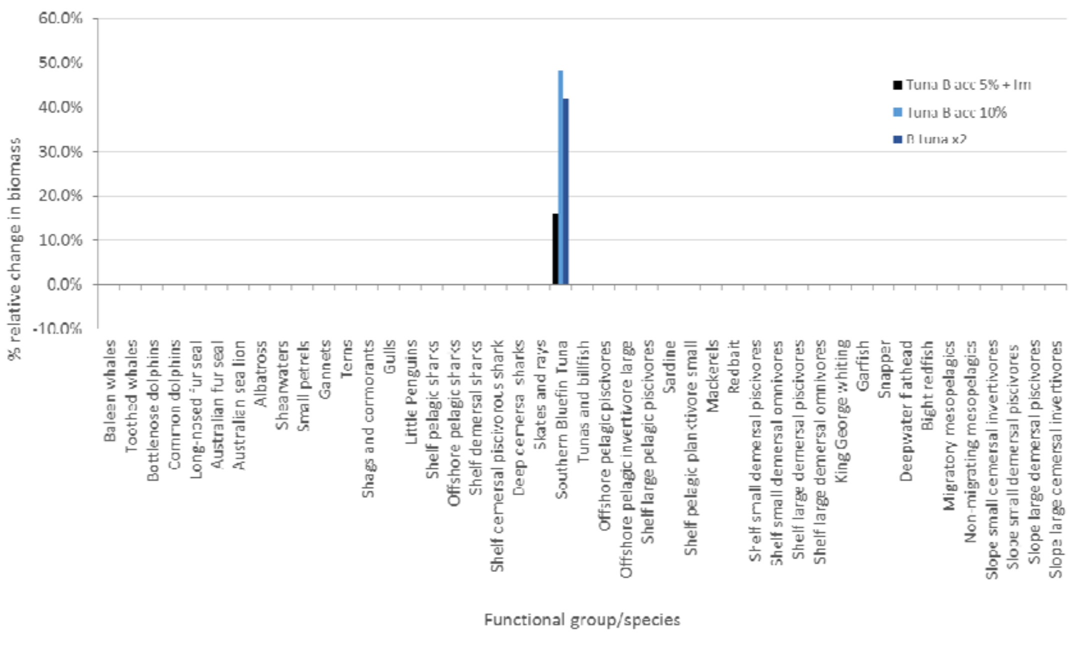


Figure 5.18. EwE relative changes (%) in biomasses of) vertebrates relative to Status Quo scenario.

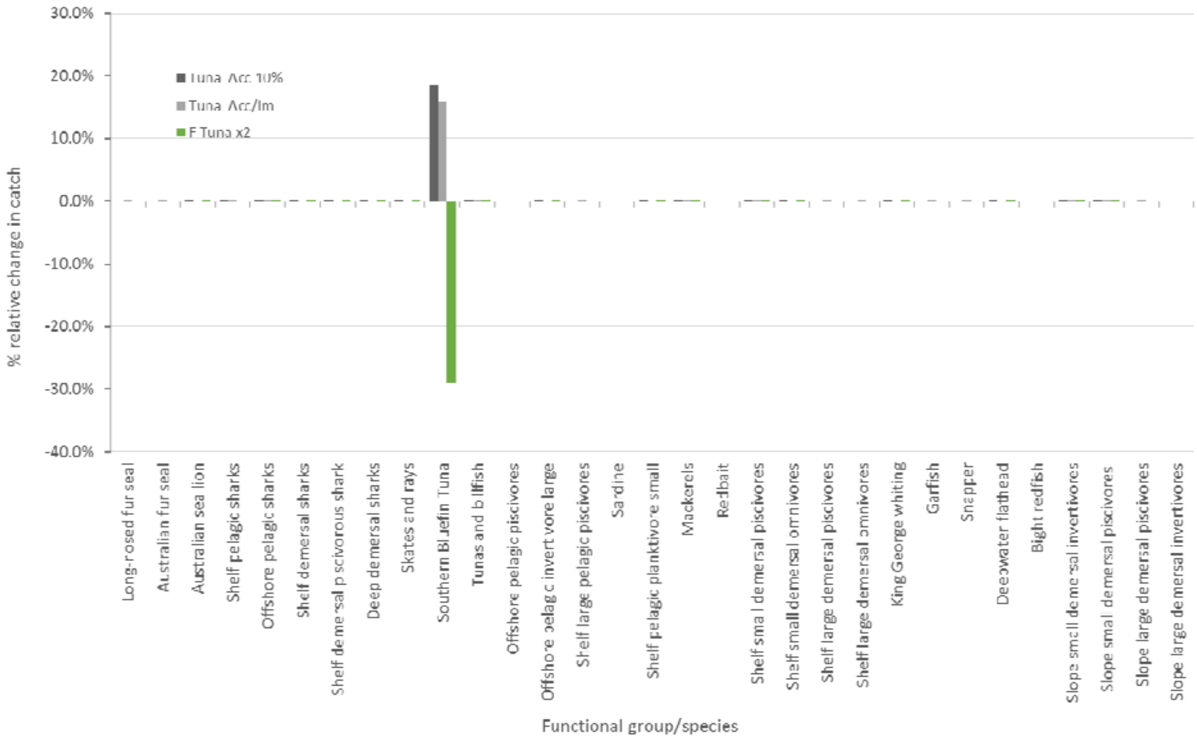


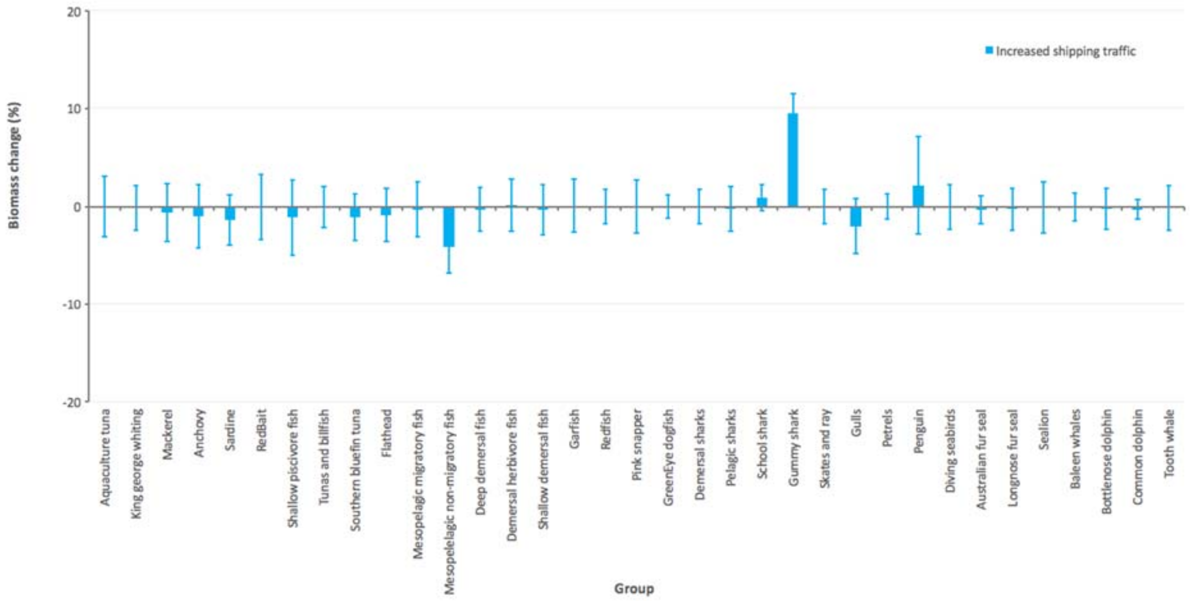
Figure 5.19. EwE relative changes in catches of vertebrates relative to the Status Quo scenario. Changes in catch of Invertebrates were all less than a few per cent and are not shown.

Scenario 6: Shipping traffic and oil spills

Relative changes of biomass caused by increased shipping traffic relative to the *Status Quo* were not really seen across the whole ecosystem (Figure 5.20). The most negative direct impacts (still <5%) were observed for the benthic inshore filter feeders (directly affected by more activity in the gulfs). The majority of the other effects were not significant (in terms of relative biomass or catch), except for (i) gummy shark, where loss of access by that fishery (displaced by the vessel traffic) saw that stock increase by nearly 10% as a result (though this was insufficient to have broad scale significant cascading effects on the majority of its prey) and (ii) mesopelagic fish (<5% change, due to trophic interactions with its predators, particularly sharks).

Oil spills led to short term drops (of <2-3%) in the biomass or abundance of all impacted groups in the immediate vicinity of the collision and spill (i.e. in the box where the spill occurred). Oil spills from ship collisions had very little long-term impact on the system (Figure 5.21), with offshore winter spills (where ambient conditions drive the material onshore and along the coast) having the greatest potential to cause damage to the system (primarily amongst the shelf or coastal invertebrates). However, even then the maximum declines were <5% and the confidence intervals overlap with the "no change" zero line indicating that impacts are likely only to be short term and local. Note that these results only reflect acute (direct contact and mortality) outcomes as chronic effects mediated by uptake and transmission through the food web are not represented.

(a)



(b)

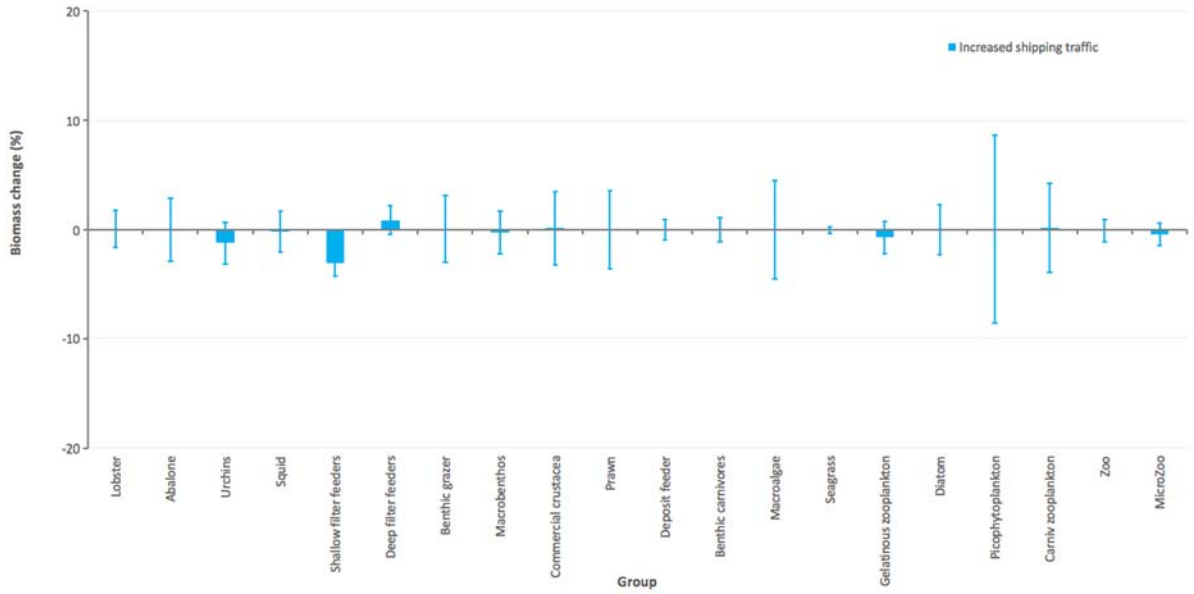
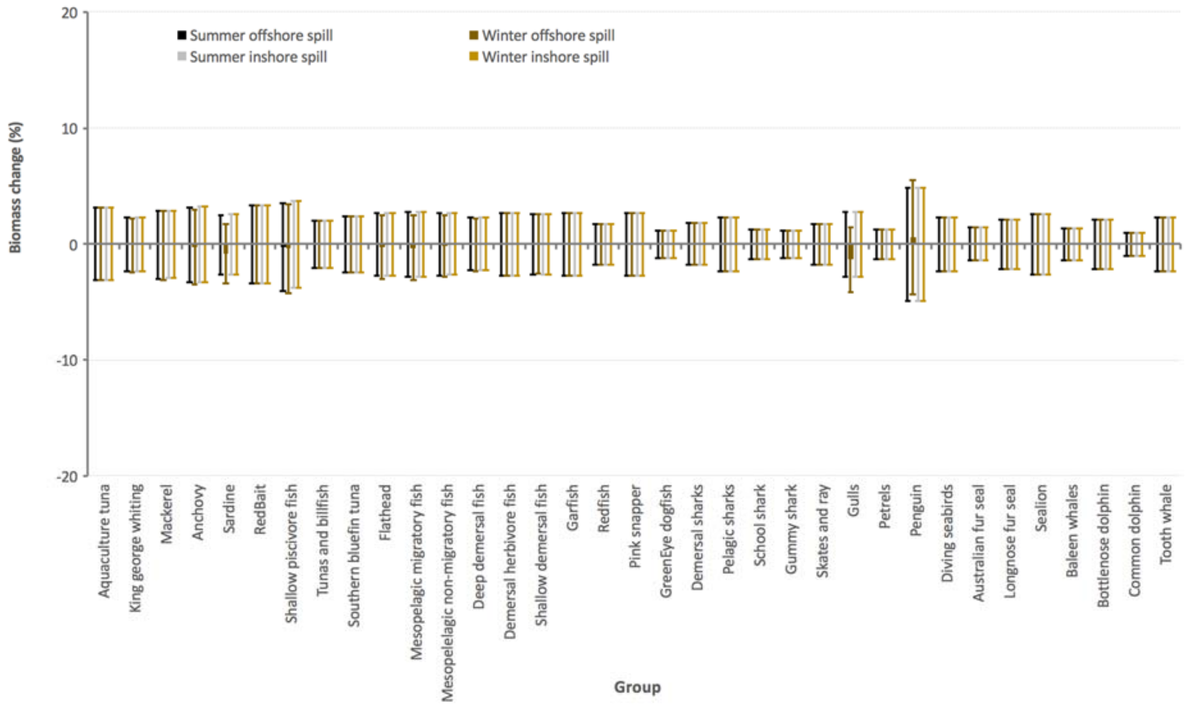


Figure 5.20. Relative changes (%) in total biomass of (a) vertebrates and (b) invertebrates functional groups under the shipping scenario – calculated in comparison to the Status Quo scenario. Note the scale of the y-axis is much smaller than for the other scenarios reported in this chapter.

(a)



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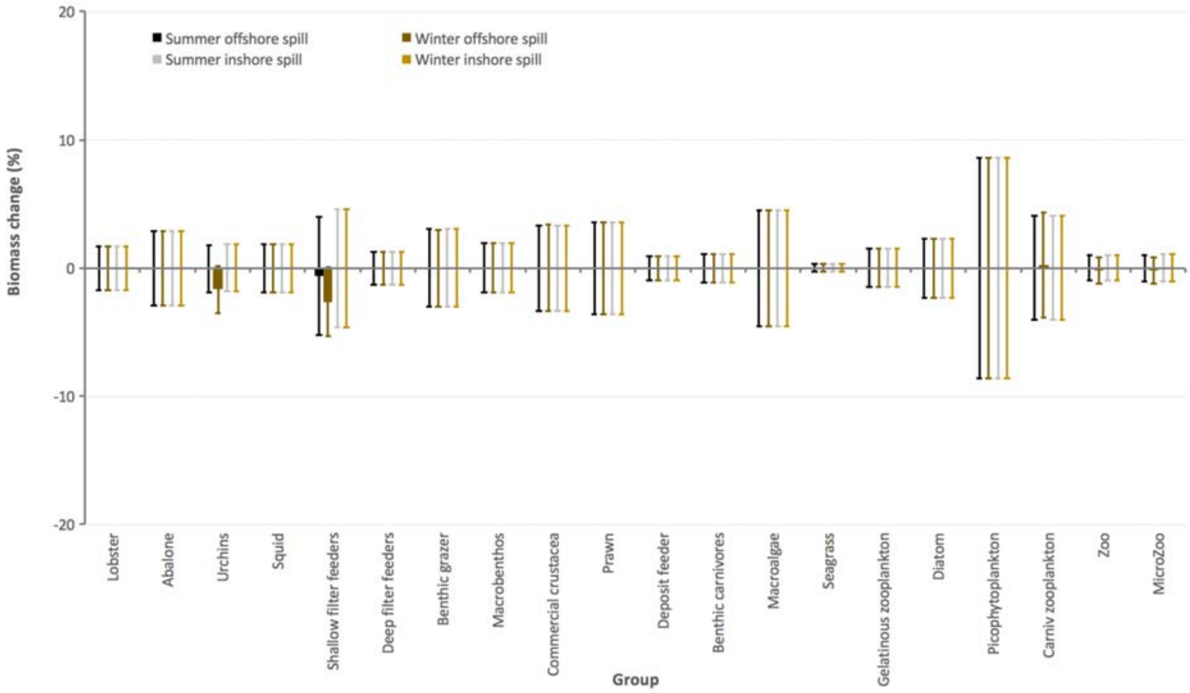


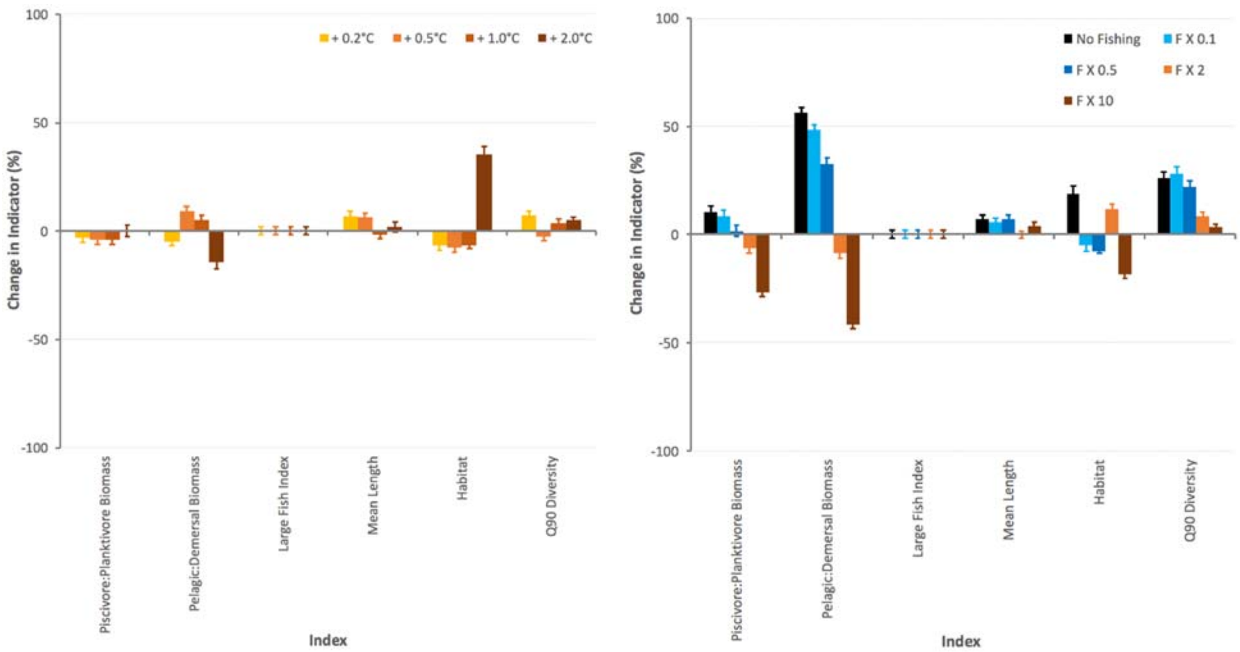
Figure 5.21 Relative changes (%) in total biomass of (a) vertebrates and (b) invertebrates functional groups under the ship collision and oil spill scenario(s) – calculated in comparison to the Status Quo scenario. Note the scale of the y-axis is much smaller than for the other scenarios reported in this chapter.

5.4.1 Scenario-based shifts in ecosystem indicators

Interpreting many of the individual ecosystem indicators is complicated, for example (counter-intuitively) any adjustment to spatial management leads to a decline in overall habitats (Figure 5.22c) due to fishing when there is no spatial management, but due to predation when there is increased spatial management. The nonlinear influence of climate means biomass ratios such as pelagic:demersal biomass show no clear trend, where the pelagic:demersal biomass ratio declines under intensive fishing pressure (the opposite to the response seen in other systems under pressure). The large fish index proves to be effectively insensitive to the scenarios; while diversity (being a complex mixture of richness and evenness) also shows nonlinear responses to many of the scenarios.

Clearer signals can be seen in the aggregate performance of the system – how it is expressed in multi-dimensional space as captured by the principal components analysis (Figure 5.23), in that higher space gradients in fishing and climate pressure see the system drawn away from its current state, with greater pressure leading to more change. Also, in comparison to the no fishing scenario (which also lacked a climate signal), the current state of the system shows a clear anthropogenic signal (clustering away from the no fishing run). Imposition of greater spatial management can move the system more towards the un-impacted state in one dimension, but not both and so is not enough by itself to mitigate the effects of human activities. The increased shipping scenario sits a little apart from current conditions, suggesting greater impacts than perhaps suggested by the individual biomasses, catches and ecological indicators. All the other scenarios (the spills, and mortality or recruitment events) cluster around the current state of the system, showing how little influence they have on the system overall.

(a) (b)



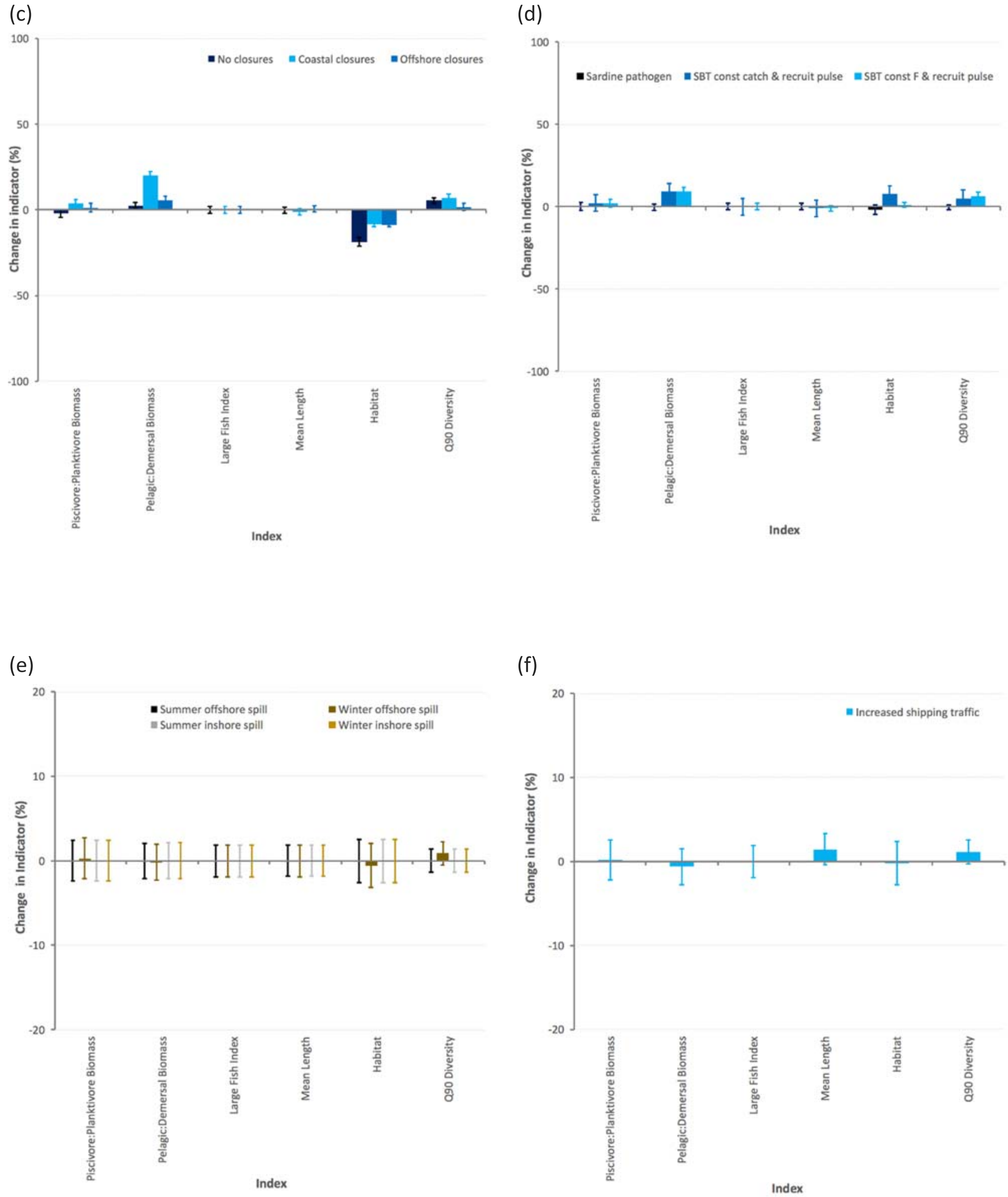


Figure 5.22. Relative changes in the ecosystem performance indicators for (a) ocean warming scenarios, (b) fishing scenarios, (c) spatial management scenarios, (d) sardine and SBT scenarios, (e) spill scenarios and (f) shipping scenario. All calculated compared to Status Quo.

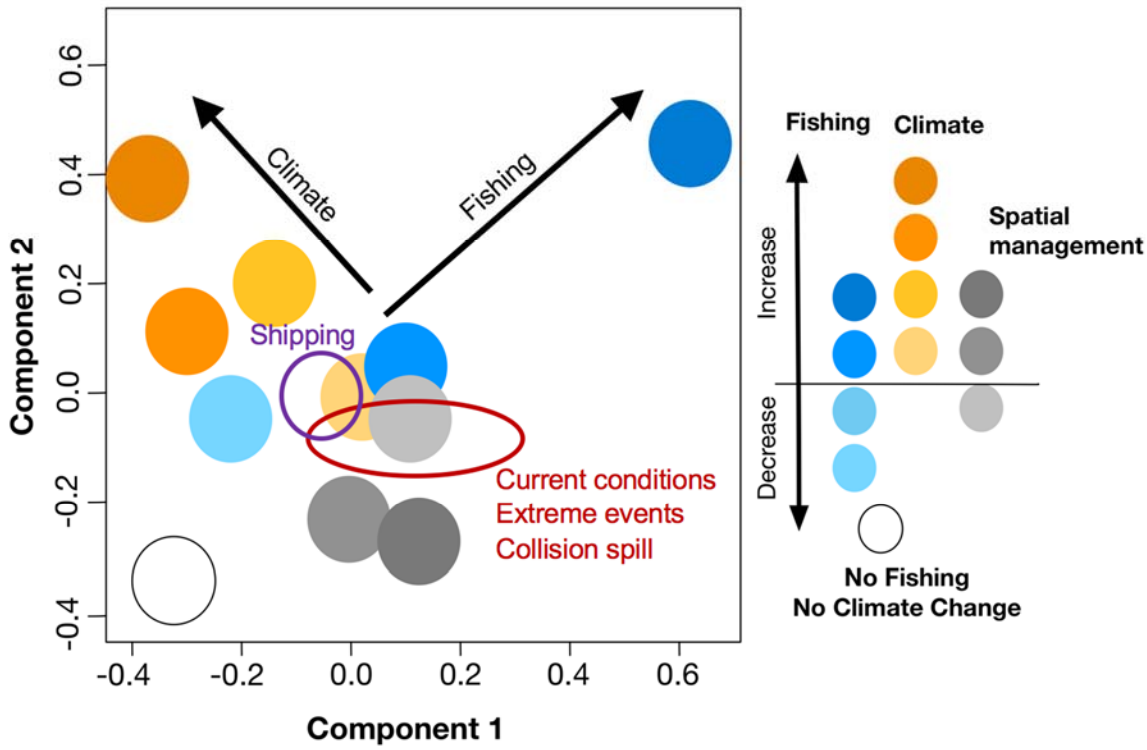


Figure 5.23. Plot of the large-scale clusters formed by the scenarios in the principal components analysis (first two principal components only. The rough axes caused by gradients of ocean warming and fishing drawn on for reference.

5.5 Discussion

The GAB ecosystem as modelled comprised mostly oceanic and abyssal habitat, with about a third being shelf and continental slope. It also contained the two gulfs, which largely, but not wholly, support aquaculture and the inshore fisheries targeting many highly valuable species such as sardine, rock lobster and abalone. The gulfs are dominated in terms of biomass by macroalgae and seagrasses that also accounted for some of the largest biomasses in the whole ecosystem in both ecosystem models. However, they were not the dominant drivers across the whole ecosystem; small and large phytoplankton tend to drive the dynamics of the broader system (given it is predominantly over deeper shelf, slope and open ocean waters). Three types of food webs have been hypothesised for the broader GAB ecosystem, two were known prior to this study and a third "hybrid" food web arose from the results of Theme 2 investigations (see Theme 2 Final Report). The dynamics of the different hypothesised food webs were seen in a gross form in the Atlantis model, but could not be exactly simulated in the EwE model; instead in that model we attempted to account for differing rates of productivity between the two groups based on information from Theme 2 as to the likely composition of the phytoplankton biomass regionally.

5.5.1 Scenario comparisons

The scenarios we investigated are intended as a demonstration of how the ecosystem models could be employed, both to synthesise information on the system and to provide insight into how the system might respond to specific events or changes in broad scale drivers of the system. Therefore, the chosen and approved scenarios were from a few broad categories of concern such as climate change, and exploitation of natural and physical resources. The climate, fisheries and spatial management scenarios are quite typical of the kinds of scenarios run with ecosystem models. The extreme events scenarios are less common, but are beginning to be explored more regularly. Very detailed scenario investigations often require very specific re-configuration of the models and sub-models, a situation that would also require consultation with relevant stakeholders, subject matter experts and relevant data, and potentially further development.

General results of the comparisons across all scenarios

Both models indicated that climate shifts have the potential to reshape GAB ecosystems. While Atlantis suggested mixed outcomes for the current GAB species, with many teleosts predicted to benefit physiologically from the warmer conditions, while invertebrates were differentially impacted (with some increasing and some decreasing) and many iconic species (sharks, mammals and birds) increasing under the lower temperature rises (due to improved feed and physiological conditions), but suffering declines as temperature rose further (again due to direct and indirect drivers). The results of the climate simulations from EwE differ as the model was driven by productivity rather than temperature – and the downscaled model projected decreasing productivity rates overall, which in turn affected higher trophic levels – with the worst climate impacts on par with doubling or more of fishing pressure.

Increased fishing pressures had by far the greatest effect – in both EwE and Atlantis. The higher levels of fishing caused the highest number of decreases in biomass of functional groups or species. Under the highest levels of fishing pressure about a third of all groups in both models declined in biomass by more than 20%, and half of those declined by more than 50%. Increasing fishing pressure had significant impacts on target finfish, chondrichthyans, and target invertebrate species such as abalone and crustaceans such as prawns and rock lobster.

Lobsters are currently experiencing declining populations (Linnane *et al.* 2010a). This observed decline may be due to either environmental drivers or overfishing, as was demonstrated in the model simulations presented here, but no firm conclusions have been drawn as yet. Combining both the increased fishing pressure and warming climate scenarios could result in greater impact (i.e. depletion) on rock lobster. Indeed, Linnane *et al.* (2010b) suggested that highly conservative management through total allowable commercial catches (TACCs), thereby reducing fishing pressure was needed to help manage the declining stocks particularly since settlement and recruitment dynamics dependent on oceanographic conditions were not well understood. In our scenarios, reducing fishing pressure, resulted in a very positive effect on rock lobster, and on SBT, though in EwE the benefits were smaller for other commercial species (Atlantis projected benefits for many groups unlike EwE).

Many of the scenarios did not substantially perturb the system, with the principal components analysis (PCA) of the Atlantis results showing little variation from current conditions and the EwE scenarios showing changes in biomass of less than 20% – except for SBT in the scenarios where tuna biomass increase was forced.

Comparison of Atlantis and EwE models are informative about potential system sensitivities and the relative need to refine understanding of ecosystem structure and function. For example, in a comparison of Atlantis and EwE models for New South Wales, Forrest *et al.* (2015) found that while the models differed in the magnitude of effect, the general direction of change was similar. Whereas, in a multi-system, multi-model comparison of the implications of fishing forage fish, EwE and Atlantis predicted a similar degree of system sensitivity in terms of the proportion of groups effected to differing degrees; however, specific details of whether individual species would increase or decrease showed less agreement (Smith *et al.* 2011). Both of these patterns of model behaviour were seen in the comparison of Atlantis and EwE scenario results for the GAB. While the models showed qualitative agreement in terms of the direction of change of the majority of groups under different fishing scenarios, the models showed greater divergence when considering the effects of climate change – while the magnitude of change was typically <20% for most species the direction of change varied across the models.

In terms of the GAB ecosystem, these differences between the results of the Atlantis and EwE models are largely due to differences in the structure of the models. Firstly, Atlantis includes age-structuring, whereas EwE does not. This means that EwE has less temporal buffering as there are no delays for maturation or growth and any biomass changes are instantaneously transmitted to predators, prey and competitors regardless of life history. Atlantis' use of age/size structure also has implications for ontogenetic, or condition dependent, shifts in predator-prey interactions, due to the use of gap limitation for vertebrate predation. This cannot be mirrored by EwE unless life history (age) stanzas are defined for the group or species. This version of the GAB EwE model does not contain such age-structuring.

Secondly, unlike Atlantis' 3D structure, EwE is not spatially explicit. Instead EwE implicitly represents spatial structures such as by depth (shelf or slope) or habitat affinities (oceanic, demersal). Ecospace models address this more explicitly but still lack the depth-layering resolution of Atlantis. This means EwE often expresses more mixing and direct interactions than Atlantis, where spatial mismatches and limitations are more common.

Thirdly, Atlantis explicitly includes habitat dependencies and sub-grid spatial structuring of benthic habitats and the species that depend upon them. If a habitat is lost or degraded, then this can influence predation success and productivity of competing habitat types. These interactions are not typically included in EwE (and were not in this case), although the latest versions of the EwE software are beginning to allow for such dependencies.

A final substantial difference between the models as they currently stand is explicit nutrient cycling – which Atlantis includes, but EwE does not. This means that plankton dynamics and the microbial loop are explicit and relatively resolved both taxonomically and by process, in Atlantis. In EwE, the plankton web is often not as resolved (though it is resolved here more than in many EwE models) and production is simplistically represented with less of the limitations seen in more biogeochemically oriented models.

Climate change

In the last 5 years, climate change scenarios have become one of the most common types of simulations run using ecosystem models. Australian ecosystems were amongst the first to be explored in this way (Fulton 2011).That early work included both EwE and Atlantis models and in SE Australia these models projected likely decreases in plankton biomass, top predators and the biomass of pelagos, while indicating that declines were more likely for benthos and demersal fish.

The representation of climate drivers (and global change more broadly) in ecosystem models has become more refined over the last five years, as information on metabolic responses to shifts in temperature and properties such as oxygen and aragonite saturation have become more readily available (e.g. Fulton and Gorton 2014, Cheung *et al.* 2016, Tittensor *et al.* in press). The species distribution based approach of Cheung *et al.* (2016) predicts a general increase in fish and fishable biomass over the next 50 years under climate scenarios; while Fulton and Gorton (2014) found a greater sensitivity to human decisions regarding exploitation and management patterns, but generally more mixed ecological outcomes and a good deal of robustness in ecosystem structure so long as the highest emission scenarios were avoided. While a good deal of uncertainty remains about the details of climate related species shifts and productivity changes, all models universally indicate that south eastern Australian ecosystems (including the GAB) are fairly responsive to changing environmental drivers – as sensitive as any other location globally, which is important given the hotspot status of some of the waters (Hobday & Pecl 2014). The ecosystem models considered here indicate that the GAB is responsive, though perhaps not quite as responsive as other areas in south eastern Australia. However, a good deal of uncertainty remains about the form of that responsiveness and whether it will be moderated by trophic interactions or habitat dependencies. In reality, the ability of species to adapt to the changing environmental drivers will also be important for the ultimate outcomes; although more information would be required to reliably include such a dynamic in either of the models considered here.

Fisheries

One of the most common uses of ecosystem models has been the exploration of the effects of fishing and alternative fisheries scenarios. A web of science search on “ecosystem AND model AND fisher* AND scenario” returns close to 500 results and the information available on the 454 published models available from the EwE *http://ecobase.ecopath.org/* website indicates that the majority have been used to look at fisheries effects in one way or another (Colleter *et al.* 2015). In the main these models indicate that fishing effects ecosystems and that excessive fishing pressure can cause large scale and detrimental impairment of ecosystem structure and function (Jackson *et al.* 2001, Coll *et al.* 2008, Arreguín-Sánchez 2011, Smith *et al.* 2011, Christensen *et al.* 2015). This is in agreement with what was observed for both the GAB ecosystem models under the various fishing scenarios. From an ecological perspective debate continues on what is the most appropriate means of exploiting marine ecosystems from the perspective of individual species of the entire ecosystem (Garcia *et al.* 2013, Garcia *et al.* 2015). For a human perspective, decisions on what is an appropriate degree of change needs to be made in conjunction with those interested in the system – as has been examined for Spencer Gulf (Gillanders *et al.* 2016). While Theme 6 did look at the value of fisheries to the region, the reshaping of the GABRP and the inability to access spatially explicit catch and effort data for the state fisheries of South Australia meant it was not possible to dynamically link this work with the ecosystem models as yet. With or without such refinements, more sophisticated fisheries scenarios could be developed in combination with stakeholders to look at more fisheries options.

Spatial management

The efficacy of spatial management is of particular interest to fisheries and conservation managers. This has made it a topic of interest to many ecosystem modellers, though the non-spatial nature of many of the EwE models means it has not received the same degree of coverage as simple fisheries scenarios. The outcomes of the studies of spatial management are also contingent on the system

structure, the levels of various stressors and the degree of on and off reserve management (Kaplan & Botsford 2005, Dichmont *et al.* 2013, Savina *et al.* 2013a, Savina *et al.* 2013b, Fulton & Gorton 2014, Pitcher *et al.* 2016).

In this instance, current fisheries management aims to achieve a truly sustainable balance between harvest and conservation. This is reflected in the way in which shifts might influence the system. Removal of spatial management sees the system degrade, with drops in biomass – particularly amongst groups, such as habitat forming benthos, that are offered little protection by any other of the fisheries management levers –while expanding closures across the shelf or offshore had significant industry consequences (with the catch of many groups dropping by 20% and as much as 70%), without there necessarily being a universal uptake in the status of all the groups in the ecosystem (even the habitat forming groups which also happen to be prey items). The mixed outcome is in part due to trophic interactions, but also reflects the differential pressure felt across groups and life histories – chondrichthyans are not as robust to fishing pressure as many of the teleosts, for instance. Similarly, in an evaluation of spatial management options for the Northern Prawn Fishery using an Ecospace model, Dichmont *et al.* (2013) found that outcomes of those options were dependent on the objectives, and finding the right balance of those objectives. An Ecospace model simulation of rock lobster in the Jurien Bay Marine Park demonstrated that closing areas without appropriate management actions to control external fishing pressure does not necessarily result in anticipated improvements in fish stocks (Lozano-Montes *et al.* 2012).

Southern bluefin tuna recovery

While ecosystem models have more typically been used to reconstruct the history of an exploited system (e.g. Christensen 1998, Cox *et al.* 2002, Cheng *et al.* 2009), they can be equally applied to looking forward to anticipate how the recovery of a stock might influence other species in the system. For example, this has been identified as an issue of interest in places such as North America where recovering populations of marine mammals are influencing ecosystem function (e.g. sea otters mediating the urchin-kelp interaction; Estes (1974) or where they are preying upon other protected species (e.g. endangered fish species; Ward *et al.* 2012). In south-eastern Australia , the broad ecosystem effects of the recovery of fur seal stocks in the Bass Strait were explored by Bulman *et al.* (2006). The recovery of southern bluefin tuna as represented in the models here had no long term effects – in Atlantis because of the transient nature of the recruitment pulse and in EwE because the stock was recovering from a low biomass and so the trophic footprint was not as great as one might anticipate. However, this might not hold true if the stock continues to grow in abundance.

One off events (e.g. Sardine pathogen and Shipping collision oil spill)

Ecosystem models have not been used as commonly to explore one off extreme or catastrophic events; although, as the capacity to include such events is realised in the models the uptake is beginning e.g. port development in Vancouver (Port Metro Vancouver 2015); the influence of the establishment of renewable energy infrastructure (Alexander *et al.* 2016) or the damming of the Amazon (Angelini *et al.* 2010) ; the impact of red tides on groupers (Gruss *et al.* 2016); or the potential footprint of outflows from the Sellafield nuclear reactor (Tierney *et al.* 2017). The exploration of pathogen events is joining the analysis of the implications of the entry of range-extending or invading species (e.g. Alva-Basurto & Arias-Gonzalez 2014, Corrales *et al.* 2017). Unlike the fairly consistent responses to persistent pressures such as gross levels of fishing pressure, the

outcome from more spatially or temporally limited events is mixed and fairly context and system specific and do not always have an all-pervasive outcome (as was the case for the spill as a result of a ship collision).

5.5.2 Future work to address gaps in knowledge

The results presented here should be considered with caution, as there is uncertainty (i) in the biomasses of many groups (e.g. mesopelagics and benthic invertebrates); (ii) across much of the model domain (as existing data is densest along the coasts, shipping routes or in the areas surveyed as part of the GABRP; (iii) the model does not capture explicit evolutionary change or very fine scale dynamics that may be important for some species (e.g. aquaculture molluscs); and (iv) there were insufficient resources to allow for multiple parameterisations of the models (which is typically modelling best practice). Comparison across the models helps robustness and test the interpretation of the results, as they are built on differing model frameworks and philosophies. Where the models agree – e.g. around fisheries and environmental drivers having similar capacity to reshape the GAB ecosystem (with fisheries being far more manageable than climate shifts) – then some confidence can be put into the model based conclusions. Where the models disagree (e.g. around specific responses such as the direction of change of some of the basal groups and their predators) then the models are flagging both the need for additional research to constrain the uncertainty, but also that decision makers acting under that uncertainty should do so with caution and in an adaptive framework so decisions can be updated as more information becomes available.

While enormous advances were made in the knowledge of the GAB ecosystem due to the GABRP, for some components of the broader GAB ecosystem (e.g. benthic invertebrates and the shelf edge ecosystem and mesopelagic components), more biological data and a broader spatial coverage would be beneficial (e.g. there were almost no data pertaining to the western GAB area apart from relatively coastal fisheries data). These species components are under-represented in terms of available data compared to more readily sampled groups (e.g. plankton groups which can be sampled remotely or via the continuous plankton recorder, or iconic species which either come to land or attract a good deal of public interest). In addition, it would be of benefit to have access to more refined spatial fisheries data. Instead much simpler gross mortality representations had to be used. This means that the resulting models are sufficient for considering simple scenarios of gross pressure or management types (such as spatial management) but are not able to look at more detailed management questions in the same way as done for Australia's Commonwealth fisheries in the region (e.g. Fulton *et al.* 2014; 2016; Dichmont *et al* 2016).

Despite these constraints the fit to data that has been achieved means the models are scenario ready and can be used to look at the relative performance of alternative scenarios against objectives specified for the ecosystem. Refining the models will help reduce uncertainty, but the broad agreement between the models does indicate the models have sufficient information content between them to provide useful insight around potential system responses. While the identification of multiple plausible parameterisations would be strongly recommended, just to make sure the true magnitude of uncertainty is appreciated, the models represent the best available synthesis of the information on the system and are scenario ready. It is important to realise that structural uncertainty is by far the most important uncertainty associated with ecosystem models and the use of the two models together already addresses this.

Future comparisons between the models would be further facilitated by:

i) the development of a spatial EwE model – i.e. an Ecospace model (especially one using the new habitat representation options (Port Metro Vancouver 2015, Lewis *et al.* 2016);
ii) the inclusion of age-structure for key groups (e.g. the main fished species and species of conservation concern) in the EwE model by replacing the existing bulk biomass pools with multi-stanza representations; and
iii) further resolution of the components of the lower trophic levels and the microbial loop.

Another way in which the models could be refined is by a more refined representation of the influence of terrestrial activities. The simplest way of doing this is via scenarios of flows into the system (e.g. from rivers, outfalls, aquifer releases) and impact-response representations of some of the activities in the region (fisheries, aquaculture, shipping, coastal development and foreshore use, and oil and gas exploration activities). A more dynamic representation is also possible in Atlantis if the model is coupled with the multi-sector economic model used in Theme 6 or if the Atlantis sector models are parameterised – as has been done for Gladstone Harbour on the Queensland coast (Fulton *et al.* 2017). Either of these means of including terrestrial influences means the modelling platforms, particularly Atlantis, can be used to assess some potential cumulative impacts – allowing for the interacting and nonlinear nature of such effects and going beyond what is possible in qualitative or additive assessments.

5.5.3 Concluding Thoughts

The GABRP has helped fill knowledge gaps and the models built from that (and other existing knowledge of the region) allow for a characterisation of the system:

- sensitive species groups in the system include plankton, pelagic species, seabirds and commercially fished invertebrates such as rock lobster;
- the PCA analysis shows that the system has an anthropogenic signature, it is not 'untouched' (the current system state does not overlap with the "no fishing, no shipping" results in Figure 5.15);
- climate and fisheries pressure have some of the greatest potentials to influence the entire ecosystem, although in different ways (the fisheries effects tend to decrease with distance from shore; while climate has a footprint that encompasses the entire region, effecting species in a variety of ways and with differing outcomes for some species compared to others);
- for single extreme events the system recovers within a decade, however if such events were to become the "new normal" then the system may undergo a "regime change" (as shown by the magnitude of the transient responses during the period of the one-off events in both models) ;
- in terms of management options, spatial management helps, but is insufficient in isolation (as pressures and processes in the system are patchy)
- the system is sufficiently interlinked that cumulative nonlinear outcomes can occur.

The GAB ecosystem is complex, with a lot of activity (natural and anthropogenic) currently concentrated in a confined area within the gulfs and along the shoreline and decreasing further offshore (see the schematic in Figure 5.16). The quantitative models presented in this report and the qualitative models summarised in the GABRP synthesis report (Ward *et al.* 2017) represent strong legacy products of the GABRP, which are available for use in risk assessments and to help all those interested in the GAB to navigate through the complexity.

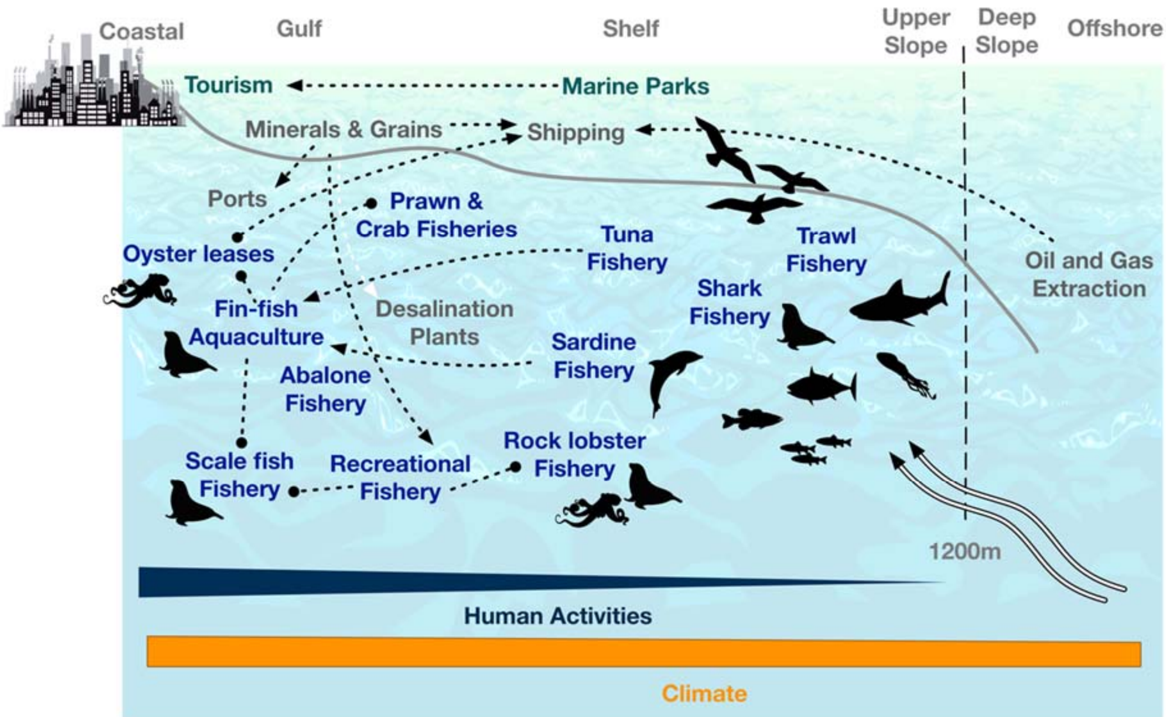


Figure 5.16. A simplified schematic of the GAB system showing the interactions between some of the activities in the region and a stylised representation of the ocean flows (wavy arrows form deep water symbolising upwelling) and the foodweb that is also present in the region (black silhouettes) and interacts with these activities (indicated by the silhouettes by the activities). Note the fishery footprint drops with depth and distance offshore, but that the climate foot is all encompassing.

6. REFERENCES

Abdou K, Halouani G, Hattab T, Romdhane MS, Lasram FB, Le Loc'h F (2016) Exploring the potential effects of marine protected areas on the ecosystem structure of the Gulf of Gabes using the Ecospace model. Aquatic Living Resources 29:18

Alexander KA, Meyjes SA, Heymans JJ (2016) Spatial ecosystem modelling of marine renewable energy installations: Gauging the utility of Ecospace. Ecological Modelling 331:115-128

Allen KR (1971) Relation between production and biomass. J Fish Res Board Can 28:1573-1581

Alva-Basurto JC, Arias-Gonzalez JE (2014) Modelling the effects of climate change on a Caribbean coral reef food web. Ecological Modelling 289:1-14

Angelini R, Aloisio GR, Carvalho AR (2010) Mixed food web control and stability in a Cerrado river (Brazil). Pan-American Journal of Aquatic Sciences 421-431

Arnould JPY, Warneke RM (2002) Growth and condition in Australian fur seals (*Arctocephalus pusillus doriferus*) (Carnivora: Pinnipedia). Australian Journal of Zoology 50:53-66

Arreguín-Sánchez F (2011) Ecosystem dynamics under "top-down" and "bottom-up" control situations generated by intensive harvesting rates. Hidrobiologica 21:323-332

Audzijonyte A, Gorton R, Kaplan IC, Fulton EA (2017) Atlantis User’s Guide Part I: General Overview, Physics & Ecology.

Ayers MJ, Scharler UM, Fennessy ST (2013) Modelling ecosystem effects of reduced prawn recruitment on the Thukela Bank trawling grounds, South Africa, following nursery loss. Marine Ecology Progress Series 479:143-161

Bannister JL (1974) Whale populations and current research off Western Australia. In: Schevill WE, Ray GC, Norris KS (eds) The whale problem: a status report. Harvard University Press, Cambridge, MA

Barlow J, Boveng P (1991) Modelling age-specific mortality for marine mammals populations. Mar Mamm Sci 7:84-119

Barlow J, Kahru M, Mitchell BG (2008) Cetacean biomass, prey consumption, and primary production requirments in te California Current ecosystem. Marine Ecology Progress Series 371:285-295

Bax NJ, Williams A (2000) Habitat and Fisheries Production in the Southeast Fishery Ecosystem Final Report to the FRDC. CSIRO Marine Research, Hobart, Tas.

Baylis AMM, Page B, Goldsworthy SD (2008) Colony-specific foraging areas of lactating New Zealand fur seals. Marine Ecology Progress Series 361:279-290

Baylis AMM, Page B, McKenzie J, Goldsworthy SD (2012) Individual foraging site fidelity in lactating New Zealand fur seals: Continental shelf vs. oceanic habitats. Mar Mamm Sci 28:276-294

Beer S, Koch E (1996) Photosynthesis of marine macroalgae and seagrasses in globally changing CO 2 environments. Marine Ecology Progress Series:199-204

Beeton R, Buxton CD, Cochrane P, Dittmann S, Pepperell JG (2015) Commonwealth Marine Reserves Review: Report of the Expert Scientific Panel.

Berry TE, Osterrieder SK, Murray DC, Coghlan ML, Richardson AJ, Grealy AK, Stat M, Bejder L, Bunce M (2017) DNA metabarcoding for diet analysis and biodiversity: A case study using the endangered Australian sea lion (Neophoca cinerea). Ecol Evol

Bethge P, Nicol S, Culik BM, Wilson RP (1997) Diving behaviour and energetics in breeding little penguins (*Eudyptula minor*). Journal of Zoology, London 242:483-502

Bilgmann K, Möller LM, Harcourt RG, Gibbs SE, Beheregaray LB (2007) Genetic differentiation in bottlenose dolphins from South Australia: association with local oceanography and coastal geography. Marine Ecology Progress Series 341:265-276

BirdLife International (2016a) *Pelagodroma marina*. The IUCN Red List of Threatened Species 2016: e.T22698453A89659253. http://dx.doi.org/10.2305/IUCN.UK.2016-3.RLTS.T22698453A89659253.en

BirdLife International (2016b) *Thalassarche cauta*. The IUCN Red List of Threatened Species 2016: e.T22729604A95019083. http://dx.doi.org/10.2305/IUCN.UK.2016-3.RLTS.T22729604A95019083.en

BirdLife International (2016c) *Thalassarche melanophris*. The IUCN Red List of Threatened Species 2016: e.T22698375A93680491. http://dx.doi.org/10.2305/IUCN.UK.2016-3.RLTS.T22698375A93680491.en

BirdLife International (2017) *Thalassarche carteri*. (amended version published in 2016) The IUCN Red List of Threatened Species 2017: e.T22728372A112018859. http://dx.doi.org/10.2305/IUCN.UK.2017-1.RLTS.T22728372A112018859.en

Blaber SJM, Bulman CM (1987) Diets of fishes of the upper continental slope of eastern Tasmania: content, calorific values, dietary overlap and trophic relationships. Marine Biology 95:345-356

Blaber SJM, Wassenberg TJ (1989) Feeding ecology of the piscivorous birds *Phalacrocorax varius*, *Phalacrocorax melanoleucos* and *Sterna bergii* in Moreton Bay, Australia - diets and dependence on trawler discards. Marine Biology 101:1-10

Bourdaud P, Gascuel D, Bentorcha A, Brind'Amour A (2016) New trophic indicators and target values for an ecosystem-based management of fisheries. Ecol Indic 61:588-601

Braley M, Goldsworthy SD, Page B, Steer M, Austin JJ (2010) Assessing morphological and DNA-based diet analysis techniques in a generalist predator, the arrow squid *Nototodarus gouldi*. Molecular Ecology Resources 10:466-474

Bray DJ (2017) Centroberyx australis in Fishes of Australia, accessed 11 Sep 2017, http://fishesofaustralia.net.au/home/species/1402.

Bryars S, Svane I (2008) Chpter 35. Blue swimmer and sand crabs in Gulf St Vincent and Investigator Strait. In: Shepherd SA, Bryars S, Kirkegaard I, Harbinson P, Jennings JT (eds) Natural History of Gulf St Vincent. Royal Society of South Australia Inc, Adelaide

Bulman C, Althaus F, He X, Bax NJ, Williams A (2001) Diets and trophic guilds of demersal fishes of the south-eastern Australian shelf. Marine and Freshwater Research 52:537-548

Bulman C, Condie S, Furlani D, Cahill M, Klaer N, Goldsworthy S, Knuckey I (2006) Trophic dynamics of the eastern shelf and slope of the South East Fishery: impacts of an on the fishery. Final Report to the Fisheries Research and Development Corporation (FRDC 2002/028). CSIRO Marine and Atmospheric Research, Hobart, Tasmania.

Bulman C, Wayte SE, Elliott N (1994) Orange roughy surveys, 1988 and 1989. CSIRO Division of Fisheries, Marine Laboratories, Hobart

Bulman CM, Butler AJ, Condie S, Ridgway K, Koslow JA, He X, Williams A, Bravington M, Stevens JD, Young JW (2002) A Trophodynamic Model for the Tasmanian Seamounts Marine Reserve: Links between Pelagic and Deepwater Ecosystems. CSIRO Final Report. 37 pp.

Bulman CM, Blaber SJM (1986) Feeding ecology of *Macruronus novaezelandiae* (Hector) (Teleostei: Merlucciidae) in south-eastern Australia. Australian Journal of Marine and Freshwater Research 37:621-639

Bulman CM, Condie SA, Neira FJ, Goldsworthy SD, Fulton EA (2010) The trophodynamics of small pelagic fishes in the southern Australian ecosystems and the implications for ecosystem modelling of southern temperate fisheries. Final Report to the Fisheries Research and Development Corporation (FRDC 2008/023). CSIRO Marine and Atmospheric Research, Hobart, Tasmania.

Bulman CM, He X, Koslow JA (2002) Trophic ecology of the mid-slope demersal fish community off southern Tasmania, Australia. Marine and Freshwater Research 53:59-72

Bulman CM, Koslow JA (1992) Diet and food consumption of a deep-sea fish, orange roughy *Hoplostethus atlanticus* (Pisces: Trachichthyidae), off southeastern Australia. Marine Ecology Progress Series 82:119-125

Bunce A (2001) Prey consumption of Australiasian gannets (*Morus serrator*) breeding in Port Phillip Bay, southeast Australia, and potential overlap with commercial fisheries. ICES Journal of Marine Science 58:904-915

Bunce A, Norman Fl, Brothers N, Gales R (2002) Long-term trends in the Australasian gannet (Morus serrator) population in Australia: the effect of climate change and commercial fisheries. Marine Biology 141:263-269

Bundy A (2001) Fishing on ecosystems: the interplay of fishing and predation in NewFoundland-Labrador. Can J Fish Aquat Sci 58:1153–1167

Burbidge AA, Johnstone RE, Fuller PJ The status of seabirds in Western Australia (1996) Proc The Status of Australia's Seabirds; Proceedings of the National Workshop, Canberra, 1-2 November 1993. Biodiversity Group, Environment Australia, Canberra

Burnell OW, Barrett SL, Hooper GE, Beckmann CL, Sorokin SJ, Noell CJ (2015) Spatial and temporal reassessment of by-catch in the Spencer Gulf Prawn Fishery. Report to PIRSA Fisheries and

Aquaculture. South Australian Research and Development Institute (Aquatic Sciences), Adelaide

Butler A, Bulman C, He X, Koslow T, Williams A, Condie S (2002) Tasmanian seamounts: Diversity, biogeography, and benthopelagic connections.

Buxton CD, Cochrane P (2015) Commonwealth Marine Reserves Review: Report of the Bioregional Advisory Panal.:341

Cailliet GM, Natanson LJ, Welden BA, Ebert DAp (1985) Preliminary studies on the age and growth of the white shark, *Carcharodon carcharias*, using vertebral bands. In: Sibley G (ed) Biology of the White Shark, a Symposium Memoirs of the Southern California Academy of Sciences, Volume 9, Book 9. Southern California Academy of Sciences, Los Angeles

Caines R (2005) Trophic Guild-Structures in Pelagic Fish Communities in the Eastern Great Australian Bight Ecosystem. Honours Honours Thesis, University of South Australia, Adelaide

Campbell R, Holley D, Collins P, Armstrong S (2014) Changes in the abundance and distribution of the New Zealand fur seal (Arctocephalus forsteri) in Western Australia: are they approaching carrying capacity? Australian Journal of Zoology 62:261-267

Carroll G, Hedley S, Bannister J, Ensor P, Harcourt R (2014) No evidence for recovery in the population of sperm whale bulls off Western Australia, 30 years post-whaling. Endangered Species Research 24:33-43

CCSBT (2017) Commission for the Conservation of Southern Bluefin website. https://www.ccsbt.org

Chaalali A, Saint-Beat B, Lassalle G, Le Loc'h F, Tecchio S, Safi G, Savenkoff C, Lobry J, Niquil N (2015) A new modeling approach to define marine ecosystems food-web status with uncertainty assessment. Progress in Oceanography 135:37-47

Charlton-Robb K, Gershwin L-A, Thompson R, Austin JJ, Owen K, McKechnie S (2011) A new dolphin species, the Burrunan dolphin *Tursiops australis* sp. nov., endemic to southern Australian coastal waters. PLoS ONE 6:e24047

Cheng J, Cheung WWL, Pitcher TJ (2009) Mass-balance ecosystem model of the East China Sea. Progress in Natural Science 19:1271-1280

Cheung W, Reygondeau G, Frölicher TL (2016) Large benefits to marine fisheries of meeting the 1.5°C global warming target. Science 354

Chiaradia A, Dann P, Jessop R, Collins P (2002) The diet of Crested Tern (*Sterna bergii*) chicks on Phillip Island, Victoria, Australia. Emu 102:367-371

Christensen V (1998) Fishery-induced changes in a marine ecosystem: insight from models of the Gulf of Thailand. Journal of Fish Biology 53:128-142

Christensen V, Coll M, Buszowski J, Cheung WWL, Frolicher T, Steenbeek J, Stock CA, Watson RA, Walters CJ (2015) The global ocean is an ecosystem: simulating marine life and fisheries. Glob Ecol Biogeogr 24:507-517

Christensen V, Pauly D (1992a) Ecopath II-a software for balancing steady-state ecosystem models and calculating network characteristics. Ecological modelling 61:169-185

Christensen V, Pauly D (1992b) A guide to Ecopath II software system (version 2.1). ICLARM, Malaysia

Christensen V, Walters CJ (2004) Ecopath with Ecosim: methods, capabilities and limitations. Ecological Modelling 172:109-139

Christensen V, Walters CJ, Pauly D, Forrest R (2008) Ecopath with Ecosim version 6 User Guide, November 2008. Lenfest Ocean Futures Project 2008.

Claudet J, Osenberg CW, Benedetti-Cecchi L, Domenici P, García-Charton JA, Pérez-Ruzafa Á, Badalamenti F, Bayle-Sempere J, Brito A, Bulleri F (2008) Marine reserves: size and age do matter. Ecology letters 11:481-489

Cliff G, Dudley SFJ (1992) Sharks caught in the protective gillnets off Natal, South Africa. 6. The copper shark *Carcharhinus brachyurus* (Gunther). South African Journal of Marine Science 12:663–674

Codarin A, Wysocki LE, Ladich F, Picciulin M (2009) Effects of ambient and boat noise on hearing and communication in three fish species living in a marine protected area (Miramare, Italy). Marine pollution bulletin 58:1880-1887

Coll M, Libralato S, Tudela S, Palomera I, Pranovi F (2008) Ecosystem overfishing in the ocean. PLoS ONE 3:1-10

Coll M, Steenbeek J (2017) Standardized ecological indicators to assess aquatic food webs: The ECOIND software plug-in for Ecopath with Ecosim models. Environ Modell Softw 89:120-130

Coll M, Steenbeek J, Sole J, Palomera I, Christensen V (2016) Modelling the cumulative spatial–temporal effects of environmental drivers and fishing in a NW Mediterranean marine ecosystem. Ecological Modelling 331:100-114

Colleter M, Valls A, Guitton J, Gascuel D, Pauly D, Christensen V (2015) Global overview of the applications of the Ecopath with Ecosim modeling approach using the EcoBase models repository. Ecological Modelling 302:42-53

Condie SA, Waring J, Mansbridge JV, Cahill ML (2005) Marine connectivity patterns around the Australian continent. Environmental modelling & software 20:1149-1157

Copley PB The status of seabirds in South Australia. In: Ross GJB, Weaver K, Greig JC (eds). Proc The Status of Australia's Sea birds: Proceedings of the National Seabird Workshop. Biodiversity Group, Environment Australia

Cornejo-Donoso J, Antezana T (2008) Preliminary trophic model of the Antarctic Peninsula Ecosystem (Sub-area CCAMLR 48.1). Ecological Modelling 218:1-17

Cornwall CE, Eddy TD (2015) Effects of near-future ocean acidification, fishing, and marine protection on a temperate coastal ecosystem. Conservation Biology 29:207-215

Corrales X, Ofir E, Coll M, Goren M, Edelist D, Heymans JJ, Gal G (2017) Modeling the role and impact of alien species and fisheries on the Israeli marine continental shelf ecosystem. J Mar Syst 170:88-102

Costa DP, Dann P, Disher W (1986) Energy requirements of free ranging little penguin, *Eudyptula minor*. Comparative Biochemistry and Physiology 85A:135-138

Costa DP, Gales NJ (2000) Foraging energetics and diving behaviour of lactating New Zealand sea lions, *Phocarctos hookeri*. Journal of Experimental Biology 203:3655-3665

Costa DP, Gentry RL (1986) Reproductive energetics of the northern fur seal. In: Gentry RL, Kooyman GL (eds) Fur Seals: Maternal Strategies on Land and at Sea. Princeton University Press, Princeton, New Jersey

Coulson JC, Duncan N, Thomas C (1982) Changes in the breeding biology of the herring gull (*Larus argentatus*) induced by reduction in the size and density of the colony. Journal of Animal Ecology 51:739-756

Cox SP, Essington TE, Kitchell JF, Martell SJD, Walters CJ, Boggs C, Kaplan I (2002) Reconstructing ecosystem dynamics in the central Pacific Ocean, 1952–1998. II. A preliminary assessment of the trophic impacts of fishing and effects on tuna dynamics. Canadian Journal of Fisheries and Aquatic Sciences 59:1736-1747

Currie D, Sorokin S, Ward T (2006) Survey of recreational rock lobster fishing in South Australia during 2004/05. South Australia Research and Development Institute Research Report Series

Currie DR, Dixon CD, Roberts SD, Hooper GE, Sorokin SJ, Ward TM (2009) Fishery-independent by-catch survey to inform risk assessment of the Spencer Gulf Prawn Trawl Fishery. Report to PIRSA Fisheries. South Autralian Research and Development Institute (Aquatic Sciences), Adelaide

Currie DR, Sorokin SJ (2010) A preliminary evaluation of the distribution and trophodynamics of demersal fish from Spencer Gulf. Report to the South Australian Department for the Environment and Heritage. South Australian Research and Development Institue (Aquatic Sciences), Adelaide. SARDI Publication No. F2010/000088-1. SARDI Research Report Series No. 424.

Cury P, Bakun A, Crawford RJ, Jarre A, Quinones RA, Shannon LJ, Verheye HM (2000) Small pelagics in upwelling systems: patterns of interaction and structural changes in “wasp-waist” ecosystems. ICES Journal of Marine Science 57:603-618

Daly K (2007) The diet and guild structure of the small pelagic fish community in the eastern Great Australian Bight, South Australia. Honours Honours, Adelaide University,

Dann P, Carron M, Chambers B, Chambers L, Dornom T, McLaughlin A, Sharp B, Talmage ME, Thoday R, Unthank S (2005) Longevity in Little Penguins *Eudyptula minor*. Marine Ornithology 33:71-72

Dann P, Cullen JM (1990) Survival, Patterns of Reproduction and Lifetime Reproductive Success in Little Blue Penguins (*Eudyptula minor*) in Victoria, Australia. In: Davis LAJD (ed) Penguin Biology. Academic Press, San Diego

Daunt F, Wanless S, Greenstreet SPR, Jensen H, Hamer KC, Harris MP (2008) The impact of the sandeel fishery closure on seabird food consumption, distribution, and productivity in the northwestern North Sea. Canadian Journal of Aquatic Sciences 65:362-381

de Mutsert K, Steenbeek J, Lewis K, Buszowski J, Cowan JH, Christensen V (2016) Exploring effects of hypoxia on fish and fisheries in the northern Gulf of Mexico using a dynamic spatially explicit ecosystem model. Ecological Modelling 331:142-150

Det Norske Veritas (2011) Assessment of the Risk of Pollution from Marine Oil Spills in Australian Ports and Waters. Report for Australian Maritime Safety Authority Assessment of Risk of Marine Oil Pollution 14 December 2011. Report No PP002916

Department of the Environment (2015) South-east marine region profile. A description of the ecosystems, conservation values and uses of the South-east Marine Region. Comonwealth of Australia.

Diaz-Pulido G, McCook LJ, Larkum AW, Lotze HK, Raven JA, Schaffelke B, Smith JE, Steneck RS (2007) Vulnerability of macroalgae of the Great Barrier Reef to climate change.

Dichmont CM, Ellis N, Bustamante RH, Deng R, Tickell S, Pascual R, Lozano-Montes H, Griffiths S (2013) EDITOR'S CHOICE: Evaluating marine spatial closures with conflicting fisheries and conservation objectives. Journal of Applied Ecology 50:1060-1070

Dichmont CM, Fulton EA, Gorton R, Sporcic M, Little LR, Punt AE, Dowling N, Haddon M, Klaer N, Smith DC (2017) From data rich to data-limited harvest strategies-does more data mean better management? Ices Journal of Marine Science 74:670-686

Dimmlich WF, Ward TM, Breed WG (2009) Spawning dynamics and biomass estimates of an anchovy Engraulis australis population in contrasting gulf and shelf environments. Journal of Fish Biology 75:1560-1576

Doney SC, Ruckelshaus M, Duffy JE, Barry JP, Chan F, English CA, Galindo HM, Grebmeier JM, Hollowed AB, Knowlton N (2011) Climate change impacts on marine ecosystems.

Duarte CM, Kirkman H (2001) Methods for the measurement of seagrass abundance and depth distribution. In: Short FT, Coles RG (eds) Global seagrass research methods. Elsevier Amsterdam, The Netherlands

Duke NC (2016) Oil spill impacts on mangroves: Recommendations for operational planning and action based on a global review. Marine pollution bulletin 109:700-715

Earl J, Fowler AJ, Dittmann S (2011) Temporal variation in feeding behaviour and trophic ecology of the temperate hemiramphid, *Hyporhamphus melanochir*. Environmental Biology of Fishes 90:71-83

Eddy TD, Araujo JN, Bundy A, Fulton EA, Lotze HK (2017a) Effectiveness of lobster fisheries management in New Zealand and Nova Scotia from multi-species and ecosystem perspectives. Ices Journal of Marine Science 74:146-157

Eddy TD, Lotze HK, Fulton EA, Coll M, Ainsworth CH, de Araujo JN, Bulman CM, Bundy A, Christensen V, Field JC, Gribble NA, Hasan M, Mackinson S, Townsend H (2017b) Ecosystem effects of invertebrate fisheries. Fish and Fisheries 18:40-53

Edgar GJ (1990) Predator-prey interactions in seagrass beds. 2. Distriburtion and diet of blue mann crabs *Portunus pelagicu*s Linnaeus at Cliff Head, Western Australia. Journal of Experimental Marine Biology and Ecology 139:23-32

Edwards M, Richardson AJ (2004) Impact of climate change on marine pelagic phenology and trophic mismatch. Nature 430:881

Einoder L (2010) The foraging ecology of the short-tailed shearwater *Puffinus tenuirostris* PhD PhD, University of Adelaide, Adelaide

Einoder LD, Goldsworthy SD (2005) Foraging flights of short-tailed shearwaters (Puffinus tenuirostris) from Althorpe Island: Assessing their use of neritic waters. Trans R Soc S Aust 129:209-216

Ellis D, Kiessling I (2015) Ranching of southern blufin tuna in Australia. Advances in Tuna Aquaculture: From Hatchery to Market:217

Ellis J, Wilhelm S, Hedd A, Fraser G, Robertson G, Rail J-F, Fowler M, Morgan K (2013) Mortality of migratory birds from marine commercial fisheries and offshore oil and gas production in Canada. Avian Conservation and Ecology 8

Erftemeijer PL, Lewis RRR (2006) Environmental impacts of dredging on seagrasses: a review. Marine pollution bulletin 52:1553-1572

Essington TE, Beaudreau AH, Wiedenmann J (2006) Fishing through marine food webs. Proceedings of the National Academy of Sciences of the United States of America 103:3171-3175

Estes JA (1974) Sea otters: their role in structuring nearshore communties. Science 185:1058-1060

Evans K, Hindell M (2004) The diet of sperm whales (*Physeter macrocephalus*), in southern Australian waters. ICES Journal of Marine Science 61

Eveson JP, Hobday AJ., Hartog JR, Spillman CM, Rough K (2014) Forecasting spatial distribution of Southern Bluefin Tuna habitat in the Great Australian Bight. Final Report to FRDC Project No. 2012/239. (CSIRO Oceans & Atmosphere: Hobart, Tas.

Feng M., Zhang X, Sloyan B, Chamberlain M. (2017) Contribution of the deep ocean to the future changes of the Indonesian Throughflow. Geophys. Res. Lett. 44, 2859–2867.

Flood MJ, Stobutzki I, Andrews J, Ashby C, Begg GA, Fletcher R, Gardner C, Georgeson L, Hansen S, Hartmann K (2016) Multijurisdictional fisheries performance reporting: how Australia's nationally standardised approach to assessing stock status compares. Fisheries Research 183:559-573

Forrest RE, Savina M, Fulton EA, Pitcher TJ (2015) Do marine ecosystem models give consistent policy evaluations? A comparison of Atlantis and Ecosim. Fisheries Research 167:293-312

Forrestal F, Coll M, Die DJ, Christensen V (2012) Ecosystem effects of bluefin tuna Thunnus thynnus thynnus aquaculture in the NW Mediterranean Sea. Marine Ecology Progress Series 456:215-231

Fowler AJ, Lloyd MT, Schmarr D (2009) A preliminary consideration of by-catch in the Marine Scalefish fishery of South Australia.

Fowler AJ, McGarvey R, Burch P, Feenstra JE, Jackson WB, Lloyd MT (2013) Snapper (*Chrysophrys auratus*) Fishery. Fishery Assessment. Report to PIRSA Fisheries and Aquaculture. . South Australian Research and Development Institute (Aquatic Sciences), Adelaide

Fowler AJ, McGarvey R, Carroll J, Feenstra JE (2014) King George Whiting (*Sillaginodes punctatus*) Fishery. Fishery Assessment Report to PIRSA Fisheries and Aquaculture. South Australian Research and Development Institute (Aquatic Sciences), Adelaide

Fowler AJ, McGarvey R, Carroll J, Feenstra JE, Jackson WB, Lloyd MT (2016) Snapper (*Chrysophrys auratus*) Fishery. SARDI Research Report Series No 930. South Australian Research annd Development Institute Henley Beach, SA

Fragnito K (2013) Identifying the foraging behaviour and foraging habitat of the Australian sea lion, *Neophoca cinerea* using National Geographic Crittercam. Honours thesis. Honours, University of Adelaide,

Fraser GS (2014) Impacts of offshore oil and gas development on marine wildlife resources. Peak Oil, Economic Growth, and Wildlife Conservation. Springer

Fretzer S (2016) Using the Ecopath approach for environmental impact assessment-A case study analysis. Ecological Modelling 331:160-172

Froese R, Pauly D (2017) FishBase. World Wide Web Electronic Publication, version (6/2017) www.fishbase.org. www.fishbase.org

Fulton E, Hutton T, van Putten I, Lozano-Montes H, Gorton R (2017) Gladstone Atlantis Model – Implementation and Initial Results. Report to the Gladstone Healthy Harbour Partnership. CSIRO, Hobart, Australia

Fulton EA (2010) Approaches to end-to-end ecosystem models. J Mar Syst 81:171-183

Fulton EA (2011) Interesting times: winners, losers, and system shifts under climate change around Australia. Ices Journal of Marine Science 68:1329-1342

Fulton EA, Gorton R (2014) Adaptive Futures for SE Australian Fisheries & Aquaculture: Climate Adaptation Simulations. CSIRO, Hobart, Tas

Fulton EA, Hutton T, van Putten IE, Lozano-Montes H and Gorton R (2017) Gladstone Atlantis Model – Implementation and Initial Results. Report to the Gladstone Healthy Harbour Partnership. CSIRO, Australia. 167 pages.

Fulton EA, Link JS, Kaplan IC, Savina-Rolland M, Johnson P, Ainsworth C, Horne P, Gorton R, Gamble RJ, Smith AD (2011) Lessons in modelling and management of marine ecosystems: the Atlantis experience. Fish and Fisheries 12:171-188

Fulton EA, Parslow JS, Smith ADM, Johnson CR (2004) Biogeochemical marine ecosystem models II: the effect of physiological detail on model performance. Ecological Modelling 173:371-406

Fulton EA, Punt AE, Dichmont CM, Gorton R, Sporcic M, Dowling N, Little LR, Haddon M, Klaer N, Smith DC (2016) Developing risk equivalent data-rich and data-limited harvest strategies. Fisheries Research 183:574-587

Fulton EA, Smith AD, Punt AE (2005) Which ecological indicators can robustly detect effects of fishing? ICES Journal of Marine Science 62:540-551

Fulton EA, Smith AD, Smith DC, Johnson P (2014) An integrated approach is needed for ecosystem based fisheries management: insights from ecosystem-level management strategy evaluation. PloS one 9:e84242

Fulton EA, Smith ADM, Johnson PM, Grist EPM (2007a) Spatial Management of Marine systems: Using an Ecosystem Model to Evaluate Integrated Performance Measures. Fisheries Research and Development Corporation. (CSIRO, Hobart)

Fulton EA, Smith ADM, Smith DC (2007b) Alternative Management Strategies for Southeast Australian Commonwealth Fisheries: Stage 2: Quantitative Management Strategy Evaluation. Australian Fisheries Management Authority

Fisheries Research and Development Corporation

Fulton EA, Smith DM (2004) Lessons learnt from a comparison of three ecosystem models for Port Phillip Bay, Australia. African Journal of Marine Science 26:219-243

Gales R, Pemberton D, Clarke M, Lu C (1992) Stomach contents of long-finned pilot whales (Globicephala melas) and bottlenose dolphins (Tursiops truncatus) in Tasmania. Mar Mamm Sci 8:405-413

Garcia S, Bianchi G, Charles T, Kolding J, Zhou S, Rice J, Rochet M-J, Delius G, Reid D, van Zwieten P, Atcheson M, Bartley D, Borges L, Bundy A, Dagorn L, Dunn D, Hall M, Heino M, Jacobsen N, Jacobsen B, Law R, Makino M, Martin F, Skern-Mauritzen M, Suuronen P, Symons D (2015) Balanced Harvest in the Real World. Scientific, Policy and Operational Issues in an Ecosystem Approach to Fisheries. International Union for Conservation of Nature

Garcia SM, Kolding J, Rice J, Rochet M-J, S. Zhou, Arimoto T, Beyer JE, Borges L, Bundy A, Dunn D, Fulton EA, Hall M, Heino M, Law R, Makino M, Rijnsdorp AD, Simard F, Smith ADM (2013) Reconsidering the Consequences of Selective Fisheries. Science, Book 335

Geers TM, Pikitch EK, Frisk MG (2016) An original model of the northern Gulf of Mexico using Ecopath with Ecosim and its implications for the effects of fishing on ecosystem structure and maturity. Deep-Sea Research Part Ii-Topical Studies in Oceanography 129:319-331

Gibbs SE, Harcourt RG, Kemper CM (2011) Niche differentiation of bottlenose dolphin species in South Australia revealed by stable isotopes and stomach contents. Wildlife Research 38:261-270

Gill P, Morrice M, Page B, Pirzl R, Levings A, Coyne M (2011) Blue whale habitat selection and within-season distribution in a regional upwelling system off southern Australia. Marine Ecology Progress Series 421:243-263

Gillanders BM, Goldsworthy SD, Prowse T, Doubell M, Middleton J, Rogers P, Tanner J, Clisby NA, James C, Luick J, Van Ruth P, Bradshaw CJA, Ward TM (2015) Spencer Gulf Research Initiative: Development of an Ecosystem Model for Fisheries and Aquaculture. University of Adelaide and SARDI Aquatic Sciences, Adelaide

Gillanders BM, Ward TM, Bailleul F, Cassey P, Deveney MR, Doubleday ZA, Goldsworthy S, Huveneers C, Jones AR, Mackay AI, Möller L, O'Connell L, Parra G, Prowse TAA, Robbins WD, Scrivens S, K.H. W (2016) Spencer Gulf Ecosystem and Development Initiative. Developing knowledge and tools to inform integrated management of Spencer Gulf: Case study on

shipping and ports. Report for Spencer Gulf Ecosystem and Development Initiative. The University of Adelaide, Adelaide

Giri K, Hall K (2015) South Australian Recreational Fishing Survey 2013/14. Department of Economic Development, Jobs, Transport and Resources

Goldsworthy SD, Bulman C, He X, Larcombe J, Littnan C (2003a) Trophic interactions between marine mammals and Australian fisheries: an ecosystem approach. In: Gales N, Hindell M, Kirkwood R (eds) Marine Mammals and Humans: Fisheries, tourism and management. CSIRO Publishing, Melbourne

Goldsworthy SD, Bulman C, He X, Larcombe J, Littnan C (2003b) Trophic interactions between marine mammals and Australian fisheries: an ecosystem approach. In: Gales N, Hindell M, Kirkwood R (eds) Marine Mammals and Humans: Fisheries, tourism and management CSIRO Publishing., Melbourne

Goldsworthy SD, Lavers J, Carey M, Lowther AD (2013a) Assessment of the status of the Flesh-footed Shearwater in South Australia: population status, subspecies status and foraging ecology. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No.F2013/000013-1. SARDI Research Report Series No. 736. 9pp.

Goldsworthy SD, Loo M, Fowler A, Steer M, Noell C (2017a) A trophic model for Gulf St Vincent: Balancing exploitation of three fisheries in an EBFM framework. Final report to the Fisheries Research and Development Corporation FRDC Project 2013/031 Final Report, 104 pp.

Goldsworthy SD, Mackay AI, Bilgmann K, Möller L, Parra G, Gill P, Bailleul F, Shaughnessy PD, Reinhold S-L, Rogers PJ (2017b) Status, distribution, and abundance of iconic species and apex predators in the Great Australian Bight. Great Australian Bight Research Program, Great Australian Bight Research Report Number 15, 229pp.

Goldsworthy SD, Mackay AI, Shaughnessy PD, Bailleul F, Holman D (2015) Maintaining the monitoring of pup production at key Australian sea lion colonies in South Australia (2014/15). Final Report to the Australian Marine Mammal Centre. South Australian Research and Development Institute (Aquatic Sciences), Adelaide

Goldsworthy SD, Page B (2007) A risk-assessment approach to evaluating the significance of seal bycatch in two Australian fisheries. Biol Conserv 139:269-285

Goldsworthy SD, Page B, Rogers P, Ward T (2011) Establishing ecosystem-based management for the South Australian Sardine Fishery: developing ecological performance indicators and reference points to assess the need for ecological allocations. FRDC Project 2005/031 Final Report. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2010/000863-1. SARDI Research Report Series No. 529. 173 pp.

Goldsworthy SD, Page B, Rogers PJ, Bulmand C, Wiebkin A, McLeay LJ, Einoder L, Baylis AMM, Braley M, Caines R, Daly K, Huveneers C, Peters K, Lowther AD, Ward TM (2013b) Trophodynamics of the eastern Great Australian Bight ecosystem: Ecological change associated with the growth of Australia's largest fishery. Ecological Modelling 255:38-57

Goldsworthy SD, Page B, Shaughnessy PD, Linnane A (2010) Mitigating seal interactions in the SRLF and the gillnet sector SESSF in South Australia. FRDC Project 2007/041 Final Report. SARDI Aquatic Sciences Publication Number F2009/000613-1, SARDI Research Report Series Number 405.

Gomez-Laich A, Wilson RP, Shepard ELC, Quintana F (2013) Energy expenditure and food consumption of foraging Imperial cormorants in Patagonia, Argentina. Marine Biology 160:1697-1707

Gomon MF, Bray DJ (2017) Centroberyx gerrardi in Fishes of Australia, accessed 11 Sep 2017, http://fishesofaustralia.net.au/home/species/3743.

Gonzalez J, Ortiz M, Rodriguez-Zaragoza F, Ulanowicz RE (2016) Assessment of long-term changes of ecosystem indexes in Tongoy Bay (SE Pacific coast): Based on trophic network analysis. Ecol Indic 69:390-399

Griffin D, Thompson P, Bax N, Bradford R, Hallegraeff G (1997) The 1995 mass mortality of pilchard: no role found for physical or biological oceanographic factors in Australia. Marine and Freshwater Research 48:27-42

Griffiths SP, Young JW, Lansdell MJ, Campbell RA, Hamption J, Hoyle SD, Langley A, Bromhead D, Hinton MG (2010) Ecological effects of longline fishing and climate change on the pelagic ecosystem off eastern Australia. Reviews in Fish Biology and Fisheries 20:239-272

Gruber SH, de Marignac JRC, Hoenig JM (2001) Survival of juvenile lemon sharks at Bimini, Bahamas, estimated by mark-depletion experiments. Transactions of the American Fisheries Society 130:376-384

Grubert MA, Wadley VA, White RWG (1999) Diet and feeding strategy of *Octopus maorum* in southeast Tasmania. Bulletin of Marine Science 65:441-451

Gruss A, Schirripa MJ, Chagaris D, Velez L, Shin YJ, Verley P, Oliveros-Ramos R, Ainsworth CH (2016) Estimating natural mortality rates and simulating fishing scenarios for Gulf of Mexico red grouper (Epinephelus morio) using the ecosystem model OSMOSE-WFS. J Mar Syst 154:264-279

Gunn J, Young J (1999) Environmental determinants of the movement and migration of juvenile southern bluefin tuna. In: Gunn J, Block B (eds) Fish Movement and Migration. Australian Society for Fish Biology

Haak DM, Fath BD, Forbes VE, Martin DR, Pope KL (2017) Coupling ecological and social network models to assess "transmission" and "contagion" of an aquatic invasive species. J Environ Manage 190:243-251

Haddon M (2015) Bight redfish (Centroberyx gerrardi) stock assessment using data to 2014/2015. For discussion bu GAB RAG 23 November 2015. CSIRO Oceans and Atmosphere, Hobart, Tasmania

Haddon M (2016) Deepwater Flathead (*Platycephalus conatus*) stock assessment using data to 2015/2016. CSIRO Oceans and Atmosphere, Hobart, Tas

Harrison S (2009) Interactions between Silver Gulls (*Larus novaehollandiae*) and Southern Bluefin Tuna (*Thunnus maccoyii*) aquaculture in the Port Lincoln area. PhD PhD, Flinders University, South Australia

Hays GC, Richardson AJ, Robinson C (2005) Climate change and marine plankton. Trends in ecology & evolution 20:337-344

Hedd A, Gales R, Brothers N (2001) Foraging strategies of shy albatross Thalassarche cauta breeding at Albatross Island, Tasmania, Australia. Marine Ecology Progress Series 224:267-282

Henry GW, Lyle JM (2003) National recreational and indigenous fishing survey.

Heupel MR, Simpfendorfer CA (2002) Estimation of mortality of juvenile blacktip sharks, *Carcharhinus limbatus*, within a nursery area using telemetry data. Canadian Journal of Fisheries and Aquatic Sciences 59:624-632

Heymans JJ, Tomczak MT (2016) Regime shifts in the Northern Benguela ecosystem: Challenges for management. Ecological Modelling 331:151-159

Hoare MJ (2008) The effects of southern rock lobster (*Jasus edwardsii*) translocation on inshore rocky reef communities in South Australia BSc, Hons Honours, Flinders University, Adelaide

Hobday A, Pecl G (2014) Identification of global marine hotspots: sentinels for change and vanguards for adaptation action. Reviews in Fish Biology and Fisheries 24:415-425

Hooker SK, Whitehead H, Gowans S (2002) Ecosystem considerations in conservation planning: energy demand for foraging bottlenose whales (*Hyperoodon ampullatus*) in a marine protected area. Biol Conserv 104:51-58

Humphries P, Hyndes GA, Potter IC (1992) Comparisons between the diets of distant taxa (teleost and cormorant) in an Australian estuary. Estuaries 15:327-334

Hunter CM, Moller H, Fletcher D (2000) Parameter uncertainty and elasticity analyses of a population model: setting research priorities for shearwaters. Ecological Modelling 134:299-323

Hurst R, Bagley N, McGregor G, Francis M (1999) Movements of the New Zealand school shark, *Galeorhinus galeus*, from tag returns. New Zealand Journal of Marine and Freshwater Research 33:29-48

Hussey NE, McCann HM, Cliff G, Dudley SFJ, Wintner SP, Fisk AT (2012) Size-based analysis of diet and trophic position of the white shark, *Carcharodon carcharias*, in South African waters. In: Domeier ML (ed) Global perspectives on the biology and life history of the white shark

Imber MJ Diets of storm petrels *Pelagodrama* and *Garrodia* and of prions *Pachyptila* (Procellariiformes). In: Cooper J (ed). Proc Proceedings of the symposium on birds of the sea and shore. African Seabird Group, Cape Town

Jackson JBC, Kirby MX, Berger WH, Bjorndal KA, Botsford LW, Bourque BJ, Bradbury RH, Cooke R, Erlandson J, Estes JA, Hughes TP, Kidwell S, Lange CB, Lenihan HS, Pandolfi JM, Peterson CH, Steneck RS, Tegner MJ, Warner RR (2001) Historical overfishing and the recent collapse of coastal ecosystems. Science 293:629-638

Jacobsen NS, Essington TE, Andersen KH (2016) Comparing model predictions for ecosystem-based management. Canadian Journal of Fisheries and Aquatic Sciences 73:666-676

Jarman SN, Gales N, Tierney M, Gill P, Elliott N (2002) A DNA-based method for identification of krill species and its application to analysing the diet of marine vertebrate predators. Mol Ecol 11:2679-2690

Jiang JW, Min Y, Chang J, Ge Y (2017) Biological interactions and cooperative management of multiple species. Plos One 12:11

Johnson P, Fulton E, Smith DC, Jenkins GP, Barrett N (2011) The use of telescoping spatial scales to capture inshore to slope dynamics in marine ecosystem modeling. Natural Resource Modeling 24:335-364

Jones K (2009) South Australian recreational fishing survey 2007/08. Fisheries Division, Primary Industries and Resources South Australia, December

Kailola PJ, Williams MJ, Stewart PC, Reichelt RE, McNee A, Grieve C (1993) Australian Fisheries Resources. Bureau of Resource Sciences and the Fisheries Research and Development Corporation, Canberra.

Kangas MI, Jackson B (1998) Sampling juvenile *Penaeus latisulcatus (*Kishinouye) with a water-jet net compared with a beam trawl: spatial and temporal variation and nursery areas in Gulf St Vincent, South Australia. Marine and Freshwater Research 49:517-523

Kaplan DM, Botsford LW (2005) Effects of variability in spacing of coastal marine reserves on fisheries yield and sustainability. Canadian Journal of Fisheries and Aquatic Sciences 62:905-912

Kaplan IC, Horne PJ, Levin PS (2012) Screening California Current fishery management scenarios using the Atlantis end-to-end ecosystem model. Progress in Oceanography 102:5-18

Kemper C, Harcourt R, Gibbs S, Miller C, Wright A (2006) Estimating population size of 'at risk' bottlenose and common dolphins in Spencer Gulf and Gulf St Vincent, South Australia. Consultancy Report to Department of the Environment and Heritage, Canberra (May 2006).

Kemper C, Ling J (1991) Whale strandings in South Australia (1881 - 1989). Trans R Soc S Aust 115:37-52

Kemper CM (2004) Osteological variation and taxonomic affinities of bottlenose dolphins, *Tursiops* spp., from South Australia. Australian Journal of Zoology 52:29-48

Kemper CM, Gibbs SE (2001) Dolphin interactions with tuna feedlots at Port Lincoln, South Australia and recommendations for minimising entanglements. Journal of Cetacean Research and Management 3:283-292

Kenney RD, Scott GP, Thompson TJ, Winn HE (1997) Estimates of prey consumption and trophic impacts of cetaceans in the USA Northwest Continental Shelf Ecosystem. Journal of the Northwest Atlantic Fishery Science 22:155-171

King MG (1977) The biology of the of the western king prawn (Penaeus latisulcatus) and aspects of the fishery in South Australia MSc Thesis, University of Adelaide,

Kirkman H (1989) Growth, density and biomass of Ecklonia radiata at different depths and growth under artificial shading off Perth, Western Australia. Australian Journal of Marine and Freshwater Research 40:169-177.

Kirkman H (1997) Seagrasses of Australia. State of the Environment Technical Paper Series (Estuaries and the Sea). Department of the Environment, Canberra, Australia.

Kirkwood R, Goldsworthy SD (2013) Fur Seals and Sea Lions. CSIRO Publishing, Collingwood, Victoria

Kirkwood R, Lynch M, Gales N, Dann P, Sumner M (2006) At-sea movements and habitats of adult male Australian fur seals (*Arctocephalus pusillus doriferus*). Canadian Journal of Zoology 84:1781-1788

Kirkwood R, Pemberton D, Gales R, Hoskins A, Mitchell T, Shaughnessy P, Arnould J (2010) Continued population recovery by Australian fur seals. Marine and Freshwater Research 61:695-701

Kirtman B, Power S, Adedoyin A, Boer G, Bojariu R, Camilloni I, Doblas-Reyes F, Fiore A, Kimoto M, Meehl G (2013) Near-term climate change: projections and predictability.

Klaer N (2013) 11. Deepwater flathead (Neoplatycephalus conatus) stock assessment based on data up to 2011/12 7. Stock Assessment for the Southern and Eastern Scalefish and Shark Fishery: 2012:183

Kleiber M (1975) The fire of life: an introduction to animal energetics. R. E. Krieger Publishing, Huntington, NY

Knight M, Tsolos A (2009) South Australian wild fisheries information and statistics report. (PDF 5.2 MB). SARDI Aquatic Sciences Publication No F2008/000804-1. SARDI Research Report Series No. 305. January 2009.

Knight MA, Tsolos A (2010) South Australian Wild Fisheries Information and Statistics Report 2008/09. South Australian Resrearch and Development Institute (Aquatic Sciences). SARDI Publication No. F2008/000804-2, SARDI Research Report Series No. 417. Adealide

Knuckey IA (2006) Southern and Eastern Scalefish and Shark Fisehry Bycatch Utilisation Scoping Study. Report to the Department of Primary Industries Agribusiness Group. FRDC Project 2006/.

Kohler NE, Casey JG, Turner PA (1996) Length-Length and Length-Weight Relationships for 13 Shark Species from the Western North Atlantic, NOAA Technical Memorandum NMFS-NE-110.

Koslow AJ, Bulman CM, Lyle JM (1994a) The mid-slope demersal fish community off southeastern Australia. Deep-Sea Research 41:113-141

Koslow J, Bulman C, Lyle J (1994b) The mid-slope demersal fish community off southeastern Australia. Deep-Sea Research Part I-Oceanographic Research Papers 41:113-141

Koslow J, Gowlett-Holmes K, Lowry J, O'hara T, Poore G, Williams A (2001) Seamount benthic macrofauna off southern Tasmania: community structure and impacts of trawling. Marine Ecology Progress Series 213:111-125

Koslow JA, Kloser RJ, Williams A (1997) Pelagic biomass and community structure over the mid-continental slope off southeastern Australia based upon acoustic and midwater trawling. Marine Ecology Progress Series 146:21-35

Laidre KL, Heide-Jørgansen MP, Jorgensen OA, Treble MA (2004) Deep-ocean predation by a high Arctic cetacean. ICES Journal of Marine Science 61:430-440

Larkum AWD (1986) A study of growth and primary production in Ecklonia radiata (C. Ag) J. Agardh (Laminariales) at a sheltered site in Port Jackson, New South Wales. Journal of Experimental Marine Biology and Ecology 96:177-190

Larsen LH, Sagerup K, Ramsvatn S (2016) The mussel path - Using the contaminant tracer, Ecotracer, in Ecopath to model the spread of pollutants in an Arctic marine food web. Ecological Modelling 331:77-85

Last PR, Stevens JD (2009) Sharks and Rays of Australia. Harvard University Press

Lavers JL (2014) Population status and threats to Flesh-footed Shearwaters (Puffinus carneipes) in South and Western Australia. ICES Journal of Marine Science 72:316-327

Lavigne DM (1996) Ecological interactions between marine mammals, commercial fisheries, and their prey: unravelling the tangled web. In: Montevecchi WA (ed) High-lattitude seabirds 4 Trophic relationships and energetics of endotherms in cold ocean systems, Book 9. Canadian Special Publication of Fisheries and Aquatic Sciences

Leaper R, Lavigne D (2007) How much do large whales eat? Jornal of Cetacean Research and Managment 9:179-188

Lercari D, Arreguin-Sanchez F (2009) An ecosystem modelling approach to deriving viable harvest strategies for multispecies management of the Northern Gulf of California. Aquat Conserv-Mar Freshw Ecosyst 19:384-397

Lewis, K.A., de Mutsert, K., Steenbeek, J., Peele, H., Cowan Jr, J.H., and Buszowski, J. (2016) Employing ecosystem models and geographic information systems (GIS) to investigate the response of changing marsh edge on historical biomass of estuarine nekton in Barataria Bay, Louisiana, USA. Ecological Modelling.

Lighthouses of Australia Inc (2004) The Bulletin, No 1/2004

Lindsay MCM, Meathrel CE (2008) Where, When and How? Limitations of the Techniques Used to Examine Dietary Preference of Pacific Gulls (Larus pacificus) Using Non-consumed Parts of Prey and Regurgitated Pellets of Prey Remains. Waterbirds 31:611-619

Link JS, Fulton EA, Gamble RJ (2010) The northeast US application of ATLANTIS: a full system model exploring marine ecosystem dynamics in a living marine resource management context. Progress in Oceanography 87:214-234

Linnane A, Gardner C, Hobday D, Punt A, McGarvey R, Feenstra J, Matthews J, Green B (2010a) Evidence of large-scale spatial declines in recruitment patterns of southern rock lobster Jasus edwardsii, across south-eastern Australia. Fisheries Research 105:163-171

Linnane A, Sloan S, McGarvey R, Ward T (2010b) Impacts of unconstrained effort: Lessons from a rock lobster (Jasus edwardsii) fishery decline in the northern zone management region of South Australia. Marine Policy 34:844-850

Lloyd M (2010) Spatial variation in growth of snapper (*Chrysophrys auratus*) in South Australia gulf waters: An investigation of diet as a contributing factor. Bachelor of Science with Honours Honours Thesis, The University of Adelaide, Adelaide

Loneragan NR, Babcock RC, Lozano-Montes H, Dambacher JM (2010) Evaluating how food webs and the fisheries they support are affected by fishing closures in Jurien Bay, temperate Western Australia. FRDC Report, Project No. 2006/038.

Lozano-Montes H, Babcock R, Loneragan N (2012) Exploring the effects of spatial closures in a temperate marine ecosystem in WesternAustralia: A case study of the western rock lobster (Panulirus cygnus) fishery. Ecological Modelling 245:31-40

Lozano-Montes HM, Loneragan NR, Babcock RC, Jackson K (2011) Using trophic flows and ecosystem structure to model the effects of fishing in the Jurien Bay Marine Park, temperate Western Australia. Marine and Freshwater Research 62:421-431

Mackinson S, Daskalov G (2007) An ecosystem model of the North Sea to support an ecosystem approach to fisheries managment: description and parameterisation. Science Series Technical Reports. Cefas Lowestoft, 142: 196pp.

Malcolm H, Bruce BD, Stevens JD (2001) A review of the biology and status of white sharks in Australian waters. Report to the Department of the Environment. pp 113.

Maldonado MT, Surma S, Pakhomov EA (2016) Southern Ocean biological iron cycling in the pre-whaling and present ecosystems. Phil Trans R Soc A 374:20150292

Marchant S, Higgins PJ (eds) (1990a) Handbook of Australian, New Zealand and Antarctic Birds, Vol 1: Ratites to Ducks. Oxford University Press, Melbourne

Marchant S, Higgins PJ (eds) (1990b) Handbook of Australian, New Zealand and Antarctic Birds, Vol 1: Ratites to Ducks. Oxford University Press, Melbourne

May JL, Blaber SJM (1989) Benthic and pelagic fish biomass of the upper continental slope off eastern Tasmania. Marine Biology 101:11-25

McAuley R, Simpfendorfer C (2003) Catch composition of the Western Australian temperate demersal gillnet and demersal longline fisheries, 1994–1999; p. 78. Department of Fisheries; Perth, Western Australia. Fisheries Research Report, 146.

McGarvey R, Feenstra JE, Ye Q (2007) Modeling fish numbers dynamically by age and length: partitioning cohorts into ‘slices’. Canadian Journal of Fisheries and Aquatic Sciences 64:1157-1173

McGarvey R, Fowler. AJ (2002) Seasonal growth of King George whiting (*Sillaginodes punctata)* from length-at-age samples truncated by legal minimum size. Fisheries Bulletin 100:545-558

McGill LM, Gerig BS, Chaloner DT, Lamberti GA (2017) An ecosystem model for evaluating the effects of introduced Pacific salmon on contaminant burdens of stream-resident fish. Ecological Modelling 355:39-48

McIntosh R, Sutherland D, Dann D, Kirkwood R, Thalman S, Alderman R, Arnould JPY, Mitchell T, Kirkman SP, Salton M, Slip D (2014) Pup estimates of Australian and New Zealand fur seals in Victoria, Tasmania and New South Wales between 2007 and 2013. Report to the Australian Marine Mammal Centre, Department of the Environment.

McIntosh RR (2007) The life history and population demographics of the Australian sea lion, *Neophoca cinerea.* PhD PhD Thesis, La Trobe University, Bundoora, Victoria.,

McIntosh RR, Page B, Goldsworthy SD (2006) Dietary analysis of regurgitates and stomach samples from free-living Australian sea lions. Wildlife Research 33:661-669

McKenzie J (2006) Population demographics of New Zealand fur seals (*Arctocephalus forsteri*). PhD PhD, La Trobe University, Bundoora

McKenzie J, Page B, Goldsworthy SD, Hindell MA (2007a) Growth strategies of New Zealand fur seals in southern Australia. Journal of Zoology 272:377-389

McKenzie J, Page B, Shaughnessy PD, Hindell MA (2007b) Age and reproductive maturity of New Zealand fur seals (*Arctocephalus forsteri*) in southern Australia. Journal of Mammalogy 88:639-648

McKenzie J, Page B, Shaughnessy PD, Hindell MA (2007c) Age and reproductive maturity of New Zealand fur seals (*Artocephalus forsteri*) in Southern Australia. Journal of Mammalogy 88:639-648

McLeay LJ (2016) Giant Crab Fishery Status Report 2014/15. SARDI Research Report Series No 895. South Australian Research and Development Institute (Aquatic Sciences), Adelaide

McLeay LJ, Page B, Goldsworthy SD, Ward TM, Paton DC (2009) Size matters: variation in the diet of chick and adult crested terns. Marine Biology 156:1765-1780

McLeod DJ, Hobday AJ, Lyle JM, Welsford DC (2012) A prey-related shift in the abundance of small pelagic fish in eastern Tasmania? ICES Journal of Marine Science

Mecenero S, Kirkman SP, Roux J-P (2006) A refined consumption model for lactating Cape fur seals (*Arctocephalus pusillus pusillus*), based on scat analyses. ICES Journal of MArine Science 63:1551-1566

Moller LM, Bilgmann K, Charlton-Robb K, Beheregaray L (2008) Multi-gene evidence for a new bottlenose dolphin species in southern Australia. Molecular phylogenetics and evolution 49:674-681

Musinguzi L, Natugonza V, Ogutu-Ohwayo R (2017) Paradigm shifts required to promote ecosystem modeling for ecosystem-based fishery management for African inland lakes. J Great Lakes Res 43:1-8

Norman F, Dann P, Menkhorst P The status of seabirds in Victoria. In: Ross GJB, Weaver K, Greig JC (eds). Proc The Status of Australia's Seabirds: Proceedings of the National Seabird Workshop, Canberra. Biodiversity Group, Environment Australia

Novaczek I (1984) Development and phenology of *Ecklonia radiata* at 2 depths in Goat Island Bay, New Zealand. Marine Biology 81:189-197

Nowacek DP, Clark CW, Mann D, Miller PJ, Rosenbaum HC, Golden JS, Jasny M, Kraska J, Southall BL (2015) Marine seismic surveys and ocean noise: time for coordinated and prudent planning. Frontiers in Ecology and the Environment 13:378-386

O'Brien J (2009) IMPACTS OF SHIPPING. Coast and Marine Publication

Ofir E, Gal G, Goren M, Shapiro J, Spanier E (2016) Detecting changes to the functioning of a lake ecosystem following a regime shift based on static food-web models. Ecological Modelling 320:145-157

Okey TA, Mahmoudi B (2002) An ecosystem model of the West Florida shelf for use in fisheries management and ecological research: Volume II. Model Construction. Florida Marine Research Institute, St Petersburg, FA, USA.

Okey TA, Pauly D, Univ. Of Alaska Sea Grant College P, Univ. Of Alaska Sea Grant College P, Univ. Of Alaska Sea Grant College P (1999) A mass-balanced model of trophic flows in Prince William Sound: Decompartmentalizing ecosystem knowledge, Vol 16. Univ Alaska Sea Grant, Fairbanks

Okey TA, Wright BA (2004) Toward ecosystem-based extraction policies for Prince William Sound, Alaska: Integrating conflicting objectives and rebuilding pinnipeds. Bulletin of Marine Science 74:727-747

Olsen A (1954) The biology, migration and growth rate of the school shark *Galeorhinus australis* (Macleay) in south-eastern Australian waters. Australian Journal of Marine and Freshwater Research 5:353-410

Page B, Goldsworthy SD, McLeay L, Wiebkin A, Peters K, Einoder L, Rogers P, Braley M, Gibbs S, McKenzie J, Huveneers C, Caines R, Daly K, Harrison S, Baylis A, Morrice M, Gill P, McIntosh R, Bool N, Ward T (2011) The diets of marine predators in southern Australia: assessing the need for ecosystem-based management of the South Australian sardine fishery. In: Goldsworthy SD, Page B, Rogers P, Ward TM (eds) Establishing ecosystem-based management for the South Australian Sardine Fishery: developing ecological performance indicators and reference points to assess the need for ecological allocations Final Report to the Fisheries Research and Development Corporation, PN 2005/031SARDI Publication No F2010/000863-1 SARDI Research Report Series No 529. South Australian Research and Development Institute

Page B, McKenzie J, Goldsworthy SD (2005) Dietary resource partitioning among sympatric New Zealand and Australian fur seals. Marine Ecology Progress Series 293:283-302

Page B, McKenzie J, Sumner MD, Coyne M, Goldsworthy SD (2006) Spatial separation of foraging habitats among New Zealand fur seals. Marine Ecology Progress Series 323:263-279

Palomera I, Olivar M, Salat J, Sabatés A, Coll M, García A, Morales-Nin B (2007) Small pelagic fish in the NW Mediterranean Sea: an ecological review. Progress in Oceanography 74:377-396

Patterson TA, Evans K, Carter TI, Gunn JS (2008) Movement and behaviour of large southern bluefin tuna (Thunnus maccoyii) in the Australian region determined using pop-up satellite archival tags. Fisheries Oceanography 17:352-367

Paulin CD (1990) *Pagrus auratus*, a new combination for the species known as “snapper” in Australasian waters (Pisces: Sparidae). New Zealand Journal of Marine and Freshwater Research 24:259-265

Pauly D (1980) On the interrelationship between natural mortality, growth parameters, and mean environmental temperature in 175 fish sticks. Journal du Conseil International pour l'Exploration de la Mer 39:175-192

Pauly D, Christensen V, Dalsgaard J, Froese R, Torres F (1998) Fishing down marine food webs. Science 279:860-863

Pavés HJ, González HE, Christensen V (2013) Structure and functioning of two pelagic communities in the North Chilean Patagonian coastal system. Hydrobiologia 717:85-108

Peters KJ (2017) Diet of the Australian sea lion (*Neophoca cinerea*): an assessment of novel DNA-based and contemporary methods to determine prey consumption. PhD PhD, University of Adelaide, Adelaide

Peters KJ, Ophelkeller K, Bott NJ, Deagle BE, Jarman SN, Goldsworthy SD (2014) Fine-scale diet of the Australian sea lion (*Neophoca cinerea*) using DNA-based analysis of faeces. Article first published online: 12 MAR 2014. Marine Ecology

Peters KJ, Ophelkeller K, Bott NJ, Goldsworthy SD (2015) PCR-based techniques to determine diet of the Australian sea lion (Neophoca cinerea): a comparison with morphological analysis. Marine ecology 36:1428-1439

Piroddi C, Bearzi G, Christensen V (2010) Effects of local fisheries and ocean productivity on the northeastern Ionian Sea ecosystem. Ecological Modelling 221:1526-1544

Pitcher CR, Ellis N, Venables WN, Wassenberg TJ, Burridge CY, Smith GP, Browne M, Pantus F, Poiner IR, Doherty PJ, Hooper JNA, Gribble N (2016) Effects of trawling on sessile megabenthos in the Great Barrier Reef and evaluation of the efficacy of management strategies. ICES Journal of Marine Science 73:i115-i126

Polovina JJ (1984) Model of a coral reef ecosystem. Coral Reefs 3:1-11

Port Metro Vancouver (2015) Roberts Bank Terminal 2 Environmental Impact Statement. Book 3. Environmental Assessment by Review Panel. Port Metro Vancouver, Vancouver

Punt A, Pribac F, Taylor B, Walker T (2005) Harvest strategy evaluation for school and gummy shark. Journal of Northwest Atlantic Fisheries Science 35:387-406

Rees AJJ, Yearsley, G.K., Gowlett-Holmes, K. and Pogonoski, J (2017) Codes for Australian Aquatic Biota (on-line version). CSIRO Marine and Atmospheric Research, World Wide Web electronic publication, 1999 onwards. .

Reily SB, Barlow J (1986) Rates of increase in dolphin population size. Fishery Bulletin 84:527-533

Richardson AJ (2008) In hot water: zooplankton and climate change. ICES Journal of Marine Science 65:279-295

Riordan J, Johnston G (2013) Morphological Sex Determination in Black-faced Cormorants (Phalacrocorax fuscescens). Waterbirds 36:94-101

Roberts SD, Steer MA (2010) By-product assessment in the Spencer Gulf Prawn Fishery with an emphasis on developing managment option for Balmain bugs. South Australian Research and Development Institue (Aquatic Sciences), Adelaide. SARDI Publication No. F2010/000165-1. SARDI Research Report Series No. 439.

Rogers P, Earl J, Ivey A (2013a) Review of impacts of localised depletion of small pelagic fishes on predators and ecosystems. Prepared for the Department of the Environment (on behalf of the expert panel) 16

Rogers P, Huveneers C, Page B, Hamer D, Goldsworthy SD, Mitchell JG, Seuront L (2012) A quantitative comparison of the diets of sympatric pelagic sharks in gulf and shelf ecosystems off southern Australia. ICES Journal of Marine Science 69:1382–1393

Rogers PJ, Geddes M, Ward TM (2003) Blue sprat *Spratelloides robustus* (Clupeidae; Dussumieriinae): A temperate clupeoid with a tropical life history strategy? Marine Biology 142:809–824

Rogers PJ, Huveneers C, Page B, Goldsworthy SD, Coyne M, Lowther AD, Mitchell JG, Seuront L (2015) Living on the continental shelf edge: habitat use of juvenile shortfin makos Isurus oxyrinchus in the Great Australian Bight, southern Australia. Fisheries Oceanography 24:205-218

Rogers PJ, Knuckey I, Hudson RJ, Lowther AD, Guida L (2017) Post-release survival, movement, and habitat use of school shark Galeorhinus galeus in the Great Australian Bight, southern Australia. Fisheries Research 187:188-198

Rogers PJ, Ward TM (2007) Life history strategy of sandy sprat Hyperlophus vittatus (Castelnau, 1875): comparison with temperate and tropical clupeoids of the Indo-Pacific Region. Journal of Applied Ichthyology 23: 583-591

Rogers PJ, Ward TM, van Ruth PD, Williams A, Bruce BD, Connell SD, Currie DR, Davies CR, Evans K, Gillanders BM, Goldsworthy SD, Griffin DA, Hardman-Mountford NJ, Ivey AR, Kloser RJ, Middleton JK, Richardson AE, Ross A, Tanner JE, Young J (2013b) Physical processes, biodiversity and ecology of the Great Australian Bight region: a literature review. CSIRO, Australia. 197 pp.

Ruzicka JJ, Brink KH, Gifford DJ, Bahr F (2016) A physically coupled end-to-end model platform for coastal ecosystems: Simulating the effects of climate change and changing upwelling characteristics on the Northern California Current ecosystem. Ecological Modelling 331:86-99

SAFS (2017) Status of Australian Fish Stocks http://fish.gov.au

Sagarese SR, Lauretta MV, Walter JF (2017) Progress towards a next-generation fisheries ecosystem model for the northern Gulf of Mexico. Ecological Modelling 345:75-98

Sakshaug E (1997) Biomass and productivity distributions and their variability in the Barents Sea. ICES Journal of Marine Science 54:341-350

Savina M, Condie SA, Fulton EA (2013a) The Role of Pre-Existing Disturbances in the Effect of Marine Reserves on Coastal Ecosystems: A Modelling Approach. Plos One 8

Savina M, Forrest RE, Fulton EA, Condie SA (2013b) Ecological effects of trawling fisheries on the eastern Australian continental shelf: a modelling study. Marine and Freshwater Research 64:1068-1086

Savina M, Fulton E, Condie S, Forrest R, Scandol J, Astles K, Gibbs P (2008) Ecologically sustainable development of the regional marine and estuarine resources of NSW: Modelling of the NSW continental shelf ecosystem. CSIRO and NSW DPI Report

Shannon LJ, Neira S, Taylor M (2008) Comparing internal and external drivers in the southern Benguela and the southern and northern Humboldt upwelling ecosystems. African Journal of Marine Science 30:63-84

Shaughnessy PD, Goldsworthy SD, Mackay AI (2014) Status and trends in abundance of New Zealand fur seal populations in South Australia. SARDI Publication No. F2014/000338-1. SARDI Research Report Series No. 781. 33 pp.

Shaughnessy PD, McIntosh RR, Goldsworthy SD, Dennis TE, Berris M Trends in abundance of Australian sea lions, *Neophoca cinerea*, at Seal Bay, Kangaroo Island, South Australia. In: Trites AW, Atkinson SK, DeMaster DP, Fritz LW, Gelatt TS, Rea LD, Wynne KM (eds). Proc Sea Lions of the World. Alaska Sea Grant College Program

Shaughnessy PD, McKenzie J, Lancaster ML, Goldsworthy SD, Dennis TE (2010) Australian fur seals establish haulout sites and a breeding colony in South Australia. Australian Journal of Zoology 58:94-103

Shepherd SA (1972) Studies on southern Australian abalone (genus *Haliotis*) I. Ecology of five sympatric species. Australian Journal of Marine and Freshwater Research 24:217-257

Simpfendorfer CA, McAuley R, Chidlow J, Unsworth P (2002) Validated age and growth of the dusky shark, *Carcharhinus obscurus*, from Western Australian waters. Marine and Freshwater Research 53:567-573

Smith AD, Brown CJ, Bulman CM, Fulton EA, Johnson P, Kaplan IC, Lozano-Montes H, Mackinson S, Marzloff M, Shannon LJ (2011) Impacts of fishing low–trophic level species on marine ecosystems. Science 333:1147-1150

Smith ADM, Ward TM, Hurtado F, Klaer N, Fulton EA (2015) Review and update of harvest strategy settings for the Commonwealth Small Pelagic Fishery - Single species and ecosystem considerations. Final Report of FRDC Project No. 2013/028. CSIRO Hobart

Smith DC, Fulton EA, Apfel P, Cresswell ID, Gillanders BM, Haward M, Sainsbury KJ, Smith AD, Vince J, Ward TM (2017) Implementing marine ecosystem-based management: lessons from Australia. ICES Journal of Marine Science

Smith HK (1983) Fishery and biology of *Nototodarus gouldi* (McCoy, 1888) in Western Bass Strait. Memoirs of the National Museum Victoria 44:285-290

Smith SE, Au DW, Show C (2008) Intrinsic rates of increase in pelagic elasmobranchs. In: Camhi MD, Pikitch EK, Babcock EA (eds) Sharks of the open ocean: biology, fisheries and conservation. Blackwell Publishing, Singapore

Sommer U, Lengfellner K (2008) Climate change and the timing, magnitude, and composition of the phytoplankton spring bloom. Global Change Biology 14:1199-1208

Sporcic M, Haddon M (2016) Statistical CPUE standardizations for selcted SESSF specis (data to 2015). Report for AFMA SERAG 11-12 October 2016. CSIRO O&A, Hobart

Steenbeek J, Coll M, Gurney L, Melin F, Hoepffner N, Buszowski J, Christensen V (2013) Bridging the gap between ecosystem modeling tools and geographic information systems: Driving a food web model with external spatial-temporal data. Ecological Modelling 263: 139-15

Steer MA, McGarvey R, Fowler AJ, Burch P, Feenstra JE, Jackson WB, Lloyd MT (2012) Southern Garfish (*Hyporhamphus melanochir*) Fishery. Report to PIRSA Fisheries and Aquaculture. South Australian Research and Development Institute (Aquatic Sciences), Adelaide

Stevens J, West G (1997) Investigation of school and gummy shark nursery areas in south eastern Australia.

Suprenand PM, Ainsworth CH (2017) Trophodynamic effects of climate change-induced alterations to primary production along the western Antarctic Peninsula. Marine Ecology Progress Series 569:37-54

Tanner JE, Deakin S (2001) Active habitat selection for sand by juvenile western king prawns, *Melicertus latisulcatus* (Kishinouye). Journal of Experimental Marine Biology and Ecology 261:199-209

Thomson R, Upston J (2016) SESSF catches and discards for TAC purposes. CSIRO O&A, Hobart

Tierney KM, Muir GKP, Cook GT, MacKinnon G, Howe JA, Heymans JJ, Hughes DJ, Xu S (2017) Ecosystem uptake and transfer of Sellafield-derived radiocarbon (C-14) part 2: The West of Scotland. Marine Pollution Bulletin 115:57-66

Tittensor DP, Eddy TD, Lotze HK, Galbraith ED, Cheung W, Barange M, Blanchard JL, Bopp L, Bryndum-Buchholz A, Büchner M, Bulman C, Carozza DA, Christensen V, Coll M, Dunne JP, Fernandes JA, Fulton EA, Hobday AJ, Huber V, Jennings S, Jones M, Lehodey P, Link JS, Mackinson S, Maury O, Niiranen S, Oliveros-Ramos R, Roy T, Schewe J, Shin Y-J, Stock CA, Underwood PJ, Volkholz J, Watson JR, Walker ND (in press) A protocol for the intercomparison of marine fishery and ecosystem models: Fish-MIP v1.0. Geoscientific Model Development

Todd VL, Todd IB, Gardiner JC, Morrin EC, MacPherson NA, DiMarzio NA, Thomsen F (2014) A review of impacts of marine dredging activities on marine mammals. ICES Journal of Marine Science 72:328-340

Tomczak MT, Niiranen S, Hjerne O, Blenckner T (2012) Ecosystem flow dynamics in the Baltic Proper—Using a multi-trophic dataset as a basis for food–web modelling. Ecological Modelling 230:123-147

Trites AW, Livingston PA, Vasconcellos MC, Mackinson S, Springer AM, Pauly D (1999) Ecosysetm change and the decline of marine mammals in the Eastern Bering Sea: testing the ecosystem shift and commercial whaling hypothesis. Fisheries Centre Research Reports, Vol 7, Book 7

Trites AW, Pauly D (1998) Estimating mean body masses of marine mammals from maximum body lengths. Canadian Journal of Zoology 76:886-896

Tuck GN, Knuckey I, Klaer N (2013) Informing the review of the Commonwealth Policy on Fisheries Bycatch through assessing trends in bycatch of key Commonwealth fisheries. Final Report FRDC Project: 2012/046. FRDC & CSIRO Marine and Atmospheric Research

Upston J, Thomson R (2016) Integrated Monitoting Program for the Southern and Eastern Scalefish and Shark Fisehry -Discard estimation 2015. Report for AFMA. CSIRO MRI, Hobart

Vasslides JM, Townsend H, Belton T, Jensen OP (2017) Modeling the Effects of a Power Plant Decommissioning on an Estuarine Food Web. Estuaries and Coasts 40:604-616

Walker T (1998) Can shark resources be harvested sustainably? A question revisited with a review of shark fisheries. Marine and Freshwater Research 49:553-572

Walker T, Hudson R, Gason A (2005) Catch evaluation of target, by-product, and by-catch species taken by gillnets and longlines in the Shark Fishery of south-eastern Australia. Journal of Northwest Atlantic Fishery Science 35:505-530

Walter JP, Ebert DA (1991) Preliminary estimates of age of the bronze whaler *Carcharhinus brachyurus* (Chondrichthyes: Carcharhinidae) from southern Africa, with a review of some life history parameters. South African Journal of Marine Science 10:37-44

Walters CJ, Christensen V, Pauly D (1997) Structuring dynamic models of exploited ecosystems from trophic mass-balance assessments. Reviews in Fish Biology and Fisheries 7:139-172

Walters C, Pauly D, Christensen V (1999) Ecospace: Prediction of mesoscale spatial patterns in trophic relationships of exploited ecosystems, with emphasis on the impacts of marine protected areas. Ecosystems 2: 539-554

Ward EJ, Levin PS, Lance MM, Jeffries SJ, Acevedo-Gutiérrez A (2012) Integrating diet and movement data to identify hot spots of predation risk and areas of conservation concern for endangered species. Conservation Letters 5:37-47

Ward T, Hoedt F, McLeay L, Dimmlich W, Kinloch M, Jackson G, McGarvey R, Rogers P, Jones K (2001) Effects of the 1995 and 1998 mass mortality events on the spawning biomass of sardine, Sardinops sagax, in South Australian waters. ICES Journal of Marine Science 58:865-875

Ward T, Middleton J, Griffin DA, Kloser RJ, van Ruth P, Goldsworthy SD, Davies CR, Williams A, Tanner JE, Ross A, Young M, Beer A, Pascoe S, Kempton R, Fulton B and Bulman C (2017) Socio-ecological systems of the Great Australian Bight: synthesis of results and findings. Final Synthesis Report GABRP Project 7.1. Great Australian Bight Research Program, GABRP Research Report Number 28, 90pp.

Ward TM, Ivey AR, Carroll JD (2016) Spawning biomass of sardine, Sardinops sagax in waters off South Australia in 2016. Report to PIRSA Fisheries and Aquaculture. SARDI Adelaide. SARDI Publication Series No F2007/000566-7. SARDI Research Report Series No. 931. 31 pp.

Ward TM, McLeay LJ, Dimmlich WF, Rogers PJ, McClatchie S, Matthews R, KÄMpf J, VAN R (2006) Pelagic ecology of a northern boundary current system: effects of upwelling on the production and distribution of sardine (Sardinops sagax), anchovy (Engraulis australis) and southern bluefin tuna (Thunnus maccoyii) in the Great Australian Bight. Fisheries Oceanography 15:191-207

Ward TM, McLeay LJ, Rogers PJ (2003) Benthic Protection Zone of the Great Australian Bight Marine Park: 2. Monitoring Sustainable Use. Final Report to NPWSA and DEH. 82 pp.

Ward TM, Rogers PJ, McLeay LJ (2007) Developing and evaluating the use of the Daily Egg Production Method to estimate the spawning biomass of blue mackerel *Scomber australasicus* off southern and eastern Australia. In: Ward TM, Rogers PJ (eds) Development and evaluation of egg-based stock assessment methods for blue mackerel *Scomber australasicus* in southern Australia. Report to the Fisheries Research and Development Corporation, Project No. 2002/061

Ward TM, Whitten AR, Ivey AR (2015) South Australian Sardine (*Sardinops sagax*) Fishery: Stock Assessment Report 2015. Report to PIRSA Fisheries and Aquaculture. South Australian Research and Development Institute (Aquatic Sciences), Adelaide

Warham J (1996) The behaviour, population biology and physiology of the petrels. Acedemic Press, London, UK

Warneke RM (1995) Australian fur-seal *Arctocephalus pusillus* (Schreber, 1775). In: Strahan R (ed) The mammals of Australia. Oxford University Press, Melbourne

Weijerman M, Fulton EA, Kaplan IC, Gorton R, Leemans R, Mooij WM, Brainard RE (2015) An integrated coral reef ecosystem model to support resource management under a changing climate. PLoS One 10:e0144165

Weijerman M, Grace-McCaskey C, Grafeld SL, Kotowicz DM, Oleson KL, van Putten IE (2016a) Towards an ecosystem-based approach of Guam's coral reefs: The human dimension. Marine Policy 63:8-17

Weijerman M, Link J, Fulton E, Olsen E, Townsend H, Gaichas S, Hansen C, Skern-Mauritzen M, Kaplan I, Gamble R (2016b) Atlantis Ecosystem Model Summit: Report from a workshop. Ecological Modelling 335:35-38

Weimerskirch H, Cherel Y (1998) Feeding ecology of short-tailed shearwaters: breeding in Tasmania and foraging in the Antarctic? Marine Ecology-Progress Series 167:261-274

Wiebkin A (2011a) Conservation managment priorities for little penguin populations in Gulf St Vincent. Report to the Adelaide and Mount Lofty Ranges Natural Resources Managment Board. South Australian Research and Development Institute (Aquatic Sciences), Adelaide. SARDI Publication No. F2011/000188-1. SARDI Research Report Series No. 588. 97 pp.

Wiebkin A (2011b) Feeding and Breeding Ecology of Little Penguins (*Eudyptula minor*) in the Eastern Great Australian Bight. PhD, The University of Adelaide, South Australia,

Williams A, Koslow JA, Terauds A, Haskard K (2001) Feeding ecology of five fishes from the mid-slope micronekton community off southern Tasmania, Australia. Marine Biology 139:1177-1192

Wilson D, Curtotti R, Begg G, Phillips K (2009) Fishery status reports 2008. Bureau of Rural Sciences and Australian Bureau of Agriculture and Resource Economics, Canberra

Winder M, Schindler DE (2004) Climate change uncouples trophic interactions in an aquatic ecosystem. Ecology 85:2100-2106

Winship AJ, Trites AW, Rosen DA (2002) A bioenergetic model for estimating the food requirements of Steller sea lions *Eumatopias jubatus* in Alaska, USA. Marine Ecology Progress Series 229:291-312

Wintner SP, Cliff G (1999) Age and growth determinations of the white shark *Carcharodon carcharias*, from the east coast of South Africa. Fisheries Bulletin 153:153-169

Wooller RD, Bradley JS, Skira IJ, Serventy DL (1990) Reproductive success of short-tailed shearwaters *Puffinus-tenuirostris* in relation to their age and breeding experience. Journal of Animal Ecology 59:161-170

Young JW, Blaber SJM (1986) Feeding ecology of three species of midwater fishes associated with the continental slope of eastern Tasmania, Australia. Marine Biology 93:147-156

Young JW, Bradford RW, Lamb TD, Lyne VD (1996) Biomass of zooplankton and micronekton in the southern bluefin tuna fishing grounds off eastern Tasmania, Australia. Marine Ecology-Progress Series 138:1-14

Young JW, Lamb TD, Le D, Bradford RW, Whitelaw AW (1997) Feeding ecology and interannual variations in diet of southern blufin tuna *Thunnus maccoyii*, in relation to coastal and oceanic waters off eastern Tasmania, Australia. Environmental Biology of Fishes 50:275-291

Zhang X, Oke P, Feng M, Chamberlain M, Church J, Monselesan D, Sun C, Matear R, Schiller A, Fiedler R (2016) Geoscientific Model Development Discussions. doi:10.5194/gmd-2016-17

Zhang X, Church JA, Monselesan D, McInnes K (2017) Regional Sea Level Projections for Australian Coasts in the 21st Century. Geophys. Res. Lett. 44

7. EWE APPENDICES

7.1 Diet matrix of functional groups used in the initial parameterisation of the EwE GAB Ecosystem model.

No.	Prey \ predator	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	Baleen whales	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Toothed whales	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	Bottlenose dolphins	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0061	0	0	0	0	0	0
4	Common dolphins	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0125	0.0565	0	0	0	0	0
5	Long-nosed fur seal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0102	0	0	0	0	0	0
6	Australian fur seal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0000	0	0	0	0	0	0
7	Australian sea lion	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0032	0	0	0	0	0	0
8	Albatross	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0004	0	0	0	0	0	0
9	Shearwaters	0	0	0	0	0.0005	0	0.0001	0	0	0	0	0	0	0	0	0.0004	0	0	0	0	0	0
10	Small petrels	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0120	0	0.0004	0	0	0	0	0	0
11	Gannets	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0001	0	0	0	0	0	0
12	Terns	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0004	0	0	0	0	0	0	0	0
13	Shags and cormorants	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0000	0	0	0	0	0	0
14	Gulls	0	0	0	0	0	0	0.0000	0	0	0	0	0	0	0	0	0.0000	0	0	0	0	0	0
15	Little Penguins	0	0	0	0	0.0002	0	0.0000	0	0	0	0	0	0	0	0	0.0001	0	0	0	0	0	0
16	Shelf pelagic sharks	0	0	0	0	0.0001	0	0	0	0	0	0	0	0	0	0	0.0449	0	0	0	0	0	0
17	Offshore pelagic sharks	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	Shelf demersal sharks	0	0	0	0	0.0000	0.0237	0.0043	0	0	0	0	0.0009	0	0	0	0.0351	0	0	0	0	0	0
19	Shelf demersal piscivorous shark	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0005	0	0	0	0	0	0
20	Deep demersal sharks	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0001	0	0	0	0	0	0
21	Skates and rays	0	0	0	0	0.0002	0	0.0089	0	0	0	0	0	0	0	0	0.0336	0	0	0	0	0	0
22	Southern Bluefin Tuna	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0023	0	0	0	0	0	0
23	Tunas and billfish	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0029	0.0015	0	0	0	0	0
24	Offshore pelagic piscivores	0	0	0	0	0.0017	0	0.0067	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	Offshore pelagic invertivore large	0	0	0	0	0.0002	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	Shelf large pelagic piscivores	0	0	0.0013	0.0170	0.0078	0	0.0095	0.0800	0.0017	0	0.3975	0.0821	0	0	0	0.0991	0.2018	0	0	0	0	0.0092
27	Sardine	0	0.0600	0.0209	0.2082	0.0078	0	0.0004	0	0.0013	0	0.1600	0.2297	0	0.0351	0.0632	0.0702	0	0	0	0	0	0.4585
28	Shelf pelagic planktivore small	0	0	0	0.4291	0.0074	0	0.0005	0	0.0239	0	0.0975	0.3974	0.0188	0.0018	0.7038	0.1827	0	0.1194	0	0	0	0.2998
29	Mackerels	0	0.0012	0.0157	0.1169	0.0184	0.0945	0.0005	0.4680	0.0296	0	0.1100	0.0059	0	0	0.0161	0.0445	0.1067	0.2089	0	0	0	0.0473
30	Redbait	0	0.0500	0	0.0100	0.4631	0.4624	0.0007	0.0290	0.0054	0	0	0	0	0	0.0441	0.0018	0	0.0042	0	0	0	0
31	Shelf small demersal piscivores	0	0.0140	0.0009	0	0	0	0	0.0660	0	0	0	0	0	0	0	0	0	0.0062	0	0	0	0
32	Shelf small demersal omnivores	0	0	0.2955	0.0227	0.1464	0.2983	0.3865	0	0	0	0.0500	0.2248	0.5820	0.3150	0.0311	0.0154	0	0.0200	0.1252	0	0	0
33	Shelf large demersal piscivores	0	0	0.0127	0.0705	0.0121	0.0613	0.0702	0	0	0	0.0075	0.0005	0	0.0197	0.0005	0.0407	0.0055	0	0	0	0	0
34	Shelf large demersal omnivores	0	0	0.0257	0.0139	0.0001	0.0158	0.0219	0	0	0	0.0375	0.0011	0.2755	0.1541	0	0.0048	0	0	0	0	0	0
35	King George whiting	0	0.0050	0.0065	0	0.0000	0	0.0022	0	0	0	0	0	0.0780	0	0	0	0	0	0	0	0	0
36	Garfish	0	0	0	0.0095	0.0086	0.0079	0.0021	0	0.0003	0	0.1000	0.0489	0.0431	0.0066	0.1083	0.0053	0	0	0	0	0	0
37	Snapper	0	0.0010	0	0.0019	0.0003	0	0.0002	0	0	0	0	0	0	0	0	0.0377	0	0	0	0	0	0
38	Deepwater flathead	0	0.0200	0	0	0.0000	0	0.0013	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
39	Bight redfish	0	0.0600	0.0013	0	0.0048	0.0095	0.0024	0	0	0	0	0	0	0	0	0.0042	0	0.1000	0	0	0	0.0013

Appendix 7.1 cont.

No.	Prey \ predator	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44
1	Baleen whales	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Toothed whales	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	Bottlenose dolphins	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	Common dolphins	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	Long-nosed fur seal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	Australian fur seal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	Australian sea lion	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	Albatross	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	Shearwaters	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	Small petrels	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	Gannets	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	Terns	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	Shags and cormorants	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	Gulls	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	Little Penguins	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	Shelf pelagic sharks	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	Offshore pelagic sharks	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	Shelf demersal sharks	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	Shelf demersal piscivorous shark	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	Deep demersal sharks	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	Skates and rays	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	Southern Bluefin Tuna	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	Tunas and billfish	0	0.0033	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	Offshore pelagic piscivores	0.3080	0.0430	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	Offshore pelagic invertivore large	0.0970	0.0300	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	Shelf large pelagic piscivores	0	0	0	0.0007	0	0	0	0	0	0	0	0	0	0	0.0216	0	0	0	0	0	0	0
27	Sardine	0.0100	0.0020	0	0.2291	0	0	0	0	0	0	0	0	0	0	0.0303	0	0	0	0	0	0	0
28	Shelf pelagic planktivore small	0	0	0	0.2385	0	0	0	0	0	0	0	0	0	0	0.0352	0	0.1500	0	0	0	0	0
29	Mackerels	0.0660	0.1153	0	0.0929	0	0	0	0	0	0	0.1359	0	0	0	0.0043	0	0	0	0	0	0	0.0050
30	Redbait	0.0020	0.0072	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0500	0	0	0	0	0
31	Shelf small demersal piscivores	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1500	0.2000	0	0	0	0	0.0020
32	Shelf small demersal omnivores	0.0180	0.0167	0	0.1096	0	0	0	0	0.0165	0.0014	0.5012	0.0548	0	0	0.0438	0.1500	0.2000	0	0	0	0	0
33	Shelf large demersal piscivores	0.0100	0.0600	0	0.0001	0	0	0	0	0	0	0.0079	0	0	0	0	0.1500	0	0	0	0	0	0
34	Shelf large demersal omnivores	0.0240	0.0167	0	0.0296	0	0	0	0	0	0	0	0	0	0	0.0058	0.1500	0	0	0	0	0	0
35	King George whiting	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0140	0	0	0	0	0	0	0
36	Garfish	0	0	0	0.0310	0	0	0	0	0	0	0	0	0	0	0.0035	0	0	0	0	0	0	0
37	Snapper	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0004	0	0	0	0	0	0	0
38	Deepwater flathead	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
39	Bight redfish	0	0	0	0.0000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Appendix 7.1 cont.

No.	Prey \ predator	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66
1	Baleen whales	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Toothed whales	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	Bottlenose dolphins	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	Common dolphins	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	Long-nosed fur seal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	Australian fur seal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	Australian sea lion	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	Albatross	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	Shearwaters	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	Small petrels	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	Gannets	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	Terns	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	Shags and cormorants	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	Gulls	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	Little Penguins	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	Shelf pelagic sharks	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	Offshore pelagic sharks	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	Shelf demersal sharks	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	Shelf demersal piscivorous shark	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	Deep demersal sharks	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	Skates and rays	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	Southern Bluefin Tuna	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	Tunas and billfish	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	Offshore pelagic piscivores	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	Offshore pelagic invertivore large	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	Shelf large pelagic piscivores	0	0	0	0	0	0	0	0	0	0.0073	0	0	0	0	0	0	0	0	0	0	0	0
27	Sardine	0	0	0	0	0	0	0	0	0	0.1606	0	0	0	0	0	0.0100	0	0	0	0	0	0
28	Shelf pelagic planktivore small	0	0	0	0	0	0	0	0	0	0.0648	0	0	0	0	0	0.0100	0	0	0	0	0	0
29	Mackerels	0	0	0	0	0	0	0	0	0	0.1626	0	0	0	0	0	0.0300	0	0	0	0	0	0
30	Redbait	0	0	0	0	0	0	0	0	0	0.0200	0	0	0	0	0	0.0050	0	0	0	0	0	0
31	Shelf small demersal piscivores	0	0	0	0	0	0	0	0	0	0.0019	0	0	0	0	0	0	0	0	0	0	0	0
32	Shelf small demersal omnivores	0	0	0	0	0	0	0	0	0	0.0830	0.2000	0	0	0	0	0	0	0	0	0	0	0
33	Shelf large demersal piscivores	0	0	0	0	0	0	0	0	0	0.0259	0	0	0	0	0	0	0	0	0	0	0	0
34	Shelf large demersal omnivores	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35	King George whiting	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
36	Garfish	0	0	0	0	0	0	0	0	0	0.0070	0	0	0	0	0	0	0	0	0	0	0	0
37	Snapper	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	Deepwater flathead	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
39	Bight redfish	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Appendix 7.1 cont.

No.	Prey \ predator	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
40	Migratory mesopelagics	0	0.0108	0	0	0.2367	0.0005	0	0	0.0184	0.0892	0	0	0	0	0	0	0	0.0021	0	0.3167	0	0
41	Non-migrating mesopelagics	0	0.0240	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3645	0	0
42	Slope small demersal invertivores	0	0.0200	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0042	0	0.2330	0	0
43	Slope small demersal piscivores	0	0.0200	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0846	0	0	0	0
44	Slope large demersal piscivores	0	0.0026	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1954	0	0.0253	0	0
45	Slope large demersal invertivores	0	0.0226	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
46	Benthic grazers	0	0	0	0	0	0	0.0001	0	0	0	0	0	0.0024	0.0348	0	0	0	0	0	0	0	0
47	Abalone	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	Benthic detritivore	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0025	0	0.0015	0.1765	0	0.8735	0
49	Benthic carnivores (infauna)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0025	0.0014	0	0	0
50	Meiobenthos	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0005	0	0	0.0018	0
51	Shelf filter feeders	0	0	0	0	0	0	0.0001	0	0	0	0	0	0	0.0537	0	0.0001	0	0	0.0183	0	0	0
52	Deep filter feeders	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
53	Shelf macrozoobenthos	0	0.0669	0	0	0.0005	0	0.0135	0	0.0001	0	0	0.0000	0.0002	0.0116	0.0054	0.0003	0	0.0415	0.1919	0.0014	0.1219	0
54	Squid & cuttlefish shelf	0	0.0463	0.3341	0.0851	0.0774	0.0089	0.1866	0.2670	0	0	0.0200	0.0038	0	0.0221	0.0273	0.1930	0.0443	0.0505	0.1762	0	0	0.0006
55	Octopus shelf	0	0	0.2849	0.0029	0.0037	0.0015	0.2607	0.0040	0	0	0	0	0	0.0046	0	0.0259	0.0443	0.1525	0	0	0	0
56	Rock lobster	0	0	0	0	0	0	0.0030	0	0	0	0	0	0	0	0	0.0002	0	0	0	0	0	0
57	Western king prawn	0	0	0	0	0.0000	0	0.0013	0	0	0	0	0.0029	0	0	0.0001	0.0040	0	0	0.0326	0	0	0
58	Crabs & bugs	0	0	0	0	0.0017	0.0158	0.0161	0	0	0	0	0	0	0.0039	0	0.0041	0	0	0.2462	0	0	0
59	Deep macrozoobenthos	0	0.0015	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
60	Deep squid	0	0.5733	0.0004	0.0124	0	0	0	0.0810	0.0149	0	0.0200	0.0021	0	0.0019	0	0.0409	0.1895	0	0	0.0375	0	0.1833
61	Gelatinous zooplankton	0	0	0	0	0	0	0	0.0040	0	0	0	0	0	0	0	0	0	0.0050	0	0.0170	0	0
62	Large zooplankton	1.0000	0.0007	0	0	0	0	0	0.0010	0.0354	0.4916	0	0	0	0	0	0	0	0.0005	0	0.0046	0	0
63	Mesozooplankton	0	0	0	0	0	0	0	0	0.0002	0	0	0	0	0	0	0	0	0.0005	0	0	0	0
64	Microzooplankton	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
65	Nanozooplankton	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
66	Pelagic bacteria	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
67	Farmed finfish	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
68	Farmed oysters	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
69	Large phytoplankton	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
70	Small phytoplankton	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
71	Microphytobenthos	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
72	Seagrass	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0867	0	0	0	0	0.0270	0	0.0028	0
73	Macroalgae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0048	0	0	0
74	Discards	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
75	Detritus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
76	Import	0	0	0	0	0.0004	0	0	0	0.8690	0.4192	0	0	0	0.2360	0	0.0700	0.3500	0	0	0	0	0
	Sum	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

Appendix 7.1 cont.

No.	Prey \ predator	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44
40	Migratory mesopelagics	0.0280	0.4003	0.0500	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0001	0.7496	0	0.5500	0.1540
41	Non-migrating mesopelagics	0.0200	0.0033	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0080	0	0	0.0100	0.3990
42	Slope small demersal invertivores	0.0100	0.0050	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1300
43	Slope small demersal piscivores	0.0020	0.0003	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0550
44	Slope large demersal piscivores	0.0120	0.0167	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45	Slope large demersal invertivores	0.0100	0.0333	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
46	Benthic grazers	0	0	0	0	0	0	0	0.0271	0	0.0055	0	0.0352	0	0	0.0159	0.0500	0.1000	0	0	0	0	0
47	Abalone	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0045	0	0	0	0	0	0	0
48	Benthic detritivore	0	0.0084	0	0.0646	0	0	0.1101	0.0833	0.2633	0.1955	0.0297	0.0200	0.4941	0.4182	0.0100	0.0500	0	0	0.0040	0.4770	0.1300	0.1000
49	Benthic carnivores (infauna)	0	0	0	0.0297	0	0	0	0	0.1165	0.3652	0.0154	0.0612	0.3416	0	0.0032	0	0	0	0	0	0	0
50	Meiobenthos	0	0	0	0.0306	0.0988	0	0	0	0.0606	0.0261	0.0025	0.0007	0	0.0110	0	0	0	0	0.0008	0	0	0
51	Shelf filter feeders	0	0	0	0	0	0	0	0	0.4428	0.0200	0.0223	0.1913	0.0222	0	0.0366	0	0.1000	0	0	0	0	0
52	Deep filter feeders	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0036	0	0.0200	0
53	Shelf macrozoobenthos	0	0.0188	0	0.0681	0	0	0	0	0.0646	0.1198	0.1883	0.0484	0.1384	0	0.1093	0.2000	0.2000	0	0	0	0	0
54	Squid & cuttlefish shelf	0	0	0	0.0303	0	0	0	0	0	0	0.0036	0	0	0	0.0207	0	0	0	0	0	0	0
55	Octopus shelf	0	0	0	0	0	0	0	0	0	0.0000	0	0.0331	0	0	0.0144	0	0	0	0	0	0	0
56	Rock lobster	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
57	Western king prawn	0	0	0	0	0	0	0	0	0.0357	0.0016	0.0746	0.2635	0.0037	0	0.0118	0	0	0	0	0	0	0
58	Crabs & bugs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5007	0	0	0	0	0	0	0
59	Deep macrozoobenthos	0.0790	0.0015	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0540	0.2500	0.1300	0.0800
60	Deep squid	0.3000	0.1871	0.4000	0.0453	0	0	0	0	0	0	0.0180	0	0	0	0.0044	0.1000	0	0	0	0	0	0.0750
61	Gelatinous zooplankton	0	0.0010	0.5000	0	0.1420	0.3720	0.3828	0.0532	0	0	0	0	0	0	0	0	0	0.0055	0.0050	0.0030	0.0100	0
62	Large zooplankton	0.0040	0.0297	0.0500	0.0000	0.3554	0.3774	0.3038	0.4955	0	0.0307	0	0.0026	0	0	0	0	0	0.4549	0.1800	0.1900	0.1000	0
63	Mesozooplankton	0	0.0003	0	0	0.2387	0.2507	0.1803	0.2477	0	0	0	0	0	0	0	0	0	0.4679	0.0030	0.0800	0.0500	0
64	Microzooplankton	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
65	Nanozooplankton	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
66	Pelagic bacteria	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
67	Farmed finfish	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
68	Farmed oysters	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
69	Large phytoplankton	0	0	0	0	0.1651	0	0.0230	0.0933	0	0	0	0	0	0	0	0	0	0.0636	0	0	0	0
70	Small phytoplankton	0	0	0	0	0	0	0	0	0	0.2023	0.0006	0.2273	0	0	0	0	0	0	0	0	0	0
71	Microphytobenthos	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
72	Seagrass	0	0	0	0	0	0	0	0	0	0.0179	0.0001	0.0525	0	0.5708	0.1094	0	0	0	0	0	0	0
73	Macroalgae	0	0	0	0	0	0	0	0	0	0.0141	0	0.0094	0	0	0.0001	0	0	0	0	0	0	0
74	Discards	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
75	Detritus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
76	Import	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Sum	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

Appendix 7.1 cont.

No.	Prey \ predator	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66
40	Migratory mesopelagics	0.0250	0	0	0	0	0	0	0	0	0.1300	0	0	0	0	0	0.6000	0	0	0	0	0	0
41	Non-migrating mesopelagics	0.0250	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1400	0	0	0	0	0	0
42	Slope small demersal invertivores	0.0100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0150	0	0	0	0	0	0
43	Slope small demersal piscivores	0.0100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44	Slope large demersal piscivores	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45	Slope large demersal invertivores	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
46	Benthic grazers	0	0	0	0	0	0	0	0	0	0	0	0.3742	0	0.0296	0	0	0	0	0	0	0	0
47	Abalone	0	0	0	0	0	0	0	0	0	0	0	0.0123	0	0	0	0	0	0	0	0	0	0
48	Benthic detritivore	0	0.0500	0	0.0500	0.5500	0	0	0	0	0.0446	0	0	0.1000	0.2474	0.0150	0	0.1670	0	0	0	0	0
49	Benthic carnivores (infauna)	0	0.0100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
50	Meiobenthos	0	0.0200	0	0.2000	0	0	0	0	0	0	0	0	0.1000	0	0	0	0	0.1070	0	0	0	0
51	Shelf filter feeders	0	0	0	0	0	0	0	0	0.0480	0.0162	0.1000	0	0	0.1684	0	0	0	0	0	0	0	0
52	Deep filter feeders	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
53	Shelf macrozoobenthos	0	0	0	0	0.0500	0	0	0	0.1000	0.0836	0.6500	0.2393	0	0.1347	0	0	0	0	0	0	0	0
54	Squid & cuttlefish shelf	0	0	0	0	0	0	0	0	0	0.0030	0.0500	0	0	0	0	0	0	0	0	0	0	0
55	Octopus shelf	0	0	0	0	0	0	0	0	0	0.0042	0	0	0	0	0	0	0	0	0	0	0	0
56	Rock lobster	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
57	Western king prawn	0	0	0	0	0	0	0	0	0	0.0155	0	0	0	0	0	0	0	0	0	0	0	0
58	Crabs & bugs	0	0	0	0	0	0	0	0	0	0.0464	0	0	0	0	0	0	0	0	0	0	0	0
59	Deep macrozoobenthos	0.1500	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1000	0.1900	0	0	0	0	0	0
60	Deep squid	0.2000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
61	Gelatinous zooplankton	0.5800	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
62	Large zooplankton	0	0	0	0	0	0	0	0	0.1000	0.1234	0	0	0	0	0.1350	0	0.2570	0	0	0	0	0
63	Mesozooplankton	0	0	0	0	0	0	0	0	0.3270	0	0	0	0	0	0.2500	0	0.2570	0	0	0	0	0
64	Microzooplankton	0	0	0	0.2500	0	0	0	0	0	0	0	0	0	0	0	0	0	0.7890	0.2500	0	0	0
65	Nanozooplankton	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1000	0.1500	0	0
66	Pelagic bacteria	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1290	0	0.0500	0.1200	0.6000	0
67	Farmed finfish	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
68	Farmed oysters	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
69	Large phytoplankton	0	0	0	0	0	0	0	0	0.2500	0	0	0	0	0	0.4000	0	0.0700	0.1040	0.2750	0.0500	0	0
70	Small phytoplankton	0	0.0500	0	0	0	0	1.0000	1.0000	0	0	0	0	0	0	0	0	0.1200	0	0.1250	0.4800	0.4000	0
71	Microphytobenthos	0	0.0500	0	0.0025	0.0020	0.0020	0	0	0.0050	0	0	0	0.1000	0.0010	0	0	0	0	0	0	0	0
72	Seagrass	0	0.2000	0.2122	0	0	0	0	0	0	0	0	0	0	0.0286	0	0	0	0	0	0	0	0
73	Macroalgae	0	0.4200	0.7444	0	0	0	0	0	0	0	0	0.3742	0.5000	0.0903	0	0	0	0	0	0	0	0
74	Discards	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
75	Detritus	0	0.2000	0.0435	0.4975	0.3980	0.9980	0	0	0.1700	0	0	0	0.2000	0.3000	0.1000	0	0	0	0.2000	0.2000	0	1.0000
76	Import	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Sum	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

Appendix 7.1 cont.

No.	Prey \ predator	67	68	71
40	Migratory mesopelagics	0	0	0
41	Non-migrating mesopelagics	0	0	0
42	Slope small demersal invertivores	0	0	0
43	Slope small demersal piscivores	0	0	0
44	Slope large demersal piscivores	0	0	0
45	Slope large demersal invertivores	0	0	0
46	Benthic grazers	0	0	0
47	Abalone	0	0	0
48	Benthic detritivore	0	0	0
49	Benthic carnivores (infauna)	0	0	0
50	Meiobenthos	0	0	0
51	Shelf filter feeders	0	0	0
52	Deep filter feeders	0	0	0
53	Shelf macrozoobenthos	0	0	0
54	Squid & cuttlefish shelf	0	0	0
55	Octopus shelf	0	0	0
56	Rock lobster	0	0	0
57	Western king prawn	0	0	0
58	Crabs & bugs	0	0	0
59	Deep macrozoobenthos	0	0	0
60	Deep squid	0	0	0
61	Gelatinous zooplankton	0	0	0
62	Large zooplankton	0	0	0
63	Mesozooplankton	0	0	0
64	Microzooplankton	0	0	0
65	Nanozooplankton	0	0.1000	0
66	Pelagic bacteria	0	0	0
67	Farmed finfish	0	0	0
68	Farmed oysters	0	0	0
69	Large phytoplankton	0	0.4000	0
70	Small phytoplankton	0	0.5000	0
71	Microphytobenthos	0	0	0.1000
72	Seagrass	0	0	0
73	Macroalgae	0	0	0
74	Discards	0	0	0
75	Detritus	0	0	0.9000
76	Import	1.0000	0	0
	Sum	1.0000	1.0000	1.0000

7.2 Time series applied to the EwE GAB Ecosystem model

No	Name	Data Type	No	Name	Data Type
1	C Tuna	Effort by gear	45	B snapper	Relative biomass
2	C Demersal trawl	Effort by gear	46	Y Shelf pelagic sharks	Yield
3	C Small Pelagic	Effort by gear	47	Y Offshore pelagic sharks	Yield
4	C Gillnet	Effort by gear	48	Y Shelf demersal sharks	Yield
5	C Shark line	Effort by gear	49	Y Shelf demersal piscivorous shark	Yield
6	C Scalefish line	Effort by gear	50	Y Deep demersal sharks	Yield
7	C Danish Seine	Effort by gear	51	Y Skates and rays	Yield
8	C Squid	Effort by gear	52	Y SBT	Yield
9	V Lobster	Effort by gear	53	Y Tunas and billfish	Yield
10	V Scalefish line	Effort by gear	54	Y Offshore pelagic piscivores	Yield
11	V Scalefish net	Effort by gear	55	Y Offshore pelagic invertivores large	Yield
12	V Shark Line	Effort by gear	56	Y Shelf pelagic piscivores large	Yield
13	V pots	Effort by gear	57	Y Australian sardine	Yield
14	V Abalone	Effort by gear	58	Y Anchovy and other small pelagics	Yield
15	SA Sardine	Effort by gear	59	Y Mackerels	Yield
16	SA Lobster	Effort by gear	60	Y Redbait	Yield
17	SA Prawn	Effort by gear	61	Y Shelf small demersal piscivores	Yield
18	SA Pipi	Effort by gear	62	Y Shelf small demersal omnivores	Yield
19	SA Abalone	Effort by gear	63	Y Shelf large demersal piscivores	Yield
20	SA Haul net	Effort by gear	64	Y Shelf large demersal omnivores	Yield
21	SA crab	Effort by gear	65	Y King George whiting	Yield
22	SA Handline	Effort by gear	66	Y Garfish	Yield
23	SA Longline	Effort by gear	67	Y Snapper	Yield
24	SA Jig	Effort by gear	68	Y Deepwater flathead	Yield
25	SA Charter	Effort by gear	69	Y Bight redfish	Yield
26	SA pots	Effort by gear	70	Y Slope small demersal invertivores	Yield
27	SA Coorong	Effort by gear	71	Y Slope small demersal piscivores	Yield
28	WA Salmon	Effort by gear	72	Y Slope large demersal invertivores	Yield
29	WA Gillnet	Effort by gear	73	Y Slope large demersal piscivores	Yield
30	WA purse seine	Effort by gear	74	Y Benthic grazers	Yield
31	WA Abalone	Effort by gear	75	Y Abalone	Yield
32	WA rock lobster	Effort by gear	76	Y Benthic deposit feeders	Yield
33	WA line	Effort by gear	77	Y Carnivorous macro-infauna	Yield
34	SA rec Estimated	Effort by gear	78	Y Shelf filter feeders	Yield
35	B LN fur seal	Absolute biomass	79	Y Shelf macrozoobenthos	Yield
36	B Australian fur seal	Absolute biomass	80	Y Squid & cuttlefish shelf	Yield
37	B Australian sea lion	Absolute biomass	81	Y Octopus shelf	Yield
38	B Farmed finfish	Absolute biomass	82	Y Rock lobster	Yield
39	ASL catch in C Gillnet	Yield	83	Y Western king prawn	Yield
40	B Sardine spawning	Relative biomass	84	Y Crabs & bugs	Yield
41	B Deepwater flathead	Relative biomass	85	Y Deep macrozoobenthos	Yield
42	CPUE Redfish	Relative biomass	86	Y Deep squid	Yield
43	CPUE Western Deepwater sharks	Relative biomass	87	Farmed finfish	Yield
44	CPUE King George Whiting	Relative biomass			

C = Commonwealth; V; SA = South Australia; WA = Western Australia; B = Biomass; CPUE = catch per unit effort; ASL = Australian sea lion; LN = long nosed (fur seal); Y = yield; SBT = southern bluefin tuna.

8. ATLANTIS APPENDICES

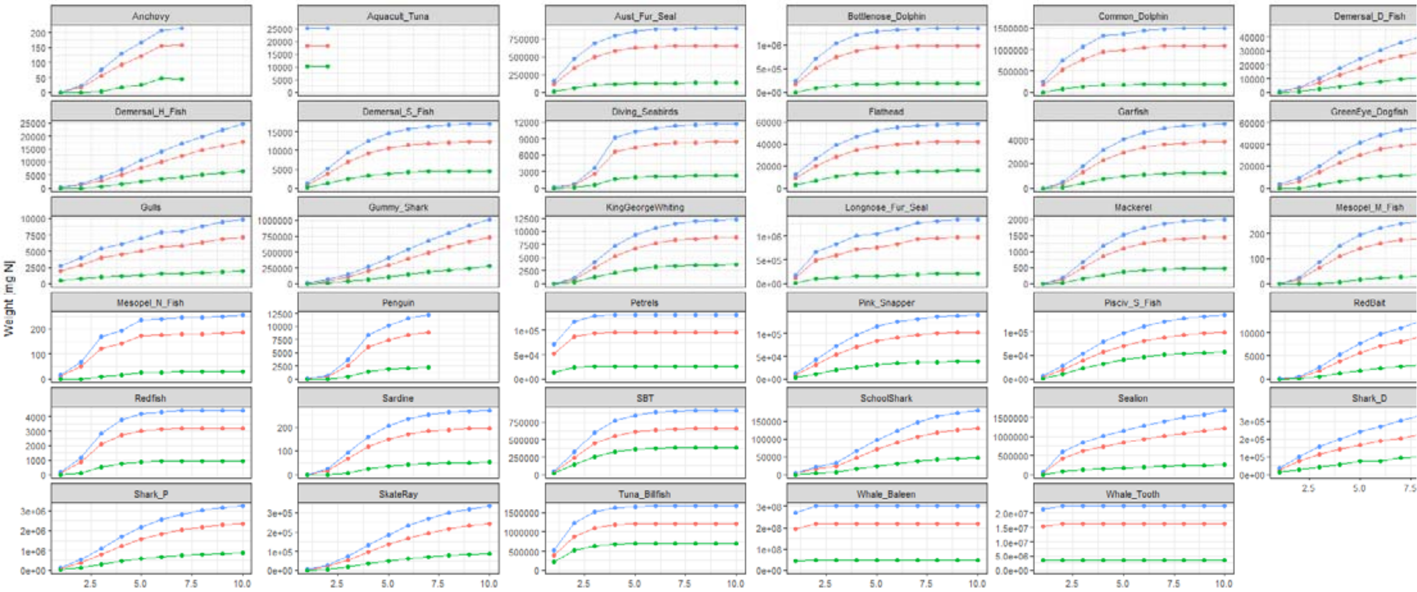
8.1 List and group compositions of functional groups in the GAB Atlantis model.

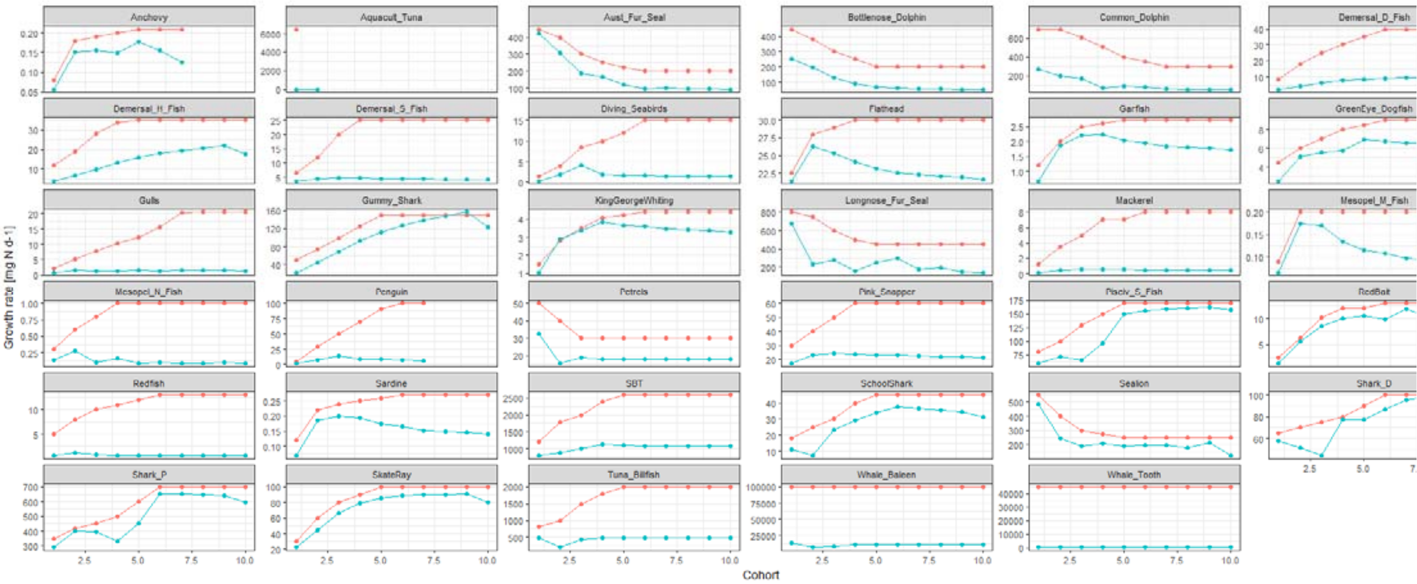
Group		Description
Pelagic invertebrates & flora		
Large phytoplankton	PL	Diatoms
Small phytoplankton	PS	Pico- and nano-phytoplankton
Microzooplankton	ZS	Heterotrophic flagellates
Mesozooplankton	ZM	Copepods, pteropods and ostracods (in water column)
Large zooplankton	ZL	Krill (Nyctiphanes), copepods and amphipods (in water column)
Gelatinous zooplankton	ZG	Jellies, salps and ctenophores
Detritus -DOM	DL	
Pelagic bacteria	PB	
Squid	CEP	Southern calamari, Australian giant cuttlefish
Benthic invertebrates & flora		
Kelp	MA	Macroalgae (kelp)
Seagrass	SG	Seagrass
Lobster	BRL	Rock lobster
Prawn	PWN	Western king prawn
Meiobenthos	BO	small benthic organisms that live in sediments <1mm e.g. foraminiferans, Nematoda, benthic ostracods, harpacticoid copepods
Benthic deposit feeders	BD	Infaunal detritivores: e.g. polychaetes , sipunculids, burrowing bivalves, percarid crustacea(isopods, amphipods, cumaceans, tanaids), holothurians (sea cucumbers), gastropods (sedentary)
Benthic carnivores	BC	Infaunal carnivores/scavengers: e.g. echinoderms (sea stars), gastropods, predatory polychaetes, slugs (fixed/sedentary)
Benthic grazers (herbivores)	BG	Echinoderms (sea-urchins), large gastropods, chitons
Urchins (Benthic grazer)	BGU	Sea urchins
Abalone (Benthic grazer)	BGA	Greenlip/blacklip abalone
Deep filter feeders	BFD	Sessile megafauna e.g. bivalves, sponges, hydroids, seapens, seafans and deep-sea corals, anemones, crinoids, bryozoan, brachiopods, ascidians (benthic tunicates)
Shallow filter feeders	BFS	Sessile megafauna e.g. bivalves (Scallops, cockles, mussels, oysters) sponges, bryozoans, barnacles, seapens, crinoids, brachiopods
Commercial crustacea	BMC	Blue, sand crabs, Balmain bug, other crabs, Giant crab
Macrozoobenthos	BMS	Large, active, primarily carnivorous megafauna e.g. Gastropods, decapod crustaceans (reptantia and natantia), stomatopods, cephalopods(Maori octopus, southern keeled octopus, southern sand octopus, and the southern hammer octopus)
Detritus POM	DR	Detritus in the sediments
Benthic bacteria	BB	
Aquaculture species		
Tuna	AQT	Farmed SBT & Yellowtail kingfish
Molluscs	AQM	Farmed oysters mussels
Fin-fish		
Sardines	FPS	Sardinops sagax
Anchovy	FPA	Engraulis australis and others sprats
Jack Mackerel	FPJ	Trachurus declivis Scomber australasicus
Southern Garfish	FSG	Garfish
Red bait	FPB	Emmelichthys nitidus

Group		Description
Shallow (shelf) piscivores	FVS	Pelagic(med/large):l Australian salmon, herring, barracouta, long-fin pike, Tommy rough, Tailor, Snook, Mackerel tuna, Teraglin, Dolphinfish, Mulloway, Yellowtail kingfish Demersal(med/small): stargazers, red cod, small tooth flounder, Perch, butterfly fish, boarfish, cobblerfish, red mullet and goatfishes, silverbelly, silver trevally, john dory, trumpeter, stargazers, john dory
SBT	FVB	Southern Bluefin tuna Thunnus maccoyii
Tuna and billfish	FVT	Frigate mackerel or tuna, skipjack tuna, Albacore tuna, Yellowfin tuna, Bonito, Bigeye, tuna, billfish, striped marlin, black marlin, blue marlin, swordfish
Myctophids	FMM	Various species of Myctophidae including: Hector's lanternfish *Lampanyctodes hectoris*, Blackring waryfish *Scopelosaurus meadi*, Dana lanternfish *Diaphus danae*, pennant pearlside *Maurolicus australis*
Non-migratory mesopelagics	FMN	Bathypelagic and non-migratory fishes including Silver lighthouse fish *Phosichthys argenteus*, big-scaled neoscopelid *Neosopelus macrolepidotus,* common black dragonfish *Idiacanthus fasciola*,
Deep demersal fish	FDD	Piscivores: Roughy (Southern Roughy), Sandpaper Fish, Zeidae, Cyttidae , gemfish, ling, Invertivores: Dories, pink ling, gemfish, blue grenadier, hapuku, cucumber fish, painted gurnard, long-finned gemfish, silverside, whiptails, Centroberyx, Beryx, cardinalfish, ribaldo, oreos
Shallow demersal fish	FDS	Omnivores (small):: Deep Velvet fish, Scarlet Cardinal fish, Smooth Cardinal fish, Southern Crested Weed Fish, Old Wife, Four-spine Leather Jacket, Smoothspine Leather Jacket, Pygmy Leatherjacket, Gulf Gurnard Perch, Little Gurnard Perch Rainbow Cale, Sculptured Seamoth, Common Bullseye, Slender Bullseye, Spotted Grubfish, Wavy Grubfish, Derwent Flounder, Spotted Flounder, Barber Perch, Many Banded Sole, Orange barred Puffer fish, Prickly Toadfish Smooth Toadfish, Soldier Fish, Latchet, Southern Shortfin Gurnard, Spiny Gurnard Southern School Whiting (silver whiting), Toothbrush Leatherjacket, Striped Perch, Ornate Cowfish, Shaws Cowfish, Rough bullseye, leatherjackets (Bridled, Mosaic, Velvet, Gunn's, Degens, Rough), Crested Flounder, Squareback Butterflyfish, Goblin Fish, Syngnathids ocean perch, latchet, Omnivores (med): Blue morwong, grey morwong, short boarfish, Small tooth flounder, nannygai, gurnard perch, rock ling, southern tongue sole, Spikey globefish, common stink fish, spotted stinkfish, beaked salmon, senator wrasse, fringed stargazer, southern gobbleguts, and Chinaman leather jacket, jackass morwong, black bream, Purple throated and Blue Wrasse
King George Whiting	FKG	Sillaginodes punctatus
Shallow demersal herbivores	FDH	(silver) Drummer, rock blackfish, luderick, dusky morwong, marblefish, fantail mullet, sea mullet, sand mullet, herring cale
Flatheads	FFH	Platycephalus conatus
Pink snapper	FSN	Chrysophrys auratus
Redfish	FRD	Centroberyx gerrardi
Sharks		
Demersal sharks	SHD	whiskery shark, broadnose shark, Port Jackson shark, carpet , wobbegong, saw shark, cat shark

Group		Description
Pelagic sharks	SHP	White, bronze & dusky whaler sharks, smooth hammerhead shark, Shortfin mako, blue shark
Green-eye dogfish	SDG	Deepwater Dogfish, gulper sharks
Gummy shark	SHG	Mustelus antarcticus
School shark	SHS	Galeorhinus galeus
Skates and rays	SSK	Various species including:
Top predators		
Gulls	SBG	Seagulls
Petrels	SBA	Shearwaters, albatross, petrels
Diving seabirds	SBD	Australian gannet, terns
Little Penguin	SBP	Eudyptula minor
Australian fur seal	SFA	Arctocephalus pusillus doriferus
Long-nosed fur seal	SFL	Arctocephalus forsteri
Australian sea lion	SL	Neophoca cinerea
Baleen whales	WHB	Pygmy blue, humpback, SRW
Toothed whales	WHT	Sperm, beaked, pilot, killer
Bottle nosed Dolphins	DOB	Tursiops truncatus
Common dolphin	DOC	Delphinus delphis

8.2 Initial weight (ug N) and growth rates for vertebrate functional groups in the GAB Atlantis model





8.3 Trophic links for the groups in the GAB-Atlantis model.

Table 8.3.1 Trophic links for the primary producers included in the GAB-Atlantis model

	Macro-algae	Sea-grass	Diatom	Pico-phytoplankton	Pelagic Bacteria	Sediment Bacteria	Labile Detritus	Refractory Detritus	Carrion
Aquaculture Mollusc	0	0	0.254	0.085	0.00023	0.00023	0.00004	3E-06	0.00003
Mackerel	0	0	0.3	0.02	0	0	1E-06	1E-08	0
Sardine	0	0	0.19	0	0	0	0.05	0.0007	0
Anchovy	0	0	0.3	0.3	0	0	0	0	0
Redbait	0	0	0.18	0	0	0	0	0	0
Flatheads	0	0	0	0	0	0	0.0005	0.00005	0
Myctophids	0	0	0.01	0	0	0	0	0	0
Deep Dem fish	0.4	0	0	0	0	0	0	0	0
Dem Herbie fish	0.45	0.1	0	0	0	0	0	0.0005	0
Garfish	0.4	0.5	0.3	0.02	0	0	0	0	0
Redfish	0	0	0	0	0	0	0.0001	0	0.005
Pink snapper	0	0	0.03	0.005	0	0	0	0	0
School shark	0	0	0	0	0	0	0.00001	0	0.00001
Gulls	0.3	0	0	0	0	0	0.1	0.001	0.1
Petrels	0	0	0	0	0	0	0	0	0.2
Terns	0	0	0	0	0	0	0	0	0.1
Sea lion	0	0	0	0	0	0	0	0	0.3
Baleen whales	0	0	0.00001	0.0001	1E-06	0	0	0	0
Abalone	0.4	0.016	0	0	0	0	0	0	0
Urchins	0.42	0.6	0	0	0	0	0.08	0.0001	0
Shallow filter feed	0	0	0.2	0.085	0.00023	0.00023	0.04	0.0003	0.003
Deep filter feeder	0	0	0.08	0.085	0.00023	0.00023	0.04	0.0003	0.003
Benthic grazers	0.15	0.09	0	0	0	0	0	0	0
Commercial crust	0.00005	0.001	0.00001	0.00001	0.0001	0	0.00005	0.00003	0.005
Prawns	0.05	0.005	0	0	0	0	0.00005	0.00003	0.005
Deposit feeders	0	0	0	0	0	1E-09	0.0001	0.0001	1E-06
Benthic Carnivores	0	0	0	0	0	1E-09	0.0001	0.0001	1E-06
Gelatinous zooplankton	0	0	0.1568	0.3	4E-06	0	0	1E-06	5E-08
Large zooplankton	0	0	0.79	0	0	0	0	0	0
Mesozooplankton	0	0	0.25	0.015	0	0	0	0	0
Microzooplankton	0	0	0.007	0.015	0.0001	0	0.001	5E-06	0
Meiobenthos	0	0	0	0	0	0	0.0002	3E-06	0

A grey box indicates a potential trophic link between predator (rows) and prey (columns) with darker grey indicative of a greater linkage.

Table 8.3.2 Trophic links for the secondary trophic order invertebrates in the GAB-Atlantis model. A grey box indicates a potential trophic link between predator (rows) and prey (columns).

	Rock lobster	Abalone	Urchins	Squid	Shallow filter feeders	Deep filter feeders	Benthic Grazers	Shallow Macrobenthos	Comm crust	Prawns	Deposit feeders	Benthic Carnivore	Gelatinous zooplankton	Large zooplankton	Meso-zooplankton	Micro-zooplankton	Meio-benthos
Aquacult Mollusc	0	0	0	0	0	0	0	0	0	0	0	0	0.00378	0	0.00014	1E-06	0
KG Whiting	0	0	0.0001	0	0.0001	0.0001	0.0001	0.005	0	0.0001	0.3	0.01	0.0005	0.0005	0.005	0	0.4
Mackerel	0	0	0	0.05	0	0	0	0	0	0.005	0.005	0	0.04	0.8	0.1	0.005	0
Sardine	0	0	0	0	0	0	0	0	0	0	0	0	0.035	0.1	0.1275	0.01	0
Anchovy	0	0	0	0	0	0	0	0	0	0	0	0	0.1	0.75	0.4	0.05	0
Redbait	0	0	0	0.002	0.2	0.2	0.05	0.0294	0.16	0.0009	0	0.042	0.003	0.7	0.3	0.09	0
Shallow piscivore	0	0	0	0.99	0	0	0	0	0	0.009	0	0	0.0056	0.17	0	0	0
SBT	0	0	0	0.99	0	0	0	0	0	0.02	0	0	0.0056	0	0	0	0
Tuna & billfish	0	0	0	0.99	0	0	0	0	0	0.02	0	0	0.0056	0	0	0	0
Flatheads	0	0.00051	0.0015	0.84	0.3	0.25	0.25	0.003	0.25	0.00079	0.0004	0.0672	0.07	0.08	0.04	0	0.00085
Myctophids	0	0	0	0	0	0	0	0	0	2.3E-05	0	0	0.2	0.4	0.4	0.1	0
Non-migratory mesopelagics	0	0	0	0.72	0	0	0	0	0	0.0225	0	0	0.0056	0.04	0.00036	0	0
Deep demersals	0.00346	0.00051	0	0.99	0	0.28	0	0.08748	0	0.00113	0.00778	0.476	0.0112	0.45	0.0036	0	0
Herbivorous fish	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Shallow demersals	0.00346	0.00051	0.00252	0	0	0	0	0.13997	0	0	0	0.476	0	0	0	0	0.0085
Garfish	0	0	0	0	0	0	0	0	0	0	0	0.05	0.005	0.01	0.01	0.01	0.05
Redfish	0	0	0	0.002	0	0	0	0.2	0.2	0.05	0.15	0.05	0.01	0.4	0.5	0.01	0
Pink Snapper	0	0.005	0	0.002	0.002	0.05	0.08	0.2	0.005	0.03	0.1	0.4	0.05	0.2	0.0135	0.0001	0.0008
Dogfish	0.01728	2.5E-05	0	0.99	0	0.45	0	0.85	0	0.00788	0.00518	0.476	0.00252	0	0	0	0
Dem sharks	0.03456	0.00017	0.0015	0.00874	0.005	0.16	0.005	0.05832	0.0001	0.00011	0.02592	0.476	0	0	0	0	0
Pelagic sharks	0	0	0	0.4374	0	0	0	0	0	0	0	0	0	0	0	0	0
Gummy sharks	**0**	0	0	0.3	0	0	0.0045	0.45	0.041	0.009	0.0015	0.0036	0	0	0	0	0
School sharks	0.08	0.05	0.065	0.3	0.03	0.099	0.045	0.494	0.041	0.009	0.0015	0.0042	0	0	0	0	0
Skates & rays	0.3456	0.00505	0.009	0	0	0.16	0	0.027	0	1.9E-05	0.02592	0.476	0	0	0	0	0.0085
Gulls	0	0.01	0.03	0.02	0.99	0.15	0.01	0.01	0.135	0.01	0.1	0.07	0.007	0	0	0	1E-07
Petrels	0	0	0	0.2	0	0	0	0	0	0.0001	0	0	0	0	0	0	0
Penguins	0	0	0	0.2	0	0	0	0	0	0.0001	0	0	0	0.3	0	0	0
Terns	0	0.001	0.0003	0.2	0.15	0.006	0.00001	0.0001	0.0195	0.0001	0.0001	0.00007	0.007	0.0001	1E-06	0	0
Aust. fur seal	0.1728	0.00051	0	0.99	0	0	0	0.00324	0	0.00023	0	0	0	0	0	0	0
Longnose fur seal	0.00173	5.1E-05	0	0.99	0	0	0	3.2E-05	0	2.3E-06	0	0	0	0	0	0	0
Sea lion	0.99	0.55	0.12	0.02	0.4	0	0.4	0.3	0.3	0	0	0	0	0	0	0	0
Baleen whales	0	0	0	0.05	0	0	0	0.00001	0	0.0001	0	0	0.0889	0.6	0.075	0.0001	0
Bottlenose dolphin	0.99	0.00025	0	0.6	0	0	0	0	0	0.00056	0	0	0	0	0	0	0
Common dolphin	0	0	0	0.99	0	0	0	0	0	0	0	0	0	0	0	0	0
Orca	0	0	0	0.6	0	0	0	0	0	0	0	0	0	0	0	0	0
Rock lobster	0	0.00253	0	0	0.3	0.35	0	0.324	0	0	0.016	0.476	0	0	0	0	0.0085
Squid	3.5E-05	0	0	0.22	0	0	0	0.10216	0.00002	2.3E-05	0	0	0.0002	0.0002	0.0002	0	0
Shallow filter feed	0	0	0	0	0	0	0	0	0	0	0	0	0.00378	0.00002	0.0003	3E-06	0

	Rock lobster	Abalone	Urchins	Squid	Shallow filter feeders	Deep filter feeders	Benthic Grazers	Shallow Macrobenthos	Comm crust	Prawns	Deposit feeders	Benthic Carnivore	Gelatinous zooplankton	Large zooplankton	Meso-zooplankton	Micro-zooplankton	Meio-benthos
Deep filter feeders	0	0	0	0	0	0	0	0	0	0	0	0	0.00013	0.00002	2.3E-05	5E-07	0
Shallow macrobenthos	0	0	0	0	0.001	0	0	0	0	0	0	0	0	0	0	0	0
Comm. crustacea	0	0.00001	0	0	0.002	0.01	0	0.05	0	0.0015	0.006	0.01	0.0005	0.001	0.0005	0.005	0.005
Prawns	0	0	0	0	0.05	0.05	0	0	0	3.8E-07	0.25	0.17	4.2E-05	0.00001	0	0	0.15
Deposit feeders	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.03
Benthic carnivore	0	0	0	0	0	0	0	0	0	0	0.0009	0	0	0	0	0	0.03
Gelat. zooplankton	0	0	0	0	0.00001	0	0	0	0	0	0.00001	0	0	0.05216	0.032	0.0225	0
Large zooplankton	0	0	0	0	0	0	0	0	0	0	0	0	0.0005	0.012	0.00045	0.0005	0
Meso-zooplankton	0	0	0	0	0	0	0	0	0	0	0	0	0.0003	0.00006	4.5E-05	0.00018	0
Microzooplankton	0	0	0	0	0	0	0	0	0	0	0	0	2.1E-05	0	0	1.5E-05	0

Appendix Table 8.3.3 Trophic links in the GAB Atlantis model. A grey box indicates a potential trophic link between predator (rows) and prey (columns).

	Aquacult Tuna	Aquacult Mollusc	King George Whiting	Mackerel	Anchovy	Sardine	Redbait	Shallow piscivore	Tuna & billfish	SBT	Flatheads	Myctophids	Non-mig mesopelagic	Deep Dem	Herbivorous fish
Mackerel	0	0	0	5E-06	0.0001	0.0002	0.00023	0.00001	0	0	0	0.03	0.03	0	0
Sardine	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Anchovy	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Redbait	0	0	0	0	0	0	0	0	0	0	0	0.00252	0.0105	0	0
Shallow piscivore	0	0	0.2	0.00188	0.00038	0.018	0.00675	0.00113	0	0	0	0.096	0.012	0	0.0015
SBT	0	0	0.023	0.3	0.1	0.7	0.3	0.1	0.012	0	0.1	0.1	0.1	0.01	0
Tuna & billfish	0	0	0.023	0.3	0.1	0.7	0.3	0.1	0.012	0	0.1	0.1	0.1	0.01	0
Flatheads	0	0	1E-06	0.005	0.0005	0.005	0.0675	0	0	0	0	0.00252	0.0273	0.02	0.00075
Myctophids	0	0	0	0	1E-07	0.00001	0	0	0	0	0	0	0	0	0
Non-mig mesopelagic	0	0	0	0	0.00038	0.05	0	0	0	0	0	0.048	0.0006	0	0
Deep demersals	0	0	1E-07	0.0005	0.0001	0.002	0	0	0	0	0.00062	0.036	0.003	2E-07	0
Redfish	0	0	0.005	0.005	0.005	0.005	0.005	0.05	0	0	0.1	0.003	0.05	0.1	0.05
Pink snapper	0	0	0	0	0.00001	0.0002	0	0	0	0	0	0	0	0	4.5E-06
Dogfish	0	0	0	0.05	0	0	0	0.00057	0	0	0	0.1188	0.02	0.00022	0
Demersal sharks	0	0	0	0.05	0.0002	0.0002	2.7E-05	5.7E-05	0	0	0.00062	0	0	2.2E-05	7.5E-05
Pelagic sharks	0	0	0.0004	3.8E-07	0	0	4.5E-05	6.9E-06	0.004	0.02	6.22E-07	0.012	0.00002	2E-07	4.5E-06
Gummy sharks	0	0	0	0.005	0	0	0	0.2	0	0	0	0.00252	0.00525	0.1	0.11
School sharks	0	0	0	0.005	0	0	0	0.02	0	0	0.002	0.00252	0.00525	0.1	0.08
Skates & rays	0	0	0	0	0	0	0	0	0	0	0.00062	0	0	2.2E-06	0
Gulls	0	0.01	0.25	0.0005	0.01	0.06	0.015	0.1	0.02	0.1	0.003	0.01	0.001	0.01	0.005
Petrels	0	0.01	0.25	0.005	0.001	0.35	0.225	0.1	0	0	3E-07	0.01	0.001	1E-06	5E-07
Penguins	0	0	0.25	0.015	0.3	0.3	0.45	0.3	0	0	3E-07	0.01	0.001	1E-06	5E-07
Terns	0	0.01	0.2	0.005	0.1	0.1	0.15	0.1	0	0	0.003	0.01	0.001	0.01	0.005
Aust fur seal	0	0	0.0001	0.005	0.001	0.1	0.105	0.00057	1.2E-05	0.00059	6.2E-05	3E-07	6E-08	1E-06	2.3E-05
Longnose fur seal	0	0	0.02	0.005	0.001	0.1	0.105	0.05	0.1188	0.1594	0.00622	0.3	0.016	0.1	0.0225
Sea lions	0.00001	0	0.03	0.02	0.004	0.25	0.045	0.15	0.2	0.3	0.045	0.1	0.0001	0.1	0.1
Baleen whales	0	0	0	0.005	0.001	0.005	0	0	0	0	0	0.02	0.02	0	0
Bottlenose dolphin	0	0	0.25	0.00038	0.0005	0.005	0.00061	0.00057	0.0024	0.012	0.00036	0.036	0.002	2E-06	2.3E-05
Common dolphin	0	0	0.3	0.005	0.06	0.15	0.15	0.28	0.16	0.28	0.024	0.3	0.03	0	0
Orca	0	0	0.01	0.02	0.02	0.02	0.01	0.1	0.03	0.15	0.00031	0.001	0.001	0.00022	0.0001
Squid	0	0	3E-06	3E-06	3E-06	3E-06	3E-06	0	0	0	0.00062	3.6E-05	3.6E-06	0	0
Comm crustacea	0	0.0008	0.001	0.001	0.0005	0.0005	0	0	0	0	0	0	0	0	0

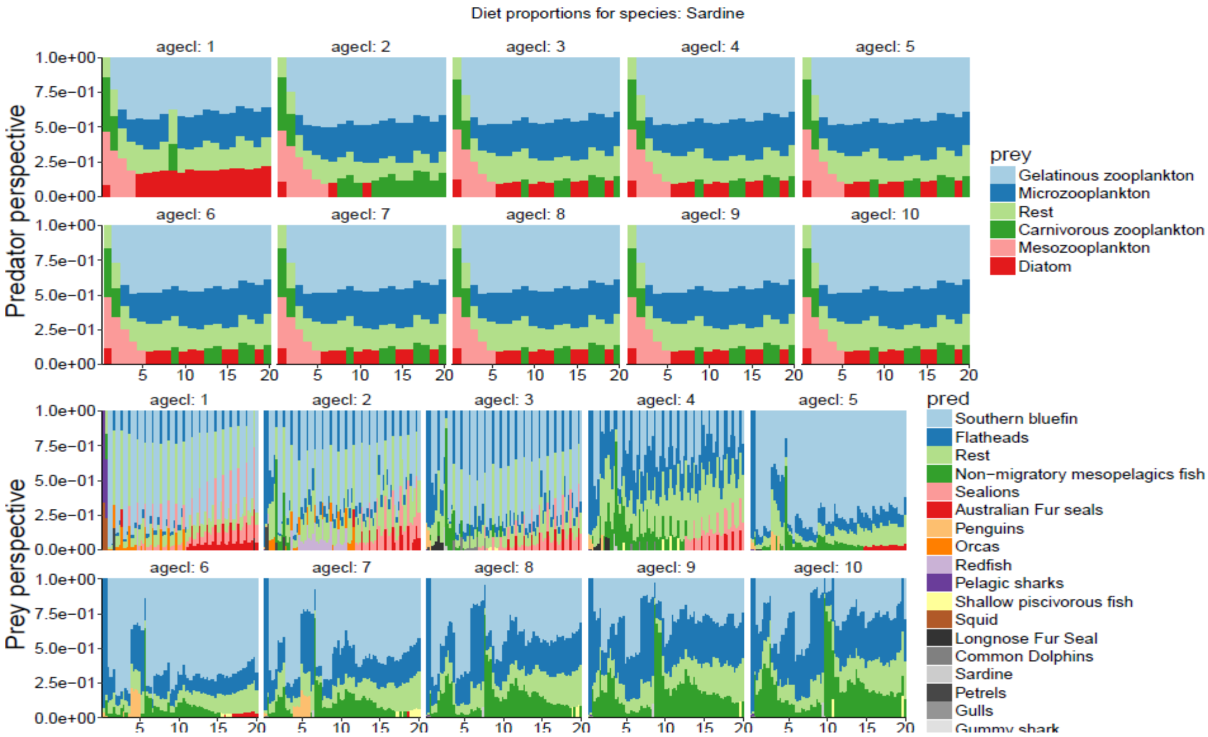
	Shallow demersal	Garfish	Redfish	Pink Snapper
Mackerel	2E-06	0.001	0	0.00001
Sardine	0	0	0	0
Anchovy	0	0	0	0
Redbait	0	0	0	0
Shallow piscivore	7.5E-05	0.00938	0.00019	0.15
SBT	0.003	0	0.05	0
Tuna & billfish	0.003	0	0.05	0
Flatheads	0.009	1E-06	0.01	0.3
Myctophids	0	0	0	0
Non-mig mesopelagic	0	0	0	0
Deep demersals	0	0	1E-08	0
Redfish	0.002	0.05	0	0.05
Pink snapper	1.1E-06	1.41E-05	2.81E-06	0
Dogfish	7.5E-06	9.4E-05	3E-05	0
Demersal sharks	7.5E-07	0	2E-06	0
Pelagic sharks	1.13E-07	0.005	2.91E-07	0
Gummy sharks	0.09	0	0	0
School sharks	0.009	0	0	0
Skates & rays	7.5E-06	0	1.9E-05	0
Gulls	0.0002	0.15	0.001	0.1
Petrels	2E-08	0.1	1E-07	0.1
Penguins	2E-08	0.1	1E-07	0.01
Terns	0.0002	0.1	0.001	0.2
Aust fur seal	0.00375	4.7E-05	9.88E-07	0.015
Longnose fur seal	3.8E-05	0.02	0.00988	0.15
Sea lions	0.004	0.1	0.02	0.35
Baleen whales	0	0	0	0
Bottlenose dolphin	3.8E-06	0.01005	9.5E-06	0.005
Common dolphin	0	0	0	0
Orca	7.5E-06	9.4E-05	3E-05	0.0001
Squid	7.5E-08	0.00151	1.00E-05	0
Comm crustacea	0	0	0	0

Appendix Table 8.3.4 Trophic links for the top predator vertebrate groups in the GAB-Atlantis model. A grey box indicates a potential trophic link between predator (rows) and prey (columns).

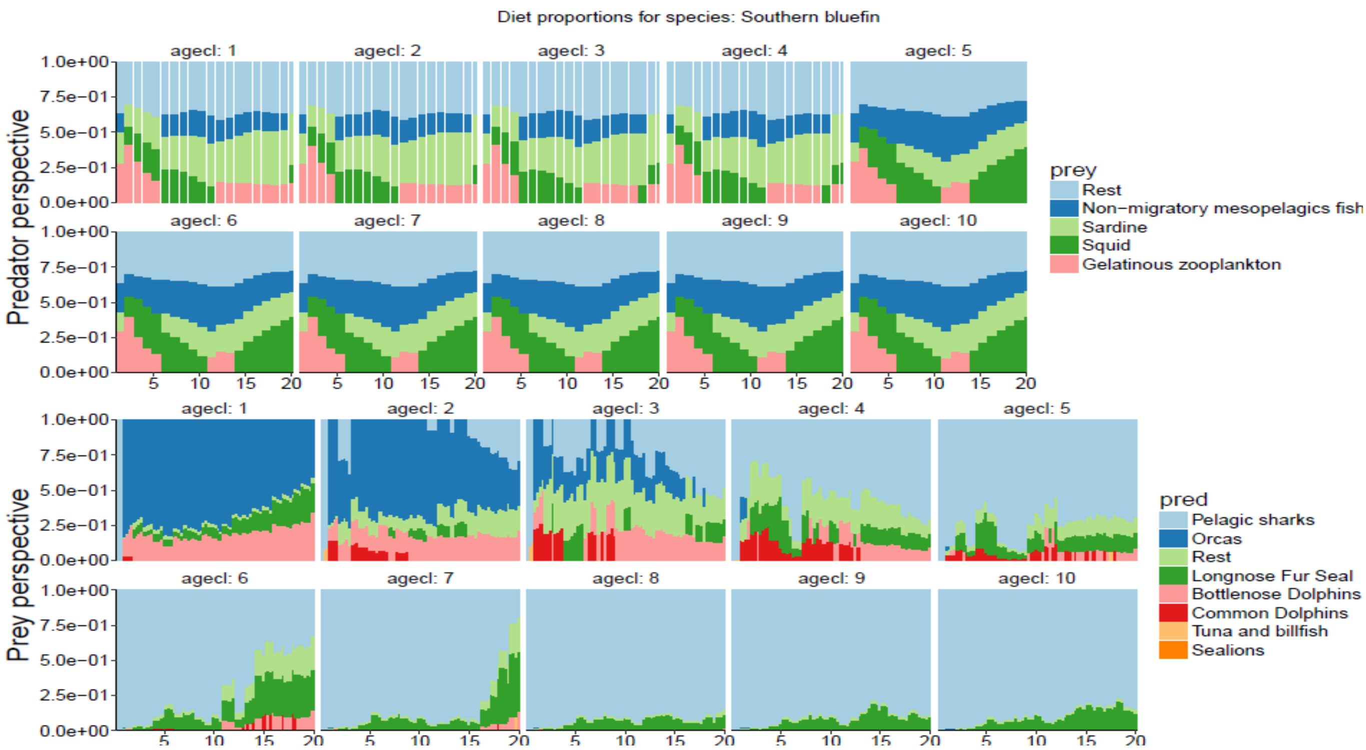
	Dogfish	Demersal sharks	Pelagic sharks	School sharks	Gummy sharks	Skate & Rays	Gulls	Petrels	Penguins	Terns	Aust Fur seal	Longnose Fur seal	Sea lions	Baleen whales	Bottle-nose dolphin	Common dolphin	Orca
Flatheads	0	0	0	0	0	0	0	0	0	5.1E-05	0	0	0	0	0	0	0
Deep demersal	0	0	0	0	0	0	0	0	0	5.1E-05	0	0	0	0	0	0	0
Shallow demersal	0	0	0	0	0	0	0	0.00126	0	5.1E-05	0	0	0	0	0	0	0
Dogfish	0.09356	0	0	0	0	0.0425	0	0	0	2.5E-06	0	0	0	0	0	0	0
Dem sharks	0.0066	0.0001	0	0	0	0.00076	0	5E-06	0	1E-06	0	0	0	0	0	0	0
Pelage sharks	0.00248	0.0024	0.32	0.012	0.0018	0.0324	0.00113	0	0.024	0	0.032	0.016	0.0032	0.02	0.006	0.0036	0.012
Skates & rays	0	0	0	0	0	0.08	0	0.0015	0	0.00051	0	0	0	0	0	0	0
Aust fur seal	0	0	0	0	0	0.00032	0.00084	0	2E-06	0.00051	0	0	0	0	0	0	0
Longnose fur seal	0.00165	0.0008	0.001	0.001	0.0015	0.0324	0.00084	0	2E-06	5.05E-07	0	0	0	0	0	0	0
Sea lion	0	0	0	0	0	0	0.01	0.015	0.02	0.01	0	0	0	0	0	0	0
Bottlenose dolphin	0	0	0	0	0	0.00972	0.0003	0	0	2.5E-05	0	0	0	0	0	0	0
Orca	0.00234	0.012	0.65	0.06	0.09	0.0001	0.00011	0	0.032	0.0001	0.016	0.008	0.0016	0.0001	0.0001	0.0001	0
Comm Crust.	0	0	0	0	0	0	0	0	0	1E-06	0	0	0	0	0	0	0

8.4 Predicted prey-predator relationships for (A) Australian sardine and (B) Southern bluefin tuna over the entire GAB model domain for the Status Quo scenario.

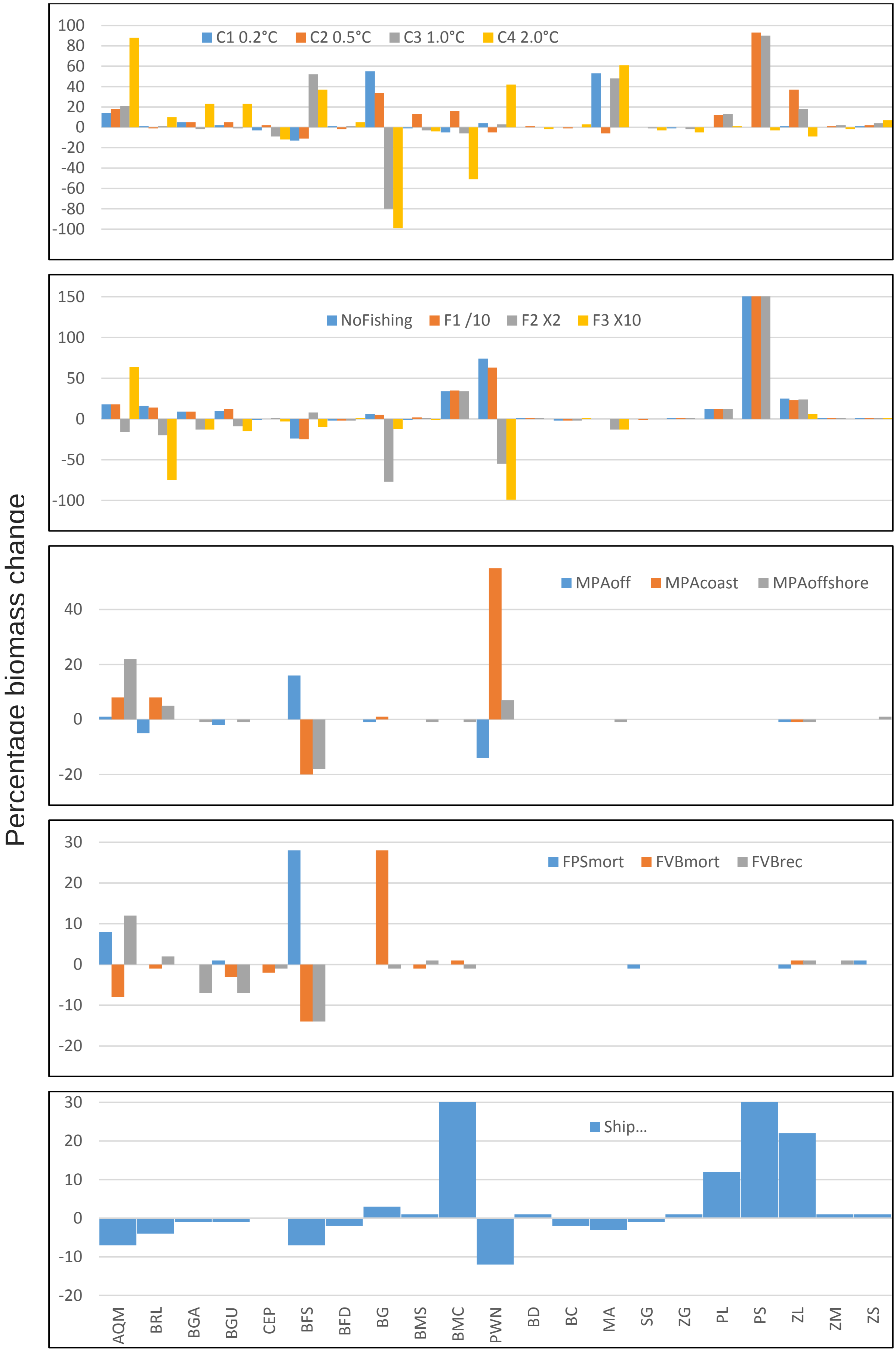
A)



B)



8.5 Relative changes in biomass of functional groups for Atlantis scenarios


Percentage biomass change
C1 0.2°C
C2 0.5°C
C3 1.0°C
C4 2.0°C
NoFishing
F1 /10
F2 X2
F3 X10
MPAoff
MPAcoast
MPAoffshore
FPSmort
FVBmort
FVBrec
Ship...
100
80
60
40
20
0
-20
-40
-60
-80
-100
150
50
-50
30
10
-10
AQM
BRL
BGA
BGU
CEP
BFS
BFD
BG
BMS
BMC
PWN
BD
BC
MA
SG
ZG
PL
PS
ZL
ZM
ZS

bp

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