NORTH WEST SHELF
JOINT ENVIRONMENTAL
MANAGEMENT STUDY

Trophic webs and modelling of Australia's North West Shelf

TECHNICAL REPORT No. 9

• C. Bulman

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Final report

North West Shelf Joint Environmental Management Study Final Report.

List of technical reports

NWSJEMS Technical Report No. 1
Review of research and data relevant to marine environmental management of Australia’s North West Shelf.
A. Heyward, A. Revill and C. Sherwood

NWSJEMS Technical Report No. 2
Bibliography of research and data relevant to marine environmental management of Australia’s North West Shelf.
P. Jernakoff, L. Scott, A. Heyward, A. Revill and C. Sherwood

NWSJEMS Technical Report No. 3
Summary of international conventions, Commonwealth and State legislation and other instruments affecting marine resource allocation, use, conservation and environmental protection on the North West Shelf of Australia.
D. Gordon

NWSJEMS Technical Report No. 4
Information access and inquiry.
P. Brodie and M. Fuller

NWSJEMS Technical Report No. 5
Data warehouse and metadata holdings relevant to Australia’s North West Shelf.
P. Brodie, M. Fuller, T. Rees and L. Wilkes

NWSJEMS Technical Report No. 6
Modelling circulation and connectivity on Australia’s North West Shelf.
S. Condie, J. Andrewartha, J. Mansbridge and J. Waring

NWSJEMS Technical Report No. 7
Modelling suspended sediment transport on Australia’s North West Shelf.
N. Margvelashvili, J. Andrewartha, S. Condie, M. Herzfeld, J. Parslow, P. Sakov and J. Waring

NWSJEMS Technical Report No. 8
Biogeochemical modelling on Australia’s North West Shelf.
M. Herzfeld, J. Parslow, P. Sakov and J. Andrewartha

NWSJEMS Technical Report No. 9
Trophic webs and modelling of Australia’s North West Shelf.
C. Bulman

NWSJEMS Technical Report No. 10
The spatial distribution of commercial fishery production on Australia’s North West Shelf.
F. Althaus, K. Woolley, X. He, P. Stephenson and R. Little

NWSJEMS Technical Report No. 11
Benthic habitat dynamics and models on Australia's North West Shelf.
E. Fulton, B. Hatfield, F. Althaus and K. Sainsbury

NWSJEMS Technical Report No. 12
Ecosystem characterisation of Australia's North West Shelf.
V. Lyne, M. Fuller, P. Last, A. Butler, M. Martin and R. Scott

NWSJEMS Technical Report No. 13
Contaminants on Australia's North West Shelf: sources, impacts, pathways and effects.
C. Fandry, A. Revill, K. Wenziker, K. McAlpine, S. Apte, R. Masini and K. Hillman

NWSJEMS Technical Report No. 14
Management strategy evaluation results and discussion for Australia's North West Shelf.
R. Little, E. Fulton, R. Gray, D. Hayes, V. Lyne, R. Scott, K. Sainsbury and D. McDonald

NWSJEMS Technical Report No. 15
Management strategy evaluation specification for Australia's North West Shelf.
E. Fulton, K. Sainsbury, D. Hayes, V. Lyne, R. Little, M. Fuller, S. Condie, R. Gray, R. Scott,
H. Webb, B. Hatfield, M. Martin, and D. McDonald

NWSJEMS Technical Report No. 16
Ecosystem model specification within an agent based framework.
R. Gray, E. Fulton, R. Little and R. Scott

NWSJEMS Technical Report No. 17
Management strategy evaluations for multiple use management of Australia's North West Shelf
– Visualisation software and user guide.
B. Hatfield, L. Thomas and R. Scott

NWSJEMS Technical Report No. 18
Background quality for coastal marine waters of the North West Shelf, Western Australia.
K. Wenziker, K. McAlpine, S. Apte, R.Masini

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ACRONYMS

ACRONYMS

ACOM	Australian Community Ocean Model
AFMA	Australian Fisheries Management Authority
AFZ	Australian Fishing Zone
AGSO	Australian Geological Survey Organisation now Geoscience Australia
AHC	Australian Heritage Commission
AIMS	Australian Institute of Marine Science
AMSA	Australian Maritime Safety Authority
ANCA	Australian Nature Conservation Agency
ANZECC	Australian and New Zealand Environment and Conservation Council
ANZLIC	Australian and New Zealand Land Information Council
APPEA	Australian Petroleum, Production and Exploration Association
AQIA	Australian Quarantine Inspection Service
ARMCANZ	Agricultural Resources Management council of Australia and New Zealand
ASIC	Australian Seafood Industry Council
ASDD	Australian Spatial Data Directory
CAAB	Codes for Australian Aquatic Biota
CAES	Catch and Effort Statistics
CALM	Department of Conservation and Land Management (WA Government)
CAMBA	China Australia Migratory Birds Agreement
CDF	Common data format
CITIES	Convention on International Trade in Endangered Species
CTD	conductivity-temperature-depth
CMAR	CSIRO Marine and Atmospheric Research
CMR	CSIRO Marine Research
COAG	Council of Australian Governments
ConnIe	Connectivity Interface
CPUE	Catch per unit effort
CSIRO	Commonwealth Science and Industrial Research Organisation
DCA	detrended correspondence analysis
DIC	Dissolved inorganic carbon
DISR	Department of Industry, Science and Resources (Commonwealth)
DEP	Department of Environmental Protection (WA Government)
DOM	Dissolved organic matter
DPIE	Department of Primary Industries and Energy
DRD	Department of Resources Development (WA Government)
EA	Environment Australia
EEZ	Exclusive Economic Zone
EIA	Environmental Impact Assessment
EPA	Environmental Protection Agency
EPP	Environmental Protection Policy
ENSO	El Nino Southern Oscillation
EQC	Environmental Quality Criteria (Western Australia)
EQO	Environmental Quality Objective (Western Australia)
ESD	Ecologically Sustainable Development
FRDC	Fisheries Research and Development Corporation
FRMA	Fish Resources Management Act
GA	Geoscience Australia formerly AGSO
GESAMP	Joint Group of Experts on Scientific Aspects of Environmental Protection
GIS	Geographic Information System
ICESD	Intergovernmental Committee on Ecologically Sustainable Development
ICS	International Chamber of Shipping
IOC	International Oceanographic Commission
IGAE	Intergovernmental Agreement on the Environment
ICOMOS	International Council for Monuments and Sites

IMO	International Maritime Organisation
IPCC	Intergovernmental Panel on Climate Change
IUNC	International Union for Conservation of Nature and Natural Resources
IWC	International Whaling Commission
JAMBA	Japan Australian Migratory Birds Agreement
LNG	Liquified natural gas
MarLIN	Marine Laboratories Information Network
MARPOL	International Convention for the Prevention of Pollution from Ships
MECO	Model of Estuaries and Coastal Oceans
MOU	Memorandum of Understanding
MPAs	Marine Protected Areas
MEMS	Marine Environmental Management Study
MSE	Management Strategy Evaluation
NCEP - NCAR	National Centre for Environmental Prediction – National Centre for Atmospheric Research
NEPC	National Environmental Protection Council
NEPM	National Environment Protection Measures
NGOs	Non government organisations
NRSMPA	National Representative System of Marine Protected Areas
NWQMS	National Water Quality Management Strategy
NWS	North West Shelf
NWSJEMS	North West Shelf Joint Environmental Management Study
NWSMEMS	North West Shelf Marine Environmental Management Study
ICIMF	Oil Company International Marine Forum
OCS	Offshore Constitutional Settlement
PFW	Produced formation water
P(SL)A	Petroleum (Submerged Lands) Act
PSU	Practical salinity units
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SOI	Southern Oscillation Index
SMCWS	Southern Metropolitan Coastal Waters Study (Western Australia)
TBT	Tributyl Tin
UNCED	United Nations Conference on Environment and Development
UNCLOS	United Nations Convention of the Law of the Sea
UNEP	United Nations Environment Program
UNESCO	United Nations Environment, Social and Cultural Organisation
UNFCCC	United Nations Framework Convention on Climate Change
WADEP	Western Australian Department of Environmental Protection
WADME	Western Australian Department of Minerals and Energy
WAEPA	Western Australian Environmental Protection Authority
WALIS	Western Australian Land Information System
WAPC	Western Australian Planning Commission
WHC	World Heritage Commission
WOD	World Ocean Database
www	world wide web

1. PROJECT OBJECTIVES

1.1 Objectives of Project 2

The high-level objective of Project 2 was to develop a range of interlinked models of the North West Shelf ecosystem which provide:

- An understanding of the links between the physical, chemical and biological environments, particularly with respect to primary producers, key species and habitat types;
- Predictions of the ecosystem response to natural forcing, including seasonal and interannual variability;
- Predictions of the effects of selected human uses on conservation and other values of the ecosystem, suitable for use in management strategy evaluation and risk assessment; and
- Identification of environmental quality indicators suitable for monitoring and use in adaptive management.

1.2 Objectives of Task 2.6 (Trophic modelling)

Evaluate spatial patterns of fishery production for the main commercial and recreational species, as well as their relationships with spatial patterns of physical variables, nutrients, primary and secondary production, and benthic habitat types.

Provide coarse level trophic models support major trophic guilds involved with fishery production.

Provide prediction of the impacts of management zoning and fishery targeting on fishery production by major guilds.

1.3 Deliverables

1. Prototype fisheries production and trophic models implemented for the coastal region from Exmouth to Port Hedland.
2. Fisheries production and trophic models implemented for the coastal region from Exmouth to Port Hedland.
3. Maps of fishery production and spatial distributions of relative abundance of key commercial fisheries, including relationships with physical factors, primary production, and benthic habitat types (used in Tasks 1.2, 1.3, 2.7, 4.2, 5.1, 5.2, 5.3 and by management agencies).
4. Food web diagrams indicating main trophic interactions and dynamical food web models for the region, including time series of biomass for the main trophic guilds (used in Tasks 1.2, 1.3, 2.7, 5.3, 5.4 and by management agencies).
5. Written report on Fishery Production and Links to Habitats and Food Web Dynamics including model documentation.

This report represents the food web dynamics component of these deliverables, i.e. the trophodynamics model implemented for the region from Exmouth Gulf to Port Hedland, food web diagrams, a dynamical food web model for the region including a time series of biomass for the main trophic guilds, and a written report on food web dynamics and model documentation.

2. INTRODUCTION

Understanding trophic interactions between key fishery species and their prey is important in determining long-term potential fishery production. Historically individual species or species group fisheries have been managed or assessed as single entities, rather than considered as an integral part of a complex ecosystem. This simplified approach has been suggested as one of the contributing factors in the spectacular collapse of some fisheries around the world. Consequently, there are major efforts globally towards broader ecosystem-based management approaches. Trophic modelling is one such element of such an approach and is applied here to the North West Shelf ecosystem. The particular trophodynamics model applied here is based on the *Ecosim/Ecopath* methodology which has been applied to many other fisheries.

2.1 North West Shelf

The North West Shelf (NWS) model area is situated between 18 and 21°S on the north-west coast of Australia (figure 2.1.1), and covers a total area of about 70 000 square km. In terms of recognised bioregions it includes the Pilbara offshore region and the southern-most part of the North West Shelf region (IMCRA Technical Group, 1998). The oceanographic environment is very dynamic being subject to several tropical cyclones every year, large tidal ranges, seasonal monsoons and interannual variability from El Niños (Condie et al. 2003). The warm, subtropical waters average about 25°C at the surface, are well mixed to a depth of about 120 m during the SW Monsoon (about April to November) and are stratified during the NE Monsoon (Nov to April), and are derived largely from the Indonesian Throughflow (Godfrey & Mansbridge, 2000). The model represents the food web of the continental shelf ecosystem in the depth range of approximately 20 to 200 m. The seabed in this area supports a high biodiversity and a variety of benthic habitat types, including soft muds on the outer shelf, course sands and occasional limestone outcrops over most of the shelf, sponge and soft coral ‘gardens’ and coral reefs.

2.2 Brief history of fishing on the North West Shelf

There is a long history of foreign fishing on the North West Shelf, starting in 1935 and ending in the late 1980s by the progressive closure of certain areas to foreign vessels. Prior to the declaration of the 200 nautical mile Australian Fishing Zone (AFZ) in 1979, foreign fishing beyond 12 nautical miles from the coast had been unregulated. Following the declaration, the Australian Fisheries Service managed the northern demersal fishery under a system of total allowable catch quota. Since there was little activity from domestic fisheries, this quota was wholly allocated to the foreign fleets (Jernakoff, 1990 in Jernakoff & Sainsbury, 1990). Fishing pressure increased from 1984 as domestic fishing fleets became increasingly active. A domestic trap fishery targeting serranids, lethrinids and lutjanids began at this time and domestic trawling began in 1988. By 1988 the areas of the North West Shelf that were accessible by foreign fishing fleets were restricted.

The major commercial species that were fished were generally those that were aimed at the Asian market, some of which were of considerable future value to the domestic fisheries and some that were not (Jernakoff, 1990 op. cit.). The lethrinids (emperors and sea-breams) were particularly targeted, with significant catches of lutjanids (sea perches and snappers), serranids (rock cods and coral trout), nemipterids (threadfin breams), saurids (lizardfishes), sparids (sea bream), haemulids (sweetlips) and carangids (trevallies, scads and queenfish). The fishery was managed to maximise the total multi-species yield which often resulted in under or over fishing the individual species (Jernakoff, 1990 op. cit.).

CSIRO's involvement began in 1979 with comprehensive research trawl surveys and assessments of the stocks on the North West Shelf. The area was surveyed from 1978 to 1997 for various purposes and at varying frequencies. The data utilised in this report come from a series of surveys in 1982-83, a sequence of annual surveys from 1986 to 1991 and annual surveys in 1995 and 1997. The period that this model represents is the late 1980s, a period when the foreign fishing effort declined and the domestic trawl fishery grew. The lethrinids, lutjanids, and serranids were quite depleted by 1986 (Sainsbury, 1986 in Jernakoff & Sainsbury, 1990), and the species composition of the catches had changed significantly from the early 1970s and was probably still changing in 1983 (Sainsbury, 1983 in Jernakoff & Sainsbury, 1990). This means that the system was not in equilibrium and had not been for many years. However, an underlying assumption of the model is that the system is in an average state, and it was assumed that the North West Shelf had reached a point of the least rate of change with fishing continuing at the relatively low 1987 rate. By driving the dynamic model with fishing mortalities, changes in biomass of the stocks could be predicted. Biomasses estimated from the 1995 and 1997 surveys were compared to the 1980s model output.

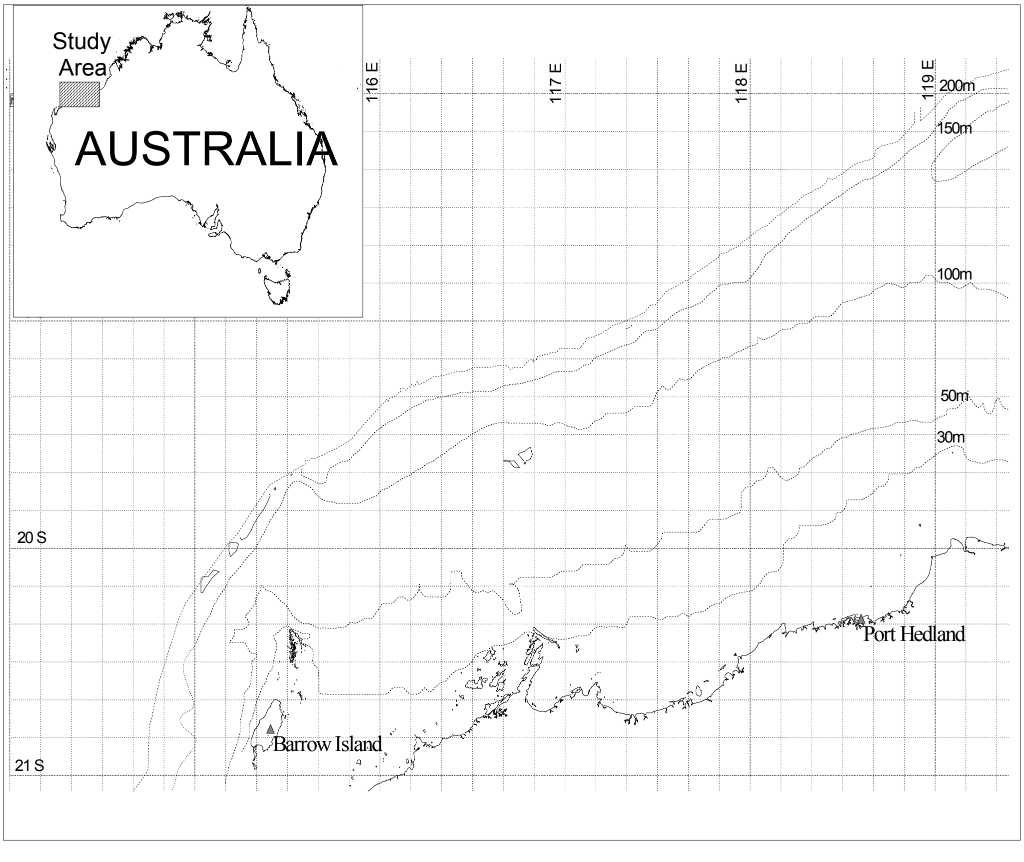


Figure 2.1.1: The North West Shelf, showing the major bathymetric contours defining the depth boundaries of the study area and the grid squares used in setting up the spatial model.

3. MODEL APPROACH

3.1 Overview of Ecopath with Ecosim models

The North West Shelf fishery was modelled with the *Ecopath* with *Ecosim* software. These models arose from the need to better understand structure, function and regulation of the ecosystem, and were originally developed to help support ecosystem-based fishery management. There are other approaches available, and none are perfect. Walters et al. (1997) discussed three approaches that have been used with varying degrees of success: multi-species virtual population analysis (MSVPA); simpler and less data hungry, differential equation models for biomass dynamics; and bioenergetic modelling. He concluded that these models had several problems that restricted their more general application in fisheries. They required specialised modelling expertise, they were difficult to parameterise, there often was not enough contrast in the time series data to discriminate between inter and intra-specific effects, and all of which resulted in a lack of transparency combined with unreliable results. Jennings et al. (2001) also reviewed several ecosystem modelling approaches including multi-species surplus production, MSVPA, and size spectra models. They also concluded that outputs were often of dubious reliability or difficult to interpret.

A simpler approach for ecosystem trophic analysis was devised by Polovina (1984), although with the same difficulties but to a lesser degree, and developed by Christensen and Pauly (1992) into the *Ecopath* mass-balance approach. The description of the average state of an ecosystem, using *Ecopath*, also serves to parameterise systems of coupled difference and differential equations, used to depict changes in biomasses and trophic interactions in time (*Ecosim*) and space (*Ecospace*) (Christensen et al. 2000). *Ecosim* tries to predict how changes in environment, the abundance of trophic groups, or a fishery will affect the ecosystem (Jennings et al. 2001). *Ecospace* attempts to predict spatial changes in distribution dynamically. The resulting Eco-modelling suite (Christensen & Pauly, 1992; Pauly & Christensen, 1993; Christensen, 1995, 1998; Kitchell et al. 1999; Walters et al. 1999; Pauly et al. 2000) is now commonly being used to efficiently summarise data on ecosystems, describe the system properties, and predict responses to policy or ecosystem changes.

The first component of the Eco-suite of models, *Ecopath*, was based on the approach by Polovina (1984) where biomass and food consumption of the various groups are estimated using mass-balance principles, and combined with an analysis of the flows between the groups by Ulanowicz (1986). *Ecopath* assumes an average state usually over a year rather than the original Polovina assumptions of steady state. *Ecopath* is based on two master equations; one describing production and one describing energy balance of each group (Christensen et al. 2000). It is based on a system of linear equations describing trophic fluxes in mass-balance. The ecosystem is compartmentalised into trophic groups. These can comprise a single species or of many species, and be grouped based on taxonomy or functional ecology. Descriptions of the model equations are given in Appendix A and more detailed accounts can be found in Walters et al. (1997) and Christensen et al. (2000). Once the model is parameterised and balanced, it can be used in the temporal and spatial extensions, *Ecosim* and *Ecospace*.

Ecosim was developed by incorporation of coupled differential and difference equations into *Ecopath*, to allow for dynamic simulations (Walters et al. 1997). For example, in *Ecosim* biomass flux rates are expressed as a function of time varying biomass and harvest rates (Christensen et al. 2000) and predator-prey interactions can be varied to emulate top-down or bottom-up control (Walters et al. 2000; Bundy, 2001). Time series data on biomass, catch rates and fishing effort can be fitted which makes this program useful to explore options for management policies (Pauly et al. 2000). *Ecopath* with *Ecosim* (EwE) is intended only to explore and filter possible scenarios rather than to provide quantitative predictions.

Ecopath with *Ecosim* (EwE) has been used to examine a number of ecosystems including the Benguelan upwelling (Jarre-Teichmann et al. 1998; Shannon & Jarre-Teichmann, 1999; Shannon et al. 2000), the Eastern Bering Sea (Trites et al. 1999), the Central Pacific top predators (Kitchell et al. 1999), the Newfoundland-Labrador coast (Bundy, 2001), and the Gulf of Thailand (Christensen, 1998). In Australia, EwE models were developed for the seamounts and midslope region off southern Tasmania (Bulman, 2002; Bulman et al. 2002), to test the hypothesis of Koslow (1997) and Williams et al. (2001) that the large populations of orange roughy and oreo dories are supported by a constant advection of prey past the seamounts in the deeper currents. Goldsworthy et al. (2003) used *Ecosim* to model the impacts of increasing seal populations on fish stocks in eastern Bass Strait.

Recent developments in ecosystem management increasingly require more spatial information. Traditional methods of stock assessment have not addressed spatial management options let alone indirect ecological impacts of policy alternatives (Walters et al. 1999). Responding to this need, the third module in the Eco-suite of models, *Ecospace*, represents the dynamical response of an ecosystem in two dimensional space. Unlike other attempts to develop spatially explicit models this new approach uses few additional data (Walters et al. 1999). Although it does not attempt to model all physical transport and migratory processes, the model may be able to provide insight into the effects of marine protected area policies on trophically linked species. As is the case for EwE, *Ecospace* is intended only to explore and filter possible scenarios rather than to provide quantitative predictions.

Ecospace was specifically developed to investigate the effects of protected areas on marine ecosystems. So far, it has not been widely applied. It has been applied: to the Prince William Sound to aid scientists in understanding the implications of the Exxon Valdez oil spill on trophic interactions over large space-time scales (Okey & Pauly, 1999); to fishing fleets in the Gulf of Mexico, and to investigate the effects of MPAs on fishing fleets in British Columbia. Also, Walters et al. (1999) presented results of a model of the shelf fishery of Brunei Darussalam with an MPA around the oilrigs and pipelines. These applications showed that *Ecospace* could predict fish distributions quite similar to those observed while accounting for spatial variation of primary production, predation and fishing. More recently, *Ecospace* has been used to model the effects of MPAs on ecosystems around Hong Kong and the People's Republic of China (Pitcher et al. 2002).

3.2 Model equation

The trophic model is based on two equations describing production and energy balance for each group:

production = catch + predation mortality + biomass accumulation + net migration + other mortality,

and

consumption = production + respiration + unassimilated food.

Ecopath also calculates:

production utilised = catch + consumption by predators,

or mathematically,

$$B_i(PB^{-1})_i EE_i - \sum_{j=1}^{n} B_j (QB^{-1})_j DC_{ij} - Y_i - E_i - BA_i = 0 \qquad 3.1$$

where:

B_i is the biomass of functional group i;

$PB^{-1}{}_i$ is production/biomass ratio and can generally be input as total mortality rate (Z);

EE_i is the ecotrophic efficiency defined as the proportion of production of i that is utilised in the system;

B_j is biomass of predator j;

$QB^{-1}{}_j$ is consumption rate for predator j;

DC_{ij} is the fraction of group i in the diet of predator j;

Y_i is the total fishery catch of group i;

E_i is the net migration of group i (emigration-immigration); and

BA_i is the biomass accumulation rate.

To parameterise the model, three of the four terms, B, PB^{-1}, QB^{-1} or EE, must be supplied. If all four of the terms are entered, biomass accumulation or net migration can be estimated. Also required are diet composition, assimilation rate, net migration, catch, and biomass accumulation, the last three of which may be zero. More detail of the model equations are in Appendix A.

4. MODEL CONSTRUCTION

4.1 Procedure

Okey and Mahmoudi (2002) documented the steps for the design, construction and balancing of an EwE model for the West Florida Shelf off the USA. Briefly these were to:

- define the system in space and time;
- define the functional groups in the model;
- estimate basic parameters for each functional group;
- estimate fisheries information;
- estimate additional parameters;
- enter parameters;
- characterise the pedigree of the parameters; and finally
- balance the model.

4.2 Model definition

In this report an *Ecopath* with *Ecosim* (EwE) model developed for the North West Shelf and the food web upon which it is based is described. The area that this model relates to has been described in section 2.1. The fishery has been variable over the years but the attempt has been to capture the trophic flows and biomasses during the late 1980s. At this time, the foreign fishery had reduced considerably following closures and the domestic fisheries were expanding. This allowed the use of 15 years of catch and effort data to “drive” the model, i.e. annual fishing effort data were input in order to try to recreate the actual changes in the system caused by fishing.

4.3 Functional groups

The fauna of the North West Shelf ecosystem, from 50 to 200 m (figure 2.1.1) was organised into functional groups based upon commercial fishery, life history traits and ecology such as size and growth, preferred depth, and trophic function. For some species such as the carangids, categorisation was complicated by increases in depth preference with increased size. This particular group was split into two stanzas, juveniles and adults, to account for specific life history parameters and traits that would affect their specific predation and fishing mortalities.

4.4 Food web

A matrix of trophic interactions was constructed based upon a preliminary inspection of past dietary studies made on the North West Shelf, and for the same or similar species in the Gulf of Carpentaria. The available trophic data was quite sparse, necessitating the assumption that the Gulf of Carpentaria data would be a reasonable approximation of the North West Shelf system. The data was also often quite aggregated, making specific linkages impossible to determine. For many species diets were deduced from other models or from *FishBase* (Froese & Pauly, 2000) and references therein. Diets of invertebrate groups were deduced from similar models such as the Florida Shelf model (Okey & Mahmoudi, 2002) or Gulf of Thailand (Christensen, 1998). More detail of the dietary matrix is given in Appendix B. A conceptual model was proposed from this dietary data (figure 4.4.1). The conceptual model groups formed the basis for the final structure of the trophic model (table 4.4.1). The food web has shallow (20 to 120 m depth) and deep (120 to 200 m depth) components to reflect both the major differences on community structure in these different depth ranges and the ontogenetic migrations from the shallow to the deep communities by some species.

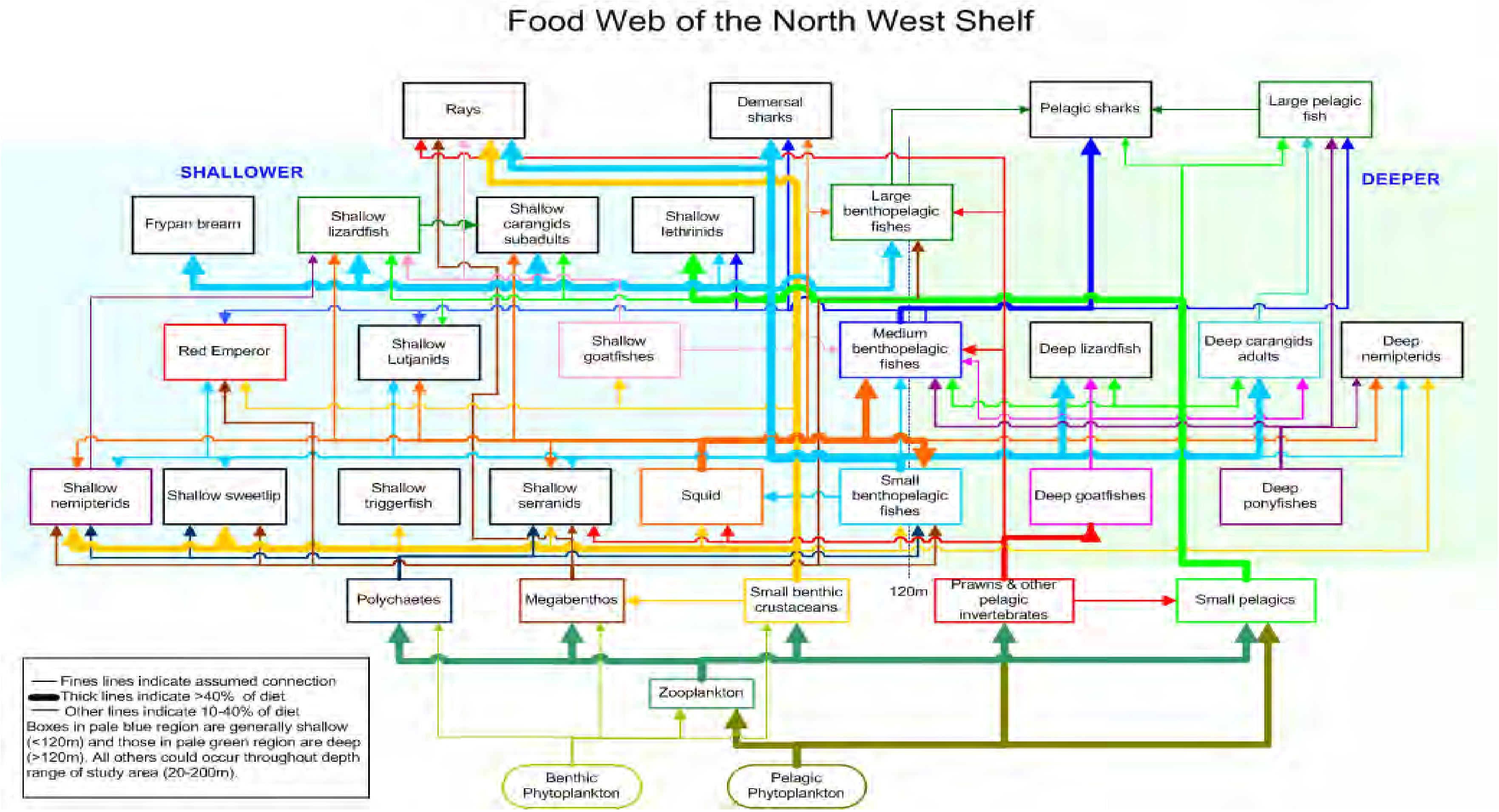


Figure 4.4.1: Food web of the North West Shelf. For ease of tracing flows from one group to another, the coloured arrows represent flows from boxes of the same colour.

Table 4.4.1: Trophic groups or species in the North West Shelf model, with representative species of the group. References refer to dietary information sources.

Group No.	Group name	Representative species in group	References
1	Coastal sharks	*Sphyrna mokarran*	Cortes, 1999
		Galeocerdo cuvieri	
		Carcharhinus plumbeus	
		Carcharhinus sorrah	Brewer et al. 1995
		Hemigaleus microstoma	
		Loxodon macrorhinus	
2	Rays	*Dasyatididae*	
		Dasyatis thetidis	
		Himantura toshi	Salini et al. 1994
		Himantura uarnak	
		Rhynchobatus djiddensis	
		Taeniura meyeni	
3	Small tunas	*Thunnus obesus*	Kim et al. 1997 in *FishBase*
		Scomberomorus commerson	Brewer et al. 1995
		Euthynnus affinis	Blaber et al. 1990
		Katsuwonus pelamis	Roger 1993. Sierra, L.M., R. Claro and O.A.
			Popova, 1994. *FishBase*
		Thunnus albacares	Maldeniya, 1996; Pimenta, Marques, Lima and Amorim, 2001
		Scomberomorus queenslandicus	Salini et al. 1994; Begg and Hopper, 1997
4	Shallow Lethrinids	*Lethrinus* sp	Unpub. Sainsbury
		Lethrinus nebulosus	Salini et al. 1994
			Walker, 1978
5	Red Emperor	*Lutjanus sebae*	Salini et al. 1994
6	Shallow Lutjanids	*Lutjanus malabaricus*	Salini et al. 1994
			unpublished raw data
		Lutjanus vittus	Salini et al. 1994
		Lutjanus erythropterus	Salini et al. 1994
		Pristipomoides multidens	Kailola et al. 1993; Richards, 1987
		Pristipomoides typus	
7	Shallow Nemipterids	*Nemipterus furcosus*	Sainsbury and Jones (unpub)
		Nemipterus celebicus	
		Scolopsis monogramma	Salini et al. 1994
8	Deep Nemipterids	*Nemipterus bathybius*	Russell, 1990.
		Nemipterus virgatus	
9	Shallow Serranids	*Epinephalus multinotatus*	estimate
10	Frypan bream	*Argyrops spinifer*	Salini et al. 1994
11	Shallow carangidae (juvenile)	*Carangoides caeruleopinnatus*	Salini et al. 1994
		Carangoides chrysophrys	Salini et al. 1994
		Carangoides gymnostethus	Salini et al. 1995
		Seriolina nigrofasciata	Salini et al. 1994
		Carangoides malabaricus	Salini et al. 1994
12	Deep carangidae (adult)	*Carangoides caeruleopinnatus*	Salini et al. 1994
		Carangoides chrysophrys	Salini et al. 1994
		Carangoides gymnostethus	Salini et al. 1994
		Seriolina nigrofasciata	Salini et al. 1994
		Carangoides malabaricus	Salini et al. 1994
		Carangoides equula	Salini et al. 1994

Group No.	Group name	Representative species in group	References
13	Small pelagic fishes	*Sardinella albella* *Herklotsichthys koningsbergeri* *Decapterus russelli* *Auxis thazard*	Okey and Mahmoudi, 2002 Blaber et al. 1990
14	Shallow lizardfish	*Saurida undosquamis*	Sainsbury and Whitelaw; Venkata Subba Rao, 1981
15	Deep lizardfish	*Saurida filamentosa*	Salini et al. 1994
16	Shallow mullidae	*Parupeneus heptacanthus*	based on deep group
17	Deep mullidae	*Upeneus moluccensis*	*FishBase*: Lee, 1973
18	Shallow Triggerfish	*Abalistes stellaris*	FishBase: Randall, 1985; Ivantsoff, 1999
19	Shallow Sweetlip	*Diagramma labiosum*	Salini et al. 1994
20	Deep Ponyfish	*Leiognathus bindus*	*FishBase*: Cabanban, 1991; Kulbicki and Wantiez, 1990; Nasir, 2000: Yamashita et al. 1987
21	Shallow small fish	small fish (<30 cm)	*FishBase*: various authors
22	Deep small fish	small fish (<30 cm)	*FishBase*: various authors; Yamashita et al. 1987
23	Shallow medium fish	medium fish (30-50 cm)	*FishBase*: various authors
24	Deep medium fish	medium fish (30-50 cm)	*FishBase*: various authors
25	Shallow large fish	large fish (>50 cm)	*FishBase*: various authors
26	Deep large fish	large fish (>50 cm	*FishBase*: various authors
27	Sessile epibenthos		Okey and Mahmoudi, 2002
28	Megabenthos	bivalves	Okey and Mahmoudi, 2002
29	Macrofauna	small infauna	Okey and Mahmoudi, 2002
30	Prawns	commercial	Gribble, 2001; Chong and Sasekumar, 1981
31	Cephalopods	squids	Okey and Mahmoudi, 2002
32	Large zooplankton	Zooplankton >20 mm, carnivorous jellies, ichthyoplankton	Okey and Mahmoudi, 2002; Optiz, 1993; Silvestre et al. 1993
33	Small zooplankton	zooplankton <20 mm including pelagic copepods	As above
34	Pelagic phytoplankton		
35	Benthic phytoplankton		
36	Microphytobenthos		
37	Detritus		

4.5 Diets

Wherever available, dietary information was taken from local studies on the North West Shelf (Sainsbury & Jones unpublished ms; Sainsbury & Whitelaw unpublished ms; CSIRO unpublished data) or from studies in the Gulf of Carpentaria (Salini et al. 1994; Brewer et al. 1995). Where dry weights were recorded, they were converted to wet weight using empirical conversion factors of seven for crustaceans and five for fish and squid. When no data were available locally, information was found from the literature, or from *FishBase* sources (table 4.4.1), and an average of the diets available were used.

Where diet information for a predator was broadly aggregated, as was often the case for fishes, the aggregated components were re-apportioned across relevant trophic groups according to the proportions of whatever prey species were specifically identified. For instance, unidentified fish in a predator's diet would be pro-rated into already identified fish species or groups for that predator. If no specific prey were identified, the aggregated diet group was re-apportioned across possible prey that would be available to the predator according to proportions in diets of predators in the same functional group. This approach assumes that all prey fish in the same depth zone and of the same or smaller size would be equally vulnerable to predation, which may not necessarily be true for all species. Predation on juveniles of species whose adults are larger than the predator is not accounted for in this approach.

In the trophic groups that consisted of many species, the overall diet was a weighted average. For those species for which there was dietary data, the components of their diets were weighted by the proportion of group biomass that they represented. The weighted components per prey type were then summed over all species in that group to give a weighted diet composition for the group. The final dietary matrix was entered into the *Ecopath* program. The model was balanced, in part, by iteratively adjusting dietary proportions since the greatest uncertainty exists in dietary analyses. Even relatively large modifications are usually tolerable within the confidence limits of the diet compositions. The final diet matrix is shown in table 4.5.1.

Table 4.5.1: Final dietary matrix in terms of proportions by weight after *Ecopath* balancing. Predator groups across the top correspond to the same numbers and prey groups down the table. The column total represents the total for that predator. Import represents the proportion of food that is obtained outside the model limits.

	Prey\Predator	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	Coastal sharks																		
2	Rays																		
3	Small tunas	0.010																	
4	Lethrinids	0.017								0.064	0.002		0.010						
5	Red Emperor									0.027									
6	Lutjanids									0.045					0.018	0.023			
7	Shallow nemipterids				0.077		0.083	0.010	0.023	0.085	0.888	0.061	0.050		0.115	0.116			
8	Deep nemipterids						0.041	0.007	0.007	0.011		0.002			0.021	0.023			
9	Serranids						0.005			0.007									
10	Frypan bream									0.011									
11	Juvenile carangids			0.005	0.016		0.014		0.006	0.047			0.015		0.050	0.051			
12	Adult carangids																		
13	Small pelagic fish	0.006	0.016	0.940	0.004		0.107	0.028	0.012		0.010	0.200	0.708	0.040	0.259	0.302			
14	Shallow lizardfish			0.005						0.058	0.004				0.010	0.028			
15	Deep lizardfish						0.003			0.024					0.010	0.020			
16	Shallow mullidae				0.014		0.020	0.020	0.019	0.013	0.011	0.014	0.095		0.068	0.049			
17	Deep mullidae						0.104	0.023	0.023	0.028		0.005			0.042	0.049			
18	Trigger fish	0.001		0.005			0.027			0.040			0.011						
19	Sweetlip									0.026									
20	Ponyfish		0.007		0.019	0.690	0.118	0.009	0.009	0.008		0.120	0.007		0.048	0.059			
21	Shallow small fish	0.005	0.020	0.005	0.165	0.049	0.145	0.067		0.132	0.024	0.139		0.004	0.130	0.093	0.040		0.025
22	Deep small fish				0.047		0.064	0.010	0.100	0.039		0.150			0.060	0.093		0.050	
23	Shallow medium fish			0.005			0.010			0.081	0.002	0.023			0.040				
24	Deep medium fish						0.001			0.005						0.040			
25	Shallow large fish	0.001					0.001												
26	Deep large fish																		
27	Sessile epibenthos		0.006					0.024	0.024			0.005		0.017					0.144

	Prey\Predator	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
28	Megabenthos	0.940	0.415		0.179	0.032	0.034	0.227	0.217	0.150	0.047	0.009	0.017	0.020				0.060	0.371
29	Macrofauna	0.014	0.287		0.060	0.226	0.152	0.397	0.391	0.080	0.002	0.035	0.082	0.099	0.029	0.053	0.113	0.069	0.309
30	Commercial prawns	0.005	0.244	0.019	0.019	0.003	0.045	0.077	0.069	0.020		0.031	0.005		0.005		0.838	0.813	
31	Squid	0.001	0.005	0.016	0.400		0.026	0.025	0.030		0.009	0.055			0.078		0.009	0.008	
32	Large zooplankton							0.007				0.094		0.060					0.052
33	Small zooplankton							0.069	0.069			0.056		0.529					0.027
34	Phytoplankton													0.029					
35	Benthic producers													0.090					0.052
36	Microphytobenthos													0.002					0.010
37	Detritus													0.111					0.010

Table 4.5.1 continued: Final dietary matrix in terms of proportions by weight after *Ecopath* balancing. Predator groups across the top correspond to the same numbers and prey groups down the table. The column total represents the total for that predator. Import represents the proportion of food that is obtained outside the model limits.

	Prey\Predator	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**
1	Coastal sharks															
2	Rays															
3	Small tunas															
4	Lethrinids							0.002								
5	Red Emperor							0.001								
6	Lutjanids							0.002								
7	Shallow nemipterids					0.097		0.022	0.047							
8	Deep nemipterids				0.004		0.029									
9	Serranids															
10	Frypan bream							0.005	0.200							
11	Juvenile carangids			0.00070		0.013	0.006	0.001								
12	Adult carangids															
13	Small pelagic fish			0.031			0.013	0.146						0.360		
14	Shallow lizardfish							0.090	0.125							
15	Deep lizardfish						0.011	0.005								
16	Shallow mullidae					0.014		0.022	0.167							
17	Deep mullidae				0.012		0.043		0.017							
18	Trigger fish							0.001								
19	Sweetlip							0.001	0.041							
20	Ponyfish	0.303			0.003		0.022	0.019								
21	Shallow small fish	0.192		0.010		0.101	0.008	0.157	0.119	0.002			0.002			
22	Deep small fish		0.015		0.009	0.014	0.031									
23	Shallow medium fish	0.010						0.010	0.035							
24	Deep medium fish						0.001									
25	Shallow large fish							0.002								
26	Deep large fish															
27	Sessile epibenthos	0.156		0.017			0.043	0.083		0.010						

	Prey\Predator	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**
28	Megabenthos	0.063		0.268	0.057	0.160	0.184	0.214	0.050							
29	Macrofauna	0.247	0.404	0.239	0.377	0.225	0.552	0.085		0.353	0.010	0.100	0.272	0.130		
30	Commercial prawns	0.020		0.001		0.206	0.021	0.020	0.100				0.017			
31	Squid	0.009		0.045		0.010	0.036	0.113	0.100					0.010		
32	Large zooplankton		0.006	0.300	0.539	0.155					0.050		0.195	0.250		
33	Small zooplankton									0.050	0.050	0.050	0.037	0.250	0.100	0.100
34	Phytoplankton		0.057							0.202	0.230	0.200			0.500	0.700
35	Benthic producers			0.088		0.005						0.300	0.101			
36	Microphytobenthos									0.050	0.220	0.150	0.033			0.100
37	Detritus		0.518							0.333	0.440	0.200	0.343		0.400	0.100

5. MODEL PARAMETERS

5.1 Biomasses of fishes estimated from science surveys

Average annual swept-area abundances were calculated for the *Soela*, *Pride of Eden* and *Southern Surveyor* surveys for the years 1986 through 1991. The total catch per species over all years was divided by the total area swept for all years. The area swept was calculated as duration of the tow (hours) x vessel speed (knots) x 1.852 km (conversion of nautical miles to kilometres) x net spread (km). The nets used in these surveys were Frank and Bryce trawls. They have a net spread of 20 m under towing speeds used (3.5 to 4.5 knots) and meshes of 22.8 cm in the wings decreasing to 45 mm in the cod end.

It was clear early on in the model initialisation that the swept area abundances for small fishes were seriously underestimated, presumably due to their low retention in the relatively large meshes of the survey trawl. To account for the underestimation of abundances of small species, the survey abundances for size selectivity and then for catchability was first adjusted.

Specific size selectivity indices were developed for those species for which catch-at-age data were available, such as *Nemipterus furcosus*. For those species where catch-at-age data were not available but length frequency data were, a mesh selectivity index appropriate to the morphology of the species, to available length-frequency samples to reconstruct a theoretical population length frequency distribution was applied. Both the sampled and reconstructed length frequency distributions were converted to biomass distributions using length-weight relationships, specific where data were available or generic where not. The proportion of the population sampled was estimated from the ratio of the sampled and reconstructed population biomass distributions. The swept-area abundance was adjusted up accordingly. Details of how these selectivities and proportions were derived are in Appendix B. In particular, for the saurids, a variety of mesh selectivities derived from this survey data, and two from Taiwanese studies was used (Liu et al. 1985; Wen et al. 1991). This resulted in a range of biomass estimates possible for these species and while the authors chose the value from this survey as most fitting for the population, one could reasonably suspect a scenario with a higher biomass of saurids probably resulting from an increase in suitable habitat because of degradation of other habitat types from trawling activities.

To account for catchability, it was adjusted for all but sharks, and tunas and small pelagics, by a catchability factor of 0.44. This was calculated from data for *Lutjanus sebae* red emperor by calculating its ratio of the stock assessment biomass estimate and survey abundance (after adjusting for size selectivity) (Appendix B, section B.9). Generally, stock assessment procedures use 0.5 as a catchability factor, so this estimate would result in slightly higher abundances.

The final abundances estimated in this way were averaged over the period 1986 to 1991 and were entered as the initial parameters in the *Ecopath* model to represent the late 1980s, and the abundances for 1995 and 1997 were entered as a time series into *Ecosim* (table 5.1.1).

Abundance for tunas was approximated by estimates of abundance for yellowfin and big-eye tuna derived from global biomass estimates and CPUE data (Appendix C). These estimates are likely to be an overestimate because the species occur more often in the deeper water outside this study area. However, it was assumed that this might compensate to some extent for other small tunas (e.g. skipjack and mackerel tuna) and billfish that occur on the shelf, and which were not adequately sampled by the gear during these surveys.

Table 5.1.1: Abundance of species estimated from scientific surveys. "1987" values are the average abundances calculated from the 1986 to 1991 surveys; [1]not scaled by 0.44; [2]estimated from CPUE approximation method; [3]estimate inaccurate and not entered into model; [4] based on Liu et al. 1985 selectivity; [5]based on Wen et al. 1991 selectivity for lizardfish.

Trophic group no.	Group name	"1987"	1995	1997
1	Coastal sharks	0.023[1]	0.089[1]	0.023[1]
2	Rays	0.129[1]	0.081[1]	0.198[1]
3	Small tunas	0.097[2]	0.000	0.001
4	Shallow lethrinids	0.139	0.686	0.089
5	Red emperor	0.119	0.206	0.176
6	Shallow lutjanids	0.265	0.460	0.782
7	Shallow nemipterids	2.434	3.176	4.728
8	Deep nemipterids	0.973	1.052	2.376
9	Shallow serranids	0.029	0.123	0.035
10	Frypan bream	0.049	0.104	0.114
11	Juvenile carangids	0.753	0.827	0.955
12	Adult carangids	0.171	0.304	0.198
13[3]	Small pelagic fish	1.803	0.531	1.827
14	Shallow lizardfish	0.316 (0.352[4], 0.400[5])	0.278 (0.314[4], 0.360[5])	0.489(0.547[4], 0.623[5])
15	Deep lizardfish	0.116 (0.132[4], 0.134[5])	0.112 (0.127[4], 0.129[5])	0.156 (0.178[4], 0.180[5])
16	Shallow mullids	1.843	1.902	3.302
17	Deep mullids	3.297	0.804	5.295
18	Trigger fish	0.175	0.341	0.348
19	Sweetlips	0.111	0.162	0.137
20	Pony fish	0.817	0.334	2.580
21	Shallow small fish	5.975	5.480	8.401
22	Deep small fish	2.343	0.534	2.485
23	Shallow medium fish	0.370	0.499	0.757
24	Deep medium fish	0.068	0.186	0.074
25	Shallow large fish	0.221	0.231	0.867

5.2 Lower trophic group biomasses

Biomasses for megabenthos, macrobenthos, commercial prawns, large zooplankton and squid were unavailable and the model was allowed to estimate them. Biomasses for phytoplankton, small zooplankton, microphytobenthos and benthic primary producers were entered as outputs from a biogeochemical model developed as part of the NWSJEMS (Herzfeld et al. 2006; table 5.2.1). The estimate for detritus was a conservative estimate based on other models such as the West Florida Shelf.

Table 5.2.1: Biomass parameter inputs for lower trophic groups in *Ecopath* model. Data from biogeochemical model (Herzfeld et al. 2006) with probable ranges in parentheses.

Trophic group no	Group	Biomass t km^{-2}
33	Small zooplankton	30 (5-30)
34	Pelagic phytoplankton	35 (27-42)
35	Benthic phytoplankton	40 (8-70)
36	Microphytobenthos	10 (10-13)

5.3 Production and consumption parameters

Nearly 600 fish species were identified from survey data of which about 100 comprised 95% of the overall trawlable fish biomass. Few production P/B and consumption Q/B parameters for these fishes were available so the parameters available in *FishBase*, and sources cited within (Froese & Pauly, 2003), or from models for similar systems, particularly for invertebrate groups were used. For species in aggregated groups, an overall P/B or Q/B was derived by weighting the individual values for each species by the species’ proportion in the group by biomass. For those large aggregated groups, only the species occurring in the top 100 most abundant species in the research surveys were considered. The production and consumption parameters input into the model are in table 7.2.1 and Appendix D.

For lower trophic groups production and consumption parameters were obtained from other models (Appendix D; table 7.2.1): for small zooplankton, pelagic and benthic phytoplankton and microphytobenthos parameters from a range determined by the biogeochemical model of the North West Shelf (Herzfeld et al. 2006) were used, and for others estimates based on values from models of similar systems such as the West Florida Shelf (Okey & Mahmoudi, 2002), Caribbean coral reef system (Optiz, 1993), South China Sea (Silvestre, 1993), Gulf of Mexico (Arreguín-Sánchez et al.1993) or the Great Barrier Reef (Gribble, 2001).

5.4 Ecotrophic efficiencies

Ecotrophic efficiencies (EE) were calculated by the model for most groups because biomass, P/B and Q/B were all entered. For the few teleost groups where biomass could not be estimated, EEs of 0.9 to 0.95 were entered. For lower trophic groups, EEs were adjusted so that growth efficiency was within 15 to 50% and resulting in EEs of between 0.5 and 0.97). A balanced *Ecopath* model requires ecotrophic efficiencies to be below one, therefore fulfilment of this requirement was the major indicator in the balancing process.

6. FISHERIES DATA

6.1 Domestic fishery catches

Data from the Catch and Effort Statistics data set (CAES) were collated into an annual catch time series for the domestic fisheries for the years 1987 to 2001 (no data was collected prior to 1986) (Appendix E). For the demersal and prawn trawls, and trap gears, annual catches for each species or taxon were summed over all reporting grid squares which matched or overlapped the study area. Catches were divided by the area of the grid squares (127 675 to 68 468 km^2), or the model area (68 500 km^2) as appropriate. The catch rates of the individual species were aggregated into trophic group catch rates. The 15 years of catch data were used in calculating the fishing mortalities of species and in the time series fitting of the *Ecosim* model.

Discard rates for the commercial trawl fisheries were estimated from a study of bycatch in the Pilbara trawl fishery in 2002 (Stephenson & Chidlow, 2003). This study found that 62% of sharks and 32% of scalefish caught were discarded, although these percentages vary widely between vessels. There were a few protected species caught, some of which were returned alive, but their overall catch was small. Benthos catch rates were highest in areas of highest trawl effort. The percentages derived from the study for individual species (see table 13: Stephenson & Chidlow, 2003) were used to estimate the annual 1987 discard rate for specific trophic groups in the domestic commercial fishery (table 6.1.1). For jellyfish and sponges an average annual catch rate was calculated by using half of the reported maximum catch rate per hour (Stephenson & Chidlow, 2003), total hours of effort per year, and the area of the study area. For the benthos groups where only numbers were reported and it was not possible to calculate biomass, the data cited in Pitcher et al. (2002) for estimating discards of invertebrates from the Hong Kong fishery (table 6.1.1) was used. These rates were also applied to the prawn fishery to estimate discards. The trap fishery was assumed to discard only 1% discard of scalefish catch but to discard invertebrates at similar rates when applicable. Discard rates were variable between years so the average of discard rates over several years of the prawn and trap fisheries were input into the model (table 6.1.2).

Longline fishery catches and discards for tunas and sharks (table 6.1.2) were calculated directly from fishery data (CSIRO data).

Table 6.1.1: Catch rates and discard rates for each trophic group for the domestic trawl fishery.

Trophic group	Catch rate t/km^2/yr	Discard t/km^2/yr 1987	Comments
Coastal sharks	0.0007	0.000693	Discard rate of 62%: Stephenson and Chidlow (2003)
Rays		0.000000	Assume 100% discard rate and half max catch rate (4.11 kg/hr): Stephenson and Chidlow (2003)
Small tunas	0.0002	0.000076	Average of scombrid discard rate (78%): Stephenson and Chidlow (2003)
Lethrinids	0.0057	0.000030	Discard rate of 10%: Stephenson and Chidlow (2003)
Red Emperor	0.0031	0.000060	Discard rate of 6%: Stephenson and Chidlow (2003)
Lutjanids	0.0050	0.002382	Average scalefish discard rate of 32%: Stephenson and Chidlow (2003)
Shallow nemipterids	0.0080	0.000304	Discard rate of 14%: Stephenson and Chidlow (2003)
Deep nemipterids		0.000000	No data. Assume not usually caught in the fishery
Serranids		0.000158	Average scalefish discard rate of 32%: Stephenson and Chidlow (2003)
Frypan bream	0.0011	0.000309	Average scalefish discard rate of 32%: Stephenson and Chidlow (2003)
Juvenile carangids		0.000000	No data. Assume 100% discarded
Adult carangids	0.0021	0.000530	Discard rate of 31%: Stephenson and Chidlow (2003)
Small pelagic fish	0.00003	0.000000	No data. Assume 100% discarded
Shallow lizardfish	0.0030	0.00203	No data. Assume 100% discarded
Deep lizardfish		0.000226	No data. Assume 100% discarded
Shallow mullidae	0.0032	0.000466	Average discard rate of 50% calculated: Stephenson and Chidlow (2003)
Deep mullidae		0.000000	No data. Assume not usually caught
Trigger fish		0.00129	No data. Assume 100% discard
Sweetlip	0.0001	0.0001	Average scalefish discard rate of 32%: Stephenson and Chidlow (2003)
Ponyfish		0.000000	No data. Assume not usually caught in fishery
Shallow small fish	0.0024	0.001340	Average discard rate of 50% : Stephenson and Chidlow (2003)
Deep small fish		0.000000	No data. Assume 100% discard
Shallow medium fish	0.0099	0.000870	Average discard rate of 50% : Stephenson and Chidlow (2003)
Deep medium fish	0.0030	0.000438	Average discard rate of 67% : Stephenson and Chidlow (2003)
Shallow large fish	0.0156	0.005051	Average discard rate of 50% : Stephenson and Chidlow (2003)
Deep large fish	0.00001	0.000000	Discard rate of 62%: Stephenson and Chidlow (2003)
Sessile epibenthos		0.004096	Discard rate calculated from half maximum sponge catch (57 kg/hr), an assumed biomass per sponge (Stephenson and Chidlow, 2003) and total annual effort in hours
Megabenthos	0.0003	0.000890	Based on estimate of discard from Hong Kong in Pitcher et al. (2002).
Macrofauna		0.000109	Discard rate of 62% Stephenson and Chidlow (2003)
Prawns	0.0053	0.000000	Discard rate of 62% Stephenson and Chidlow (2003)
Squid	0.0012	0.000303	Discard rate of 62% Stephenson and Chidlow (2003)
Large zooplankton		0.000187	Discard rate of sponges based on half maximum jellyfish catch rate (2.6 kg/hr: Stephenson & Chidlow, 2003) and annual effort in hours

6.2 Foreign fishery catches

Foreign catch data for the trawl fishery were obtained from the foreign catch data sets provided by WA Fisheries. These data were adjusted to account for discrepancies between the reporting of catches by the foreign fisheries obtained from specific vessel data and that reported to the Australian Fisheries Management Authority (AFMA) (Althaus et al. 2006). The data were analysed in the same way as the commercial data. Data from only the last three years, 1987 to 1989, of the foreign fishery were used, by which time the area of the fishery was considerably smaller than the model area. As for the domestic fisheries, the study area of 68 490 km^2 was used to calculate catch rate. The overall catch rates per species or trophic group were added across all gear types (Appendix E).

Rates of discard were harder to estimate because very little was recorded, and much was anecdotal. High-grading, i.e. trashing catch in favour of more valuable or marketable fish was practised in this fishing and the rate of discarding may have been very high (P. Stephenson, WA Fisheries pers. comm.) but no records are available to support this. Official records from the National Taiwanese University (D. Ramm 1995) showed that about 1% of fish were graded “trash” but it is unclear whether these fish were retained or discarded. Apart from fish that may have been discarded, benthos would also have been discarded. An estimate of the rate of discarding benthos from fisheries around Hong Kong was about 15.2% of total catch (Pitcher et al. 2002). The trashed benthos was dominated by jellyfish (96%). Discarding of fish was negligible in the Hong Kong fishery, which is consistent with the Taiwanese records for the NWS fishery. Average of discard rates over the whole period of the fishery were calculated for each trophic group for input into the model (table 6.1.2).

Table 6.1.2: Total landings for 1987 for each model fishery by trophic group and average discard rate per trophic group calculated over all years of the fishery operations in t/km^2 input into the model.

	Landings 1987 (t/km^2)						Discards (t/km^2)					
Group Name	**Domestic trawl**	**Trap**	**Prawn trawl**	**Foreign trawl**	**Longline**	**Total**	**Domestic trawl**	**Trap**	**Prawn trawl**	**Foreign trawl**	**Longline**	**Total**
Coastal sharks		0.000005	0.00001	0.00068	0.000008	0.0007	0.0000002	0.0000001	0.000116	0.000007	0.000066	0.000123
Rays							0.0000878					0.0000878
SmTunas		0.00001	.0000008		0.00455	0.00456	0.00000004	0.0000002	0.00018549		0.000012	0.0001857
ShLethrinids				0.00573		0.00573	0.0000002	0.000001		0.00006		0.0000591
RedEmperor	0.0000014	0.0002	.0000002	0.00294		0.00314	0.0000001	0.0000038	0.00000007	0.00003		0.0000336
ShLutjanids	0.0000039	0.00004		0.00496		0.005	0.0000018	0.0000029	0.00000015	0.00005		0.0000550
ShNemipterirds				0.00804		0.00804	0.0000001		0.00000001	0.00081		0.0000814
DpNemipterids												
ShSerranids								0.0000014				0.0000014
FryPBream				0.00108		0.00108				0.000011		0.0000110
JuvCarangids												
AdCarangids		0.000003	0.000001	0.00214		0.00214	0.0000006	0.0000004	0.00000097	0.000022		0.0000235
SmallPelagics				0.00003		0.00003				0.0000003		0.0000003
ShLizard				0.00296		0.00296	0.0000157			0.00003		0.0000456
DpLizard							0.0000157					0.0000157
ShMullidae				0.00323		0.00323	0.0000039		0.00000175	0.000033		0.0000383
DpMullidae												
ShTriggerFish							0.0000187					0.0000187
ShSweetlip				0.00005		0.00005				0.000005		0.0000005
DpPonyfish												
ShSmFish	0.00004	0.00027	0.00001	0.0021		0.00242	0.0000386	0.0000045	0.00001817	0.000021		0.0000825
DpSmFish												
ShMedFish	0.00001	0.00035		0.00955		0.00991	0.0000063	0.0000043	0.00000339	0.000097		0.0001105
DpMedFish				0.00296		0.00296	0.0000003		0.0000001	0.000030		0.0000303
ShLgFish	0.0000015	0.00008	0.0000014	0.01551		0.01559	0.0000015	0.0000022	0.00000716	0.00016		0.0001675
DpLgFish		0.00001	0.0000018			0.00001						
SessEpibenthos							0.0001214			0.00271		0.0028322
Megabenthos		0.0000002	0.00033			0.00033	0.0000028		0.00041155	0.0029		0.003354

	Landings 1987 (t/km^2)						Discards (t/km^2)					
Group Name	**Domestic trawl**	**Trap**	**Prawn trawl**	**Foreign trawl**	**Longline**	**Total**	**Domestic trawl**	**Trap**	**Prawn trawl**	**Foreign trawl**	**Longline**	**Total**
Macrofauna							0.0000003		0.00005018	0.00036		0.000409
ComPrawns			0.0053			0.0053						
Squid			0.00003	0.00112		0.00115			0.00015779	0.001122		0.0012793
LgZooplankton							0.0000055			0.000123		0.0001292
SmZooplankton												
Total	0.00006	0.00097	0.00568	0.06308	0.00456	0.07435	0.0003215	0.00002	0.00095	0.00788	0.00008	0.0091752

6.3 Species CPUE

Catch per unit effort, CPUE, per species per gear was calculated as the catch rate per unit effort corrected for area, t hr^{-1} km^{-2} yr^{-1}. The annual catch rates per species were added across the trawl-based gear types to give a total annual CPUE (Appendix C). Effort data for the line and trap fisheries were too highly uncertain and so the time series for these fisheries were not calculated. The effort data from the domestic fisheries were also quite unreliable. Estimates from 1995 showed an anomalously high rate and closer inspection of the data revealed probable errors in the effort records. Therefore, assuming those data to be incorrect, the CPUE for 1995 was therefore reduced by half to a value between those of the adjacent years. Similar errors were frequent in the data set therefore rendering the data highly unreliable (R. Little pers. comm. CSIRO). CPUE data was used only to guide impressions of the general trends of the stocks.

6.4 Fishery effort

The annual effort for each domestic fishery or gear type was calculated from CAES statistics. The reported boat days were converted to hours assuming that a trawl boat day was 16 hours, and trap and prawn trawl boat days were 12 hours (figure 6.4.1 (a)). Foreign data was as reported in Althaus et al. 2006.

For input into the model, efforts were calculated as hours per gear per year and were scaled relative to the first year entered into the model (table 6.4.1 and figure 6.4.1 (b)). However, the effort data were not validated and errors were known to exist in the data, therefore, care is needed in using this data to judge the model performance. By far the greatest effort came from the foreign trawl fleet which operated for three years before being excluded from the NWS. Foreign fishery effort about was two to three times greater than the domestic at its height. The domestic trawl fleet effort was extremely small in the early years of the fishery and so the increase in effort was relatively dramatic.

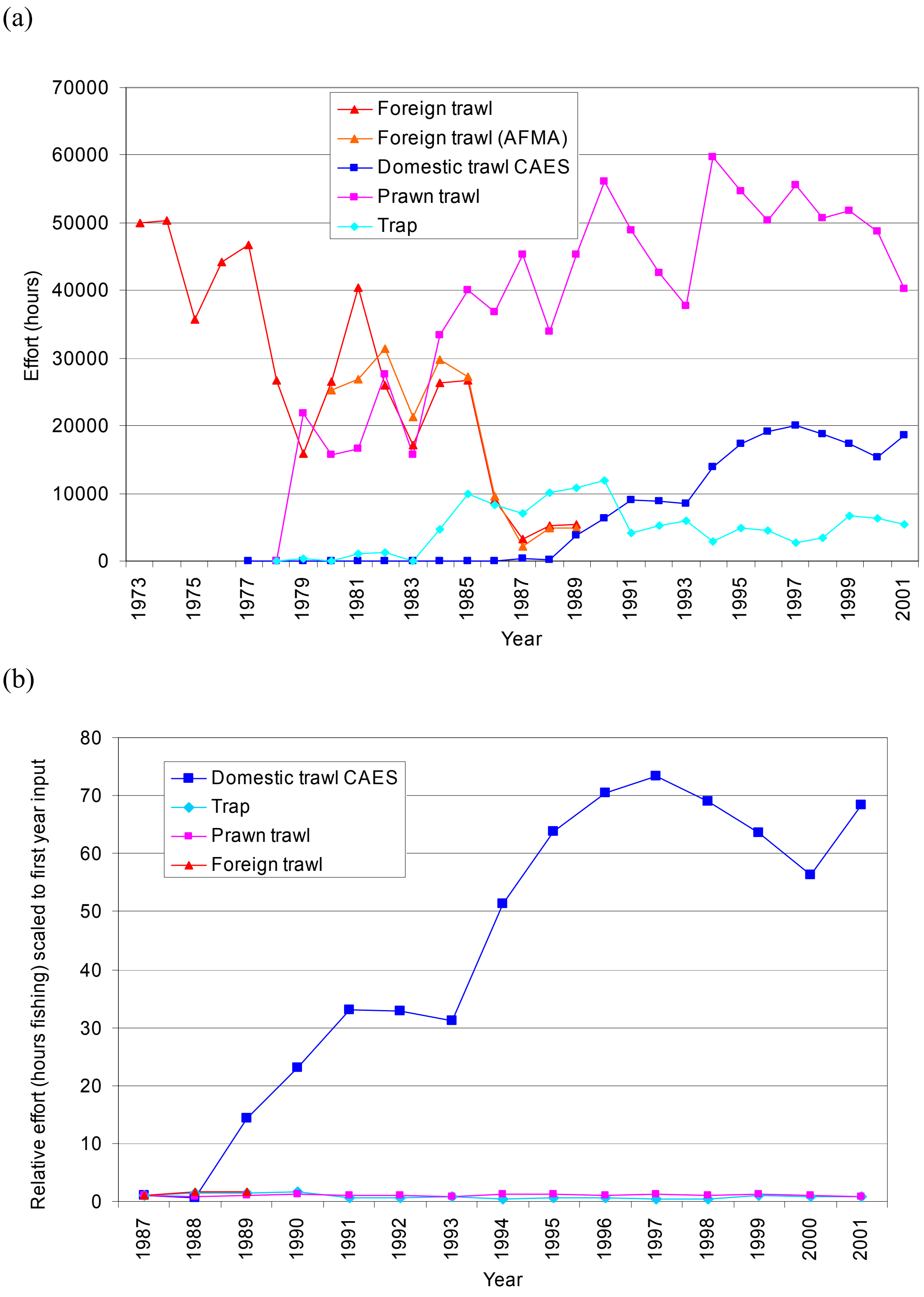


Figure 6.4.1: (a) Total effort per gear type in hours for foreign trawl fishery, (foreign and AFMA sources) and domestic trawl, prawn and trap fisheries (CAES statistics). The domestic data have not been validated and are likely to contain large errors. Effort in the domestic fishery was reported in boat days and was converted to hours, where trawl boat days = 16 hours and trap and prawn boat days = 12 hours.
(b) Effort time series for trawl and trap fisheries on the North West Shelf from 1987 to 2001 scaled relative to 1987 values.

Table 6.4.1: Annual effort per gear type, scaled relative to effort for 1987, and used as input into the model.

Year	Foreign trawl	Domestic trawl	Domestic trap	Prawn
1987	1.0000	1.0000	1.0000	1.0000
1988	1.6271	0.7059	1.4266	0.7485
1989	1.6817	14.2353	1.5126	1.0019
1990	-	23.0588	1.6678	1.2379
1991	-	33.1176	0.5953	1.0776
1992	-	32.7647	0.7268	0.9396
1993	-	31.1176	0.8246	0.8344
1994	-	51.2353	0.4182	1.3166
1995	-	63.8824	0.6745	1.2083
1996	-	70.4706	0.6324	1.1097
1997	-	73.2941	0.3710	1.2273
1998	-	69.0000	0.4789	1.1184
1999	-	63.5882	0.9376	1.1441
2000	-	56.2353	0.8870	1.0753
2001	-	68.3529	0.7707	0.8900

7. MODEL BALANCING

Balancing an *Ecopath* model means balancing the trophic flows within the defined system to be consistent with the observed growth and mortality patterns (Walters et al. 1997). If the model is out of balance, groups within it are out of balance which occurs when the total energy demand on a group exceeds its production (plus the energy needed for respiration). The ecotrophic efficiency (EE) of a group, i.e. the proportion of the group's production consumed by predators, the fishery and exported, indicates whether the group is unbalanced. When demand is greater than production, ecotrophic efficiency is greater than one, and indicates that input parameters have to be adjusted to achieve balance and reduce EE to less than one.

7.1 Strategy

The general approach to balancing the model was that adjustments were made iteratively and were largely to a balance of dietary and biomass values, with a few adjustments to production and consumption rates. The parameters were "pedigreed" by assigning a degree of confidence in each of the parameter values. This pedigree ranks the parameters according to the uncertainty of the value and is a useful tool in prioritising the amount of adjustment allowable. Overall, adjustments must be reasonable in view of the system and the specific parameters.

Generally, it is thought that the largest uncertainty is in the diet (V. Christensen in Okey & Mahmoudi, 2002) and slight adjustments in diet composition can often relieve the demand on prey groups and bring the solution into the feasible space where EE is less than one. Inspection of the consumption matrix revealed which predators placed the highest demand on a prey group whose EE was too high. Redistribution of the diet composition to reduce the consumption of the prey species was regarded as preferable to inflating the biomass of the prey species beyond the confidence limits of their estimates.

The biomass of red emperor obtained from stock assessments was used as an "anchor" by assuming high confidence in the value and not altering it. Some species biomasses, particularly the lower trophic groups such as the mega- and macrobenthos, were estimated by the program initially because there was either poor or no information about them, but wherever possible, a biomass was entered. "Top-down" adjustment can often result in over-inflation of lower trophic groups; however the primary producers and zooplankton groups were constrained as input and thus restricted potential over-inflation of the benthos groups.

Production and consumption rates were generally not altered, or were altered by very small increments only. The parameters for the aggregated groups were calculated by weighting each species' parameters according to their contribution to the group's composition and so, despite the constraint that the species should be of similar size and function and therefore have similar production and consumption parameters, a degree of flexibility would be expected. Consumption rates were mostly derived from Pauly's empirical formula which relies on an interpretation of the feeding style of the species.

7.2 The balanced Ecopath model

There were two major attempts to balance the model. The first attempt, using only the swept-area abundances calculated from the surveys, indicated that there was a large deficit of small fish in the model system. The second attempt used swept-area abundances for small fishes which were scaled by general or specific mesh selectivities derived from length frequency data. Using these data corrected for mesh selectivity it was possible to obtain a much better initial fit and obtain a balanced model with only few minor adjustments to diets and biomasses, all of which were within the level of uncertainty of those parameters (table 7.2.1).

After balancing, the overall biomass of fish required to balance the model was about 33 t km^{-2}. This is consistent with similar ecosystems elsewhere. For example, the West Florida Shelf has a total abundance of fish of about 28 t km^{-2}(Okey & Mahmoudi, 2002) and the Venezuelan shelf has a total of 44 t km^{-2} (Mendoza, 1993). At extreme ends of the scale are a Caribbean reef ecosystem estimated to have a fish biomass of 246 t km^{-2} (Optiz, 1993) while the Mexican shelf ecosystem was estimated at about 6 t km^{-2} (1.45 g dry wt 28 t km^{-2}: Sanchez et al. 1993). The Great Barrier Reef *Ecopath* model was based on a fish biomass of about 17 t km^{-2} (Gribble, 2000) although this might be underestimated (N. Gribble pers. comm. December 2003). However, as with all models, the authors do not assume that any specific numbers will be precise but that the general trends and indications will be realistic of the real ecosystem.

A dominant group in the ecosystem were the nemipterids. They represented more than 10% of the estimated fish biomass and consumed about 9% of all the fish consumed in the system (table 7.2.2). Lizardfishes were increased from the initial estimates to balance the model, to a value similar to that estimated using the selectivity of Liu et al. 1985. They represented only about 1.5% of fish biomass but their highly piscivorous diet meant that they consumed 4% of all fish consumed in the system, mostly small demersal and pelagic fish. In terms of biomass, the small pelagic and the small demersal fish groups were the largest, comprising 34% and 26% respectively of the fish biomass and were the most eaten (31% and 17% respectively of total consumption of fish in the system). Small pelagic fish group were responsible for 6% of the total fish consumption, even though they were mostly plankton feeders, because of their high biomass rather then the high proportion of fish in the diet composition. In addition, other small fish groups were also relatively abundant and, over all, the small fish categories accounted for at least three-quarters of the fish biomass. In contrast to the high biomasses of the small fish groups, the relatively low biomass of squid ate the highest proportion of all fish eaten (13%) as a result of their preference for small pelagic fishes.

Table 7.2.1: *Ecopath* balanced model parameters for the North West Shelf. TL = trophic level, B = biomass (t km^{-2}), P/B = total mortality, EE = ecological efficiency and P/Q = growth efficiency. Figures in bold are estimated by *Ecopath*. All fish biomasses except that of red emperor have been altered from the original survey abundance estimates during balancing.

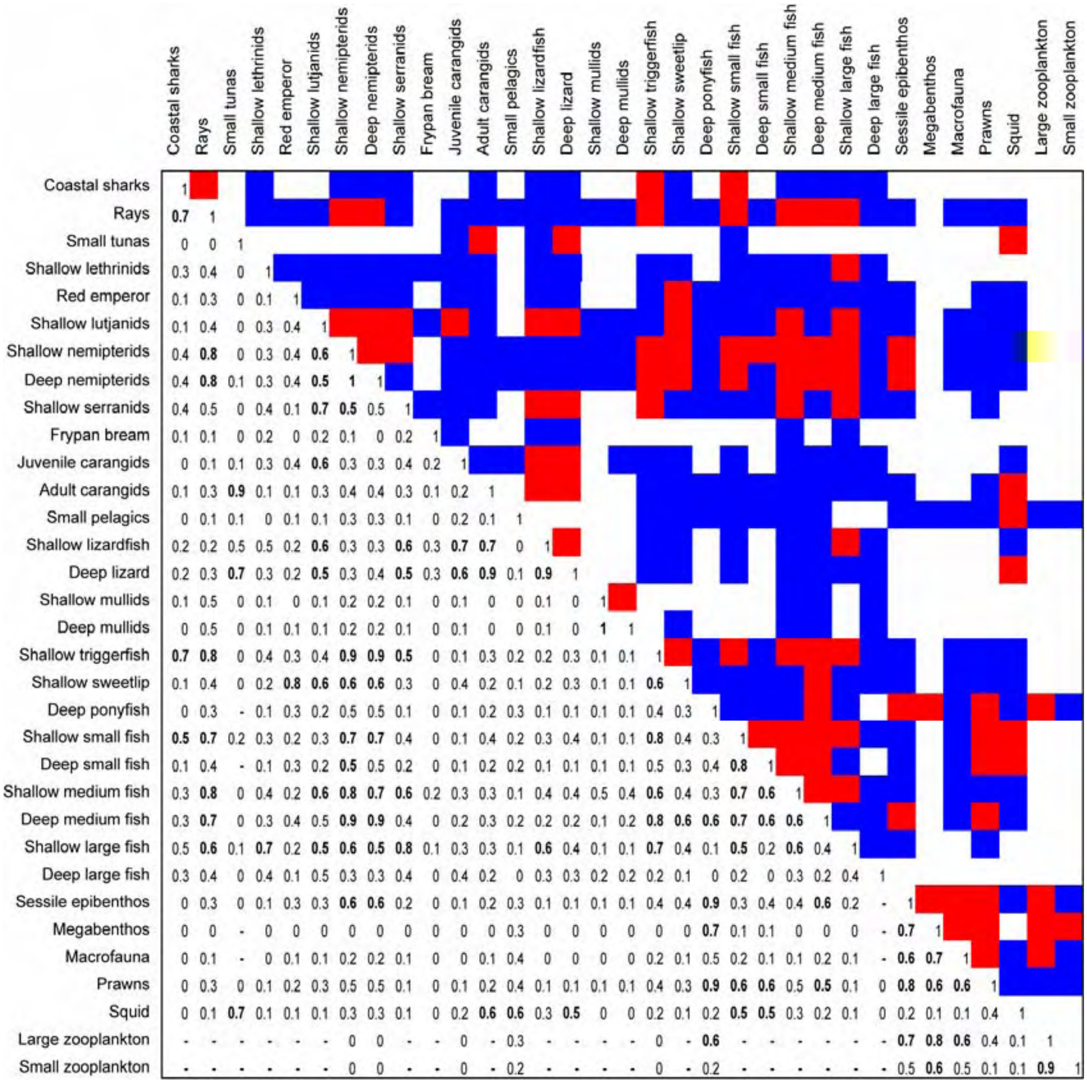
Trophic group	TL	B	P/B	Q/B	EE	P/Q
Coastal sharks	3.17	0.0300	0.330	3.8	**0.090**	**0.087**
Rays	3.30	0.0902	0.190	2.440	**0.001**	**0.078**
Small tunas	3.92	0.0970	0.550	5.240	**0.111**	**0.105**
Shallow lethrinids	4.03	0.139	0.450	7.220	**0.705**	**0.062**
Red emperor	3.45	0.119	0.490	4.600	**0.190**	**0.107**
Shallow lutjanids	3.96	0.265	0.440	5.880	**0.715**	**0.068**
Shallow nemipterids	3.41	2.434	0.900	10.020	**0.932**	**0.090**
Deep nemipterids	3.45	0.973	0.900	9.200	**0.619**	**0.098**
Shallow serranids	4.23	0.0290	0.440	5.000	**0..331**	**0.064**
Frypan bream	4.34	0.0490	0.370	4.500	**0.236**	**0.082**
Juvenile carangids	3.85	0.735	0.600	5.520	**0.928**	**0.109**
Adult carangids	3.94	0.954	0.600	2.988	**0.004**	**0.201**
Small pelagic fish	2.90	**11.341**	2.050	10.210	0.963	**0.201**
Shallow lizardfish	4.23	0.355	0.740	7.100	**0.271**	**0.104**
Deep lizardfish	4.18	0.116	0.660	7.300	**0.830**	**0.090**
Shallow mullids	3.59	1.843	1.050	13.610	**0.692**	**0.077**
Deep mullids	3.58	3.297	1.70	9.70	**0.272**	**0.175**
Trigger fish	3.13	0.175	0.57	5.600	**0.729**	**0.102**
Sweetlips	3.54	0.111	0.450	5.000	**0.114**	**0.090**
Pony fish	2.51	0.920	2.070	24.000	**0.987**	**0.086**
Shallow small fish	3.13	5.975	1.110	11.180	**0.999**	**0.099**
Deep small fish	3.17	2.500	1.780	12.960	**0.956**	**0.137**
Shallow medium fish	3.52	0.348	0.710	9.550	**0.995**	**0.074**
Deep medium fish	3.42	0.0680	0.600	6.490	**0.849**	**0.092**
Shallow large fish	3.89	0.243	0.42	6.150	**0.202**	**0.068**
Deep large fish	4.56	0.00200	0.36	4.000	**0.016**	**0.090**
Sessile epibenthos	2.49	**6.874**	0.800	12.000	0.927	**0.067**
Megabenthos	2.12	**11.818**	3.100	20.000	0.913	**0.155**
Macrofauna	2.17	**166.02**	2.900	10.000	0.726	**0.290**
Commercial prawns	2.61	**7.61**	7.570	37.900	0.965	**0.200**
Squid	3.42	**1.603**	4.590	17.550	0.783	**0.262**
Large zooplankton	2.11	**9.176**	20.000	40.000	0.661	**0.500**
Small zooplankton	2.11	30.000	40.000	80.000	**0.381**	**0.500**
Pelagic phytoplankton	1.00	35.000	240.000	-	**0.270**	-
Benthic phytoplankton	1.00	40.000	20.000	-	**0.679**	-
Microphytobenthos	1.00	24.000	24.000	-	**0.964**	-
Detritus	1.00	100.000	-	-	**0.115**	-

Table 7.2.2: Relative importance of trophic groups as proportions of the total estimated fish biomass in the NWS system and as proportions of fish eaten in the system.

Trophic group	Proportion of fish biomass	Proportion of total consumed fish	Proportion of total fish consumed by group
Coastal sharks	0.001	0.0004	0.0001
Rays	0.003	0.0008	0.0001
Small tunas	0.003	0.0010	0.0064
Shallow lethrinids	0.004	0.0028	0.0044
Red emperor	0.004	0.0020	0.0052
Shallow lutjanids	0.008	0.0044	0.0150
Shallow nemipterids	0.074	0.0650	0.0549
Deep nemipterids	0.029	0.0275	0.0231
Shallow serranids	0.001	0.0005	0.0014
Frypan bream	0.001	0.0007	0.0027
Juvenile carangids	0.022	0.0109	0.0374
Adult carangids	0.029	0.0147	0.0330
Small pelagic fish	0.338	0.3104	0.0662
Shallow lizardfish	0.011	0.0090	0.0289
Deep lizardfish	0.004	0.0024	0.0104
Shallow mullids	0.056	0.0726	0.0130
Deep mullids	0.100	0.1354	0.0206
Trigger fish	0.005	0.0029	0.0003
Sweetlips	0.003	0.0020	0.0036
Pony fish	0.028	0.0574	0.0043
Shallow small fish	0.181	0.1728	0.0361
Deep small fish	0.076	0.0898	0.0122
Shallow medium fish	0.011	0.0086	0.0103
Deep medium fish	0.002	0.0012	0.0010
Shallow large fish	0.007	0.0049	0.0094
Deep large fish	0.000	0.0000	0.0001
Commercial prawns		0.7718	0.0075
Squid		0.0934	0.1309

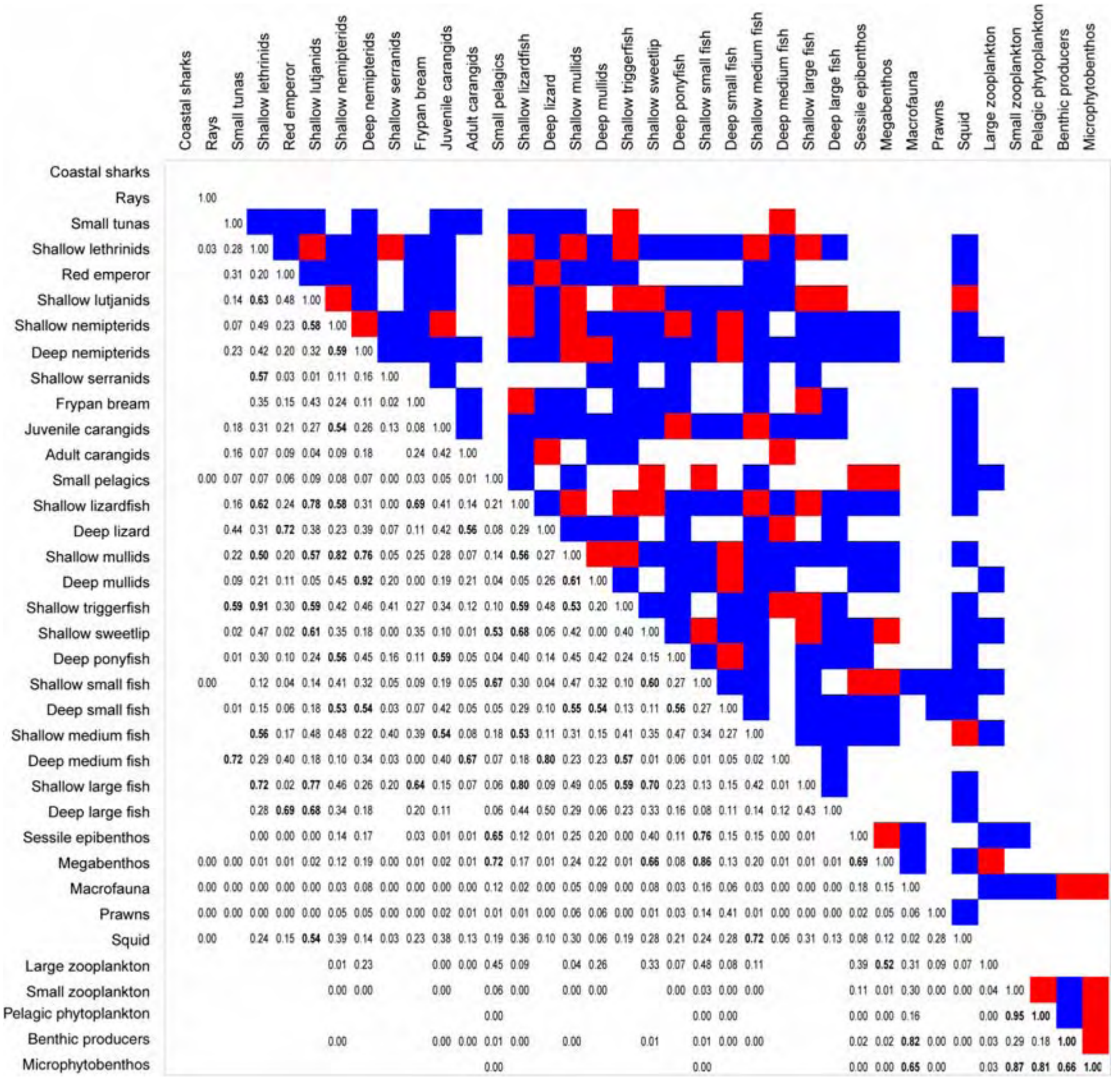
7.3 Overlap indices

The predator and prey overlap matrices indicate which pairs of predators or prey either have the most similar prey or predators respectively. Some groups overlap not only in what they eat but also what eats them. A value of one indicates complete overlap in either shared resources or predators while zero indicates no overlap. In general shallow and deep species of the same family eat similar prey; however they usually have different predators. For instance deep and shallow lizardfish share 95% of prey (figure 7.3.1) but do not overlap with their predators. The lutjanids, deep and shallow nemipterids and serranids all overlap in their diet (figure 7.3.2) but only shallow nemipterids and shallow lutjanids and deep nemipterids are eaten by the same predators. To a large extent, the overlap indices depend on the quality of the dietary data, and the categorisation of the model. Since lower trophic levels are not usually well-specified and even the some of the aggregated fish groups could contain dozens of species, the overlap indices lose value. However in the groups representing single or only a few species the indices may be reasonably informative.



	Coastal sharks	Rays	Small tunas	Shallow lethrinids	Red emperor	Shallow lutjanids	Shallow nemipterids	Deep nemipterids	Shallow serranids	Frypan bream	Juvenile carangids	Adult carangids	Small pelagics	Shallow lizardfish	Deep lizard	Shallow mullids	Deep mullids	Shallow triggerfish	Shallow sweetlip	Deep ponyfish	Shallow small fish	Deep small fish	Shallow medium fish	Deep medium fish	Shallow large fish	Deep large fish	Sessile epibenthos	Megabenthos	Macrofauna	Prawns	Squid	Large zooplankton	Small zooplankton
Coastal sharks	1																																
Rays	0.7	1																															
Small tunas	0	0	1																														
Shallow lethrinids	0.3	0.4	0	1																													
Red emperor	0.1	0.3	0	0.1	1																												
Shallow lutjanids	0.1	0.4	0	0.3	0.4	1																											
Shallow nemipterids	0.4	0.8	0	0.3	0.4	0.6	1																										
Deep nemipterids	0.4	0.8	0.1	0.3	0.4	0.5	1	1																									
Shallow serranids	0.4	0.5	0	0.4	0.1	0.7	0.5	0.5	1																								
Frypan bream	0.1	0.1	0	0.2	0	0.2	0.1	0	0.2	1																							
Juvenile carangids	0	0.1	0.1	0.3	0.4	0.6	0.3	0.3	0.4	0.2	1																						
Adult carangids	0.1	0.3	0.9	0.1	0.1	0.3	0.4	0.4	0.3	0.1	0.2	1																					
Small pelagics	0	0.1	0.1	0	0.1	0.1	0.3	0.3	0.1	0	0.2	0.1	1																				
Shallow lizardfish	0.2	0.2	0.5	0.5	0.2	0.6	0.3	0.3	0.6	0.3	0.7	0.7	0	1																			
Deep lizard	0.2	0.3	0.7	0.3	0.2	0.5	0.3	0.4	0.5	0.3	0.6	0.9	0.1	0.9	1																		
Shallow mullids	0.1	0.5	0	0.1	0	0.1	0.2	0.2	0.1	0	0.1	0	0	0.1	0	1																	
Deep mullids	0	0.5	0	0.1	0.1	0.1	0.2	0.2	0.1	0	0.1	0	0	0.1	0	1	1																
Shallow triggerfish	0.7	0.8	0	0.4	0.3	0.4	0.9	0.9	0.5	0	0.1	0.3	0.2	0.2	0.3	0.1	0.1	1															
Shallow sweetlip	0.1	0.4	0	0.2	0.8	0.6	0.6	0.6	0.3	0	0.4	0.2	0.1	0.2	0.3	0.1	0.1	0.6	1														
Deep ponyfish	0	0.3	-	0.1	0.3	0.2	0.5	0.5	0.1	0	0.1	0.2	0.3	0.1	0.1	0.1	0.1	0.4	0.3	1													
Shallow small fish	0.5	0.7	0.2	0.3	0.2	0.3	0.7	0.7	0.4	0	0.1	0.4	0.2	0.3	0.4	0.1	0.1	0.8	0.4	0.3	1												
Deep small fish	0.1	0.4	-	0.1	0.3	0.2	0.5	0.5	0.2	0	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.5	0.3	0.4	0.8	1											
Shallow medium fish	0.3	0.8	0	0.4	0.2	0.6	0.8	0.7	0.6	0.2	0.3	0.3	0.1	0.4	0.4	0.5	0.4	0.6	0.4	0.3	0.7	0.6	1										
Deep medium fish	0.3	0.7	0	0.3	0.4	0.5	0.9	0.9	0.4	0	0.2	0.3	0.2	0.2	0.2	0.1	0.2	0.8	0.6	0.6	0.7	0.6	0.6	1									
Shallow large fish	0.5	0.6	0.1	0.7	0.2	0.5	0.6	0.5	0.8	0.1	0.3	0.3	0.1	0.6	0.4	0.1	0.1	0.7	0.4	0.1	0.5	0.2	0.6	0.4	1								
Deep large fish	0.3	0.4	0	0.4	0.1	0.5	0.3	0.3	0.4	0	0.4	0.2	0	0.3	0.3	0.2	0.2	0.2	0.1	0	0.2	0	0.3	0.2	0.4	1							
Sessile epibenthos	0	0.3	0	0.1	0.3	0.3	0.6	0.6	0.2	0	0.1	0.2	0.3	0.1	0.1	0.1	0.1	0.4	0.4	0.9	0.3	0.4	0.4	0.6	0.2	-	1						
Megabenthos	0	0	-	0	0	0	0	0	0	0	0	0	0.3	0	0	0	0	0	0	0.7	0.1	0.1	0	0	0	-	0.7	1					
Macrofauna	0	0.1	-	0	0.1	0.1	0.2	0.2	0.1	0	0	0.1	0.4	0	0	0	0	0.2	0.1	0.5	0.2	0.1	0.1	0.2	0.1	-	0.6	0.7	1				
Prawns	0	0.3	0	0.1	0.2	0.3	0.5	0.5	0.1	0	0.1	0.2	0.4	0.1	0.1	0.1	0.1	0.4	0.3	0.9	0.6	0.6	0.5	0.5	0.1	0	0.8	0.6	0.6	1			
Squid	0	0.1	0.7	0.1	0.1	0.1	0.3	0.3	0.1	0	0.2	0.6	0.6	0.3	0.5	0	0	0.2	0.1	0.2	0.5	0.5	0.3	0.2	0.1	0	0.2	0.1	0.1	0.4	1		
Large zooplankton	-	-	-	-	-	-	0	0	-	-	0	-	0.3	-	-	-	-	0	-	0.6	-	-	-	-	-	-	0.7	0.8	0.6	0.4	0.1	1	
Small zooplankton	-	-	-	-	-	-	0	0	-	-	0	-	0.2	-	-	-	-	0	-	0.2	-	-	-	-	-	-	0.5	0.6	0.5	0.1	0.1	0.9	1

Figure 7.3.1: Prey overlap. Blue squares are values between 0.1and 0.5 and red are ≥0.5 (high overlap).



	Coastal sharks	Rays	Small tunas	Shallow lethrinids	Red emperor	Shallow lutjanids	Shallow nemipterids	Deep nemipterids	Shallow serranids	Frypan bream	Juvenile carangids	Adult carangids	Small pelagics	Shallow lizardfish	Deep lizard	Shallow mullids	Deep mullids	Shallow triggerfish	Shallow sweetlip	Deep ponyfish	Shallow small fish	Deep small fish	Shallow medium fish	Deep medium fish	Shallow large fish	Deep large fish	Sessile epibenthos	Megabenthos	Macrofauna	Prawns	Squid	Large zooplankton	Small zooplankton	Pelagic phytoplankton	Benthic producers	Microphytobenthos
Coastal sharks																																				
Rays		1.00																																		
Small tunas			1.00																																	
Shallow lethrinids		0.03	0.28	1.00																																
Red emperor			0.31	0.20	1.00																															
Shallow lutjanids			0.14	**0.63**	0.48	1.00																														
Shallow nemipterids			0.07	0.49	0.23	**0.58**	1.00																													
Deep nemipterids			0.23	0.42	0.20	0.32	**0.59**	1.00																												
Shallow serranids				**0.57**	0.03	0.01	0.11	0.16	1.00																											
Frypan bream				0.35	0.15	0.43	0.24	0.11	0.02	1.00																										
Juvenile carangids			0.18	0.31	0.21	0.27	**0.54**	0.26	0.13	0.08	1.00																									
Adult carangids			0.16	0.07	0.09	0.04	0.09	0.18		0.24	0.42	1.00																								
Small pelagics		0.00	0.07	0.07	0.06	0.09	0.08	0.07	0.00	0.03	0.05	0.01	1.00																							
Shallow lizardfish			0.16	**0.62**	0.24	**0.78**	**0.58**	0.31	0.00	**0.69**	0.41	0.14	0.21	1.00																						
Deep lizard			0.44	0.31	**0.72**	0.38	0.23	0.39	0.07	0.11	0.42	**0.56**	0.08	0.29	1.00																					
Shallow mullids			0.22	**0.50**	0.20	**0.57**	**0.82**	**0.76**	0.05	0.25	0.28	0.07	0.14	**0.56**	0.27	1.00																				
Deep mullids			0.09	0.21	0.11	0.05	0.45	**0.92**	0.20	0.00	0.19	0.21	0.04	0.05	0.26	**0.61**	1.00																			
Shallow triggerfish			**0.59**	**0.91**	0.30	**0.59**	0.42	0.46	0.41	0.27	0.34	0.12	0.10	**0.59**	0.48	**0.53**	0.20	1.00																		
Shallow sweetlip			0.02	0.47	0.02	**0.61**	0.35	0.18	0.00	0.35	0.10	0.01	**0.53**	**0.68**	0.06	0.42	0.00	0.40	1.00																	
Deep ponyfish			0.01	0.30	0.10	0.24	**0.56**	0.45	0.16	0.11	**0.59**	0.05	0.04	0.40	0.14	0.45	0.42	0.24	0.15	1.00																
Shallow small fish		0.00		0.12	0.04	0.14	0.41	0.32	0.05	0.09	0.19	0.05	**0.67**	0.30	0.04	0.47	0.32	0.10	**0.60**	0.27	1.00															
Deep small fish			0.01	0.15	0.06	0.18	**0.53**	**0.54**	0.03	0.07	0.42	0.05	0.05	0.29	0.10	**0.55**	**0.54**	0.13	0.11	**0.56**	0.27	1.00														
Shallow medium fish				**0.56**	0.17	0.48	0.48	0.22	0.40	0.39	**0.54**	0.08	0.18	**0.53**	0.11	0.31	0.15	0.41	0.35	0.47	0.34	0.27	1.00													
Deep medium fish			**0.72**	0.29	0.40	0.18	0.10	0.34	0.03	0.00	0.40	**0.67**	0.07	0.18	**0.80**	0.23	0.23	**0.57**	0.01	0.06	0.01	0.05	0.02	1.00												
Shallow large fish				**0.72**	0.02	**0.77**	0.46	0.26	0.20	**0.64**	0.15	0.07	0.06	**0.80**	0.09	0.49	0.05	**0.59**	**0.70**	0.23	0.13	0.15	0.42	0.01	1.00											
Deep large fish				0.28	**0.69**	**0.68**	0.34	0.18		0.20	0.11		0.06	0.44	0.50	0.29	0.06	0.23	0.33	0.16	0.08	0.11	0.14	0.12	0.43	1.00										
Sessile epibenthos				0.00	0.00	0.00	0.14	0.17		0.03	0.01	0.01	**0.65**	0.12	0.01	0.25	0.20	0.00	0.40	0.11	**0.76**	0.15	0.15	0.00	0.01		1.00									
Megabenthos		0.00	0.00	0.01	0.01	0.02	0.12	0.19	0.00	0.01	0.02	0.01	**0.72**	0.17	0.01	0.24	0.22	0.01	**0.66**	0.08	**0.86**	0.13	0.20	0.01	0.01	0.01	**0.69**	1.00								
Macrofauna		0.00	0.00	0.00	0.00	0.00	0.03	0.08	0.00	0.00	0.00	0.00	0.12	0.02	0.00	0.05	0.09	0.00	0.08	0.03	0.16	0.06	0.03	0.00	0.00	0.00	0.18	0.15	1.00							
Prawns		0.00	0.00	0.00	0.00	0.00	0.05	0.05	0.00	0.00	0.02	0.01	0.01	0.01	0.00	0.06	0.06	0.00	0.01	0.03	0.14	0.41	0.01	0.00	0.00	0.00	0.02	0.05	0.06	1.00						
Squid		0.00		0.24	0.15	**0.54**	0.39	0.14	0.03	0.23	0.38	0.13	0.19	0.36	0.10	0.30	0.06	0.19	0.28	0.21	0.24	0.28	**0.72**	0.06	0.31	0.13	0.08	0.12	0.02	0.28	1.00					
Large zooplankton							0.01	0.23			0.00	0.00	0.45	0.09		0.04	0.26		0.33	0.07	0.48	0.08	0.11				0.39	**0.52**	0.31	0.09	0.07	1.00				
Small zooplankton							0.00	0.00			0.00		0.06	0.00		0.00	0.00			0.00	0.03	0.00	0.00				0.11	0.01	0.30	0.00	0.00	0.04	1.00			
Pelagic phytoplankton													0.00								0.00	0.00					0.00	0.00	0.16			0.00	**0.95**	**1.00**		
Benthic producers							0.00				0.00	0.00	0.01	0.00		0.00			0.01		0.01	0.00	0.00				0.02	0.02	**0.82**	0.00	0.00	0.03	0.29	0.18	**1.00**	
Microphytobenthos													0.00								0.00						0.00	0.00	**0.65**	0.00		0.03	**0.87**	**0.81**	**0.66**	**1.00**

Figure 7.3.2: Predator overlap. Blue squares are values between 0.1 and 0.5 and red are ≥0.5 (high overlap).

7.4 System analyses

Various system statistics can be estimated for a balanced *Ecopath* model but since they are dependent on the structure of the model, interpretation and comparison with other models of either the same system under different conditions or other systems can be rather futile. However some statistics can be informative. For instance, the trend of the average trophic level of a fishery over time has been used to indicate potential problems with overfishing. The average trophic level of the NWS fishery, as calculated by *Ecopath*, was 3.64 (table 7.4.1) in 1987, indicating that the fishes caught were mostly medium to top predators. An estimate of the trophic level of the catch in 1973 was 3.65, however the estimated value for 1987 was 3.57 in contrast to the model estimate of 3.27. In contrast, the mean trophic level of the Gulf of Thailand fishery was considerably lower, 3.12, in 1963 when the fishery there was developing, and further declined to 3.01 over about the following 20 years of fishing (Christensen, 1998). This decrease in mean trophic level was caused by overfishing of the larger fishes, even though the concurrent fishing of smaller fish in the Gulf of Thailand fishery would be expected to mitigate such a decline to some extent. A decline in mean trophic level was also found in the Bering Sea fishery from a 3.44 in the 1950s to 3.3 in the 1980s (Trites et al. 1999). Globally, mean trophic level of fishery landings has declined despite the complications inherent in the calculations (Pauly et al. 1998) indicating a general shift from the larger, apex predator fishes to smaller, mid-trophic level ones.

Table 7.4.1: System analysis of *Ecopath* model for North West Shelf. Full explanation of the terms used and the relation to development of ecosystems (*sensu* Odum, 1969) can be found in Christensen et al. 2002.

Parameter		
Sum of all consumption	5397.680	t km^{-2}year^{-1}
Sum of all exports	7475.389	t km^{-2}year^{-1}
Sum of all respiratory flows	2300.591	t km^{-2}year^{-1}
Sum of all flows into detritus	8445.357	t km^{-2}year^{-1}
Total system throughput	23619.00	t km^{-2}year^{-1}
Sum of all production	11793.00	t km^{-2}year^{-1}
Mean trophic level of the catch	3.25	
Gross efficiency (catch/net p.p.)	0.000013	
Calculated total net primary production	9776.000	t km^{-2}year^{-1}
Total primary production/total respiration	4.249	
Net system production	7475.409	t km^{-2}year^{-1}
Total primary production/total biomass	26.854	
Total biomass/total throughput	0.015	
Total biomass (excluding detritus)	364.039	t km^{-2}
Total catches	0.126	t km^{-2}year^{-1}
Connectance Index	0.257	
System Omnivory Index	0.185	

Table 7.4.2: Trophic level (TL) of the fishery based on total catch over all fishery fleets (kg). TL of the fishery was calculated by weighting the TL of each trophic group by its proportion of its contribution to the total catch and then summing across all trophic groups.

Year	Trophic level of catch
1973	3.65204
1974	3.62497
1975	3.71480
1976	3.68109
1977	3.67854
1978	3.70207
1979	3.63843
1980	3.68529
1981	3.68743
1982	3.68430
1983	3.66759
1984	3.63124
1985	3.64551
1986	3.61829
1987	3.57218
1988	3.51029
1989	3.54409
1990	2.82801
1991	2.79763
1992	3.07605
1993	3.29857
1994	3.19945
1995	3.31945
1996	3.43903
1997	3.40596
1998	3.40096
1999	3.27840
2000	3.38390
2001	3.48787

The NWS catches were relatively small and focused on the higher predators but it must be remembered that the foreign fishery was only about a tenth of its original effort and the domestic trawl fishery was in its infancy. Consequently, the gross efficiency of the fishery (1.3×10^{-5}, table 7.4.1) was only 0.65% of the weighted average of global fisheries (2×10^{-3}, Trites et al. 1999) but at the height of the foreign fishery this may not have been the case. While low values usually indicate specialisation on apex predators, in this case the low value is also due to the relatively low catches compared to the fish biomass available. Monitoring gross efficiency of the fishery over time provides an indication of the changes in the ecosystem and fishery, but care is needed in its interpretation. The gross efficiency of the Bering Sea fishery increased ten-fold over a 30 year period, but not from the classical "fishing down the food web" effect but rather from a change in fishery targeting between species with different diets at the same trophic level (Trites et al. 1999).

Maturity of the system, *sensu* Odum (1969), can be inferred from a variety of system statistics. However, the NWS system has been disturbed by fishing prior to the initial model condition and so is expected to return indices that suggest “immaturity” or, perhaps more correctly, a loss of maturity. This effect has been demonstrated by Christensen (1995) for models of Lake Tanganyika and Laguna de Bay, Philippines. The total primary production to respiration ratio for the NWS is 4.5 (table 7.4.1), i.e. primary production exceeds respiration by a relatively high value compared to the majority of 41 systems evaluated by Christensen and Pauly (1993). Values approaching one indicate a mature ecosystem, where the primary production of the system balances the respiration of the biomass. However respiration is not reliably calculated by *Ecopath* and so the total primary production to respiration ratio is considered to be a less reliable measure of system maturity than the others discussed below (Christensen, 1995).

The net system production for this system was 9 776 t km^{-2} year^{-1} (table 7.4.1) also being indicative of an immature system (Christensen et al. 2000). This value is relatively high compared to a variety of ecosystems cited in Trites et al. (1999). The biomass/throughput ratio should also increase as a system approaches maturity. Throughput is the sum of all flows in a system, i.e. total consumption + total export + total respiration + total flows to detritus. The total biomass supported by this flow is expected to increase as the system matures. The value for the NWS system of 0.015 is relatively small, and also supports the interpretation that this system is immature (table 7.4.1). It is similar to values for the Gulf of Mexico, Alaskan Gyre, slightly lower than Brunei, but an order of magnitude lower than that for the British Columbian shelf.

Primary production to biomass ratios are also difficult to compare since the primary production regimes in each system are different. Furthermore, systematic changes in primary production over time will also contribute to sometimes unexpected changes in this ratio. For example the ratio for the Bering Sea indicated that the system was maturing from the 1950s to 1980s, but in reality, primary production increased resulting in the decline in the ratio when an increase was expected (Trites et al. 1999).

Relatively simple linear food chains are characteristic of developing or immature ecosystems whereas more complex networks or food-webs are characteristic of mature systems (Odum, 1969). The connectance index indicates the degree of web-like links between predator and prey. However it is dependent on the taxonomic detail of the model, and although it is possible to compare the same system with the same level of taxonomic detail at different times it is not useful to compare between systems. The system omnivory index was devised as an alternative and measures how the feeding interactions are distributed within trophic levels. It is the average omnivory index of all consumers weighted by the log of their food intake (Christensen et al. 2000). An individual’s omnivory index is zero if the predator is very specialised and feeds on a single trophic level but increases if it feeds on many. However, there appears to be no direct correlation with system maturity (Christensen & Pauly, 1993).

8. TEMPORAL SIMULATIONS WITH ECOSIM

The model was run for a period of 30 years for each scenario using *Ecosim*, the temporal simulation module. The reference time series existed only for the first 15 years, i.e. from 1987 though to 2001. For the following 15 years three scenarios were investigated:

- fishing effort remained at the 2001 level (figure 8.1 (a));
- fishing effort was increased 25% over 5 years and then reduced to 50 % below the 2001 level over the last 10 years (figure 8.1 (b)); or
- fishing effort was reduced to 50% of the 2001 level over the 15 years (figure 8.1 (c)).

After year three, foreign trawling had finished but domestic trawl effort had increased by over 70 times (table 6.1.2).

Biomass estimates from the 1995 and 1997 research survey estimates, CPUE data, fishing gear effort, and catch and species F data were used as reference time series data to assess the model fit to the observed data series. The gear effort for all fisheries except the longline fishery and the species F rates drove the model, the gear effort taking precedence where available. Flow control, biomass accumulation and some minor re-assessment of dietary relationships were changed iteratively to improve the fit of the model to the time series data and the expected trajectories of the predictions.

8.1 Flow control

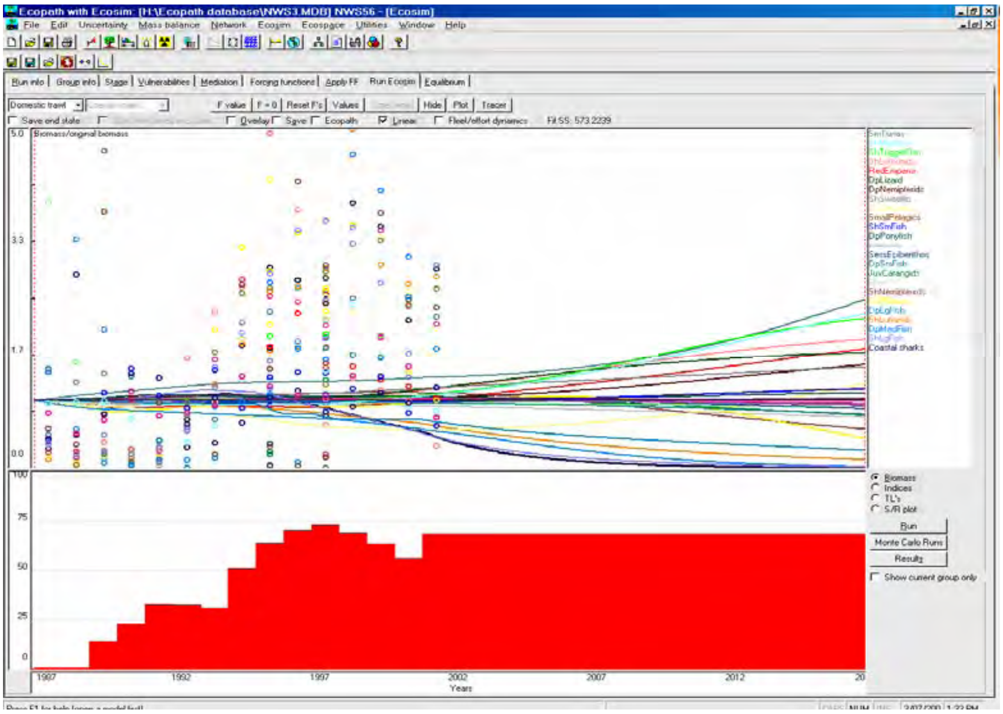
To model a more realistic system where bottom-up and top-down control was variable, the standard model formulation was used where vulnerability was calculated and assigned according to the trophic level of each functional group (table 8.1.1). This led to slight instability over a long period of time (100 years) which was stabilised by reducing the vulnerability of the mullidae groups to the default value of two, a level where control is mixed.

Table 8.1.1: Vulnerability settings for trophic groups in NWS *Ecosim* model based on trophic level. Levels for the mullidae groups were reduced to the default level of two to stabilise the numerical instability.

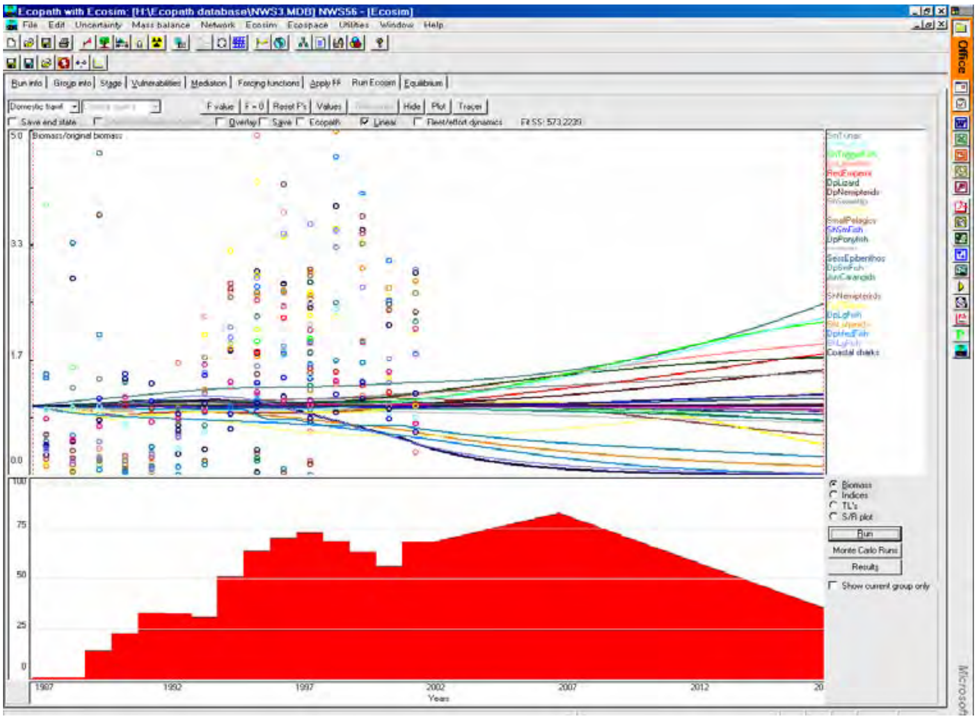
Species	Vulnerability
Coastal sharks	5.2
Rays	5.7
Small tunas	7.9
Lethrinids	8.3
Red emperor	6.3
Lutjanids	8.1
Shallow nemipterids	6.1
Deep nemipterids	6.2
Serranids	9
Frypan bream	9.5
Juvenile/small carangids	7.7
Ad/large carangids	8
Small pelagics	4.3
Shallow lizardfish	9
Deep lizardfish	8.9
Shallow mullidae	2
Deep mullidae	2
Triggerfish	5.2
Sweetlip	6.6
Ponyfish	2.9
Shallow small fish	5.1
Deep small fish	5.2
Shallow medium fish	6.5
Deep medium fish	6.1
Shallow large fish	3
Deep large fish	2.8
Sessile epibenthos	2.8
Megabenthos	1.4
Macrofauna	1.6
Commercial prawns	3.2
Squid	6.1
Large zooplankton	1.4
Small zooplankton	1.4

8.2 Biomass accumulation

It was considered that the system was declining during the period when the model was constructed. Christensen (1995) found that in a similar situation in the North Sea, biomass accumulation terms were needed to account for the changing biomasses. Although fishing pressure declined with the exclusion of the foreign trawl fishery, a very small biomass accumulation rate was allowed for red emperor, lethrinids, lutjanids, nemipterids, serranids, and medium-size demersal fish to better match the presumed trends in their respective population sizes.

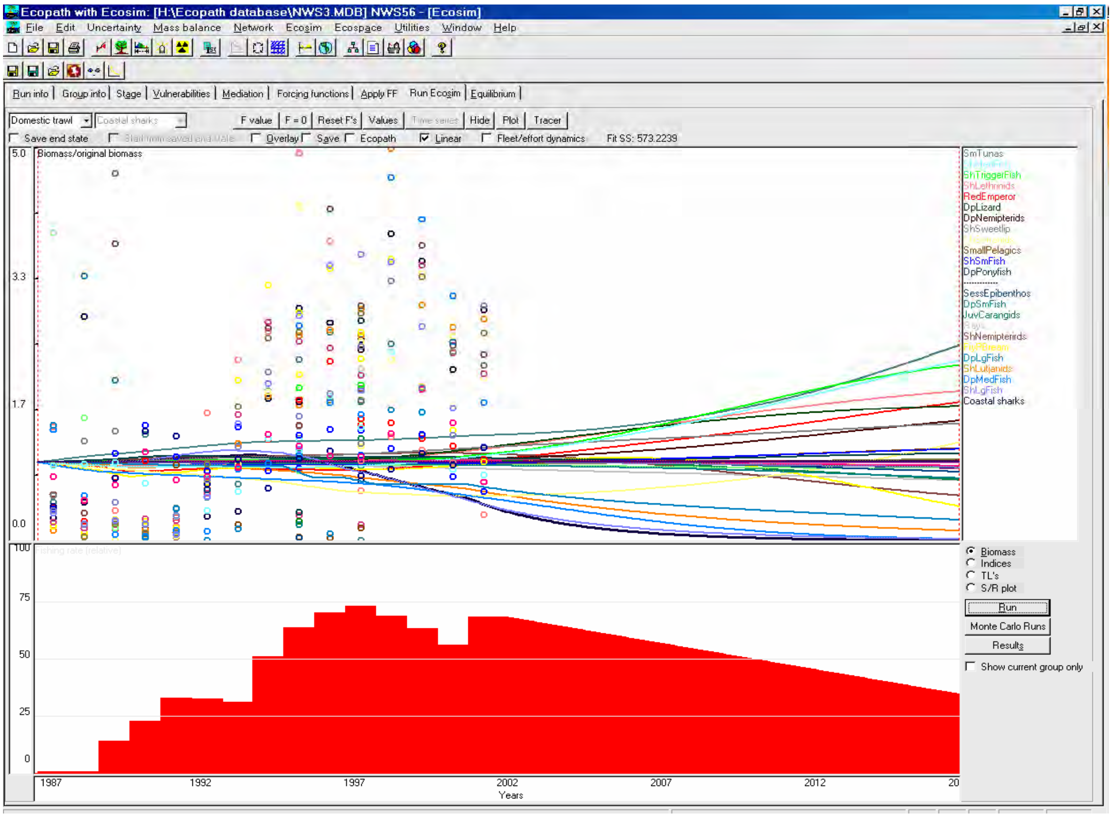


(a)



(b)

Figure 8.1: *Ecosim* output for 30 years simulation where (a) all fishery effort remains at 2001 level, (b) the domestic trawl effort is increased by 25% over 5 years and then reduced by 50% below 2001 level until end of run. Lower panes show the fishing effort trajectory in red for the domestic trawl fishery scaled relative to 1. Upper panes show the resulting biomass trajectories from the model simulation. The trajectories are colour-coded with the species names in the right-side pane. The species whose trajectories deviate from the equilibrium line are listed in order from the top and bottom of the screen (NB not all groups are listed). The colour-coded dots correspond to the CPUE and biomass time series reference data which are used to tune individual species parameters to obtain a better fitting model to the observed data however the CPUE data was considered unreliable.



(c)

Figure 8.1 continued: (c) where domestic trawl effort is reduced to 50% over 15 years. Lower panes show the fishing effort trajectory in red for the domestic trawl fishery scaled relative to 1. Upper panes show the resulting biomass trajectories from the model simulation. The trajectories are colour-coded with the species names in the right-side pane. The species whose trajectories deviate from the equilibrium line are listed in order from the top and bottom of the screen (NB not all groups are listed). The colour-coded dots correspond to the CPUE and biomass time series reference data which are used to tune individual species parameters to obtain a better fitting model to the observed data however the CPUE data was considered unreliable.

Not all species could be well-tuned probably because spatial relationships were particularly important, e.g. strong habitat associations that were not being accounted for or for non-trophic influences that were not being modelled such as migration or environmental conditions. Development of the spatially explicit model and simulations are considered in the next section.

9. SPATIAL SIMULATIONS WITH ECOSPACE

Trophic sub-webs are contained in the model structure, i.e. shallow species feeding on shallow species, deep on deep, and some species feeding ubiquitously through the whole area, and these implicitly represent some spatial structure of the ecosystem. However this is a coarse treatment of spatial structure, and it does not explicitly represent the preferred spatial ranges of species and the effects of these on trophic interactions. A preliminary spatial model in *Ecospace* to account for these preferences was developed.

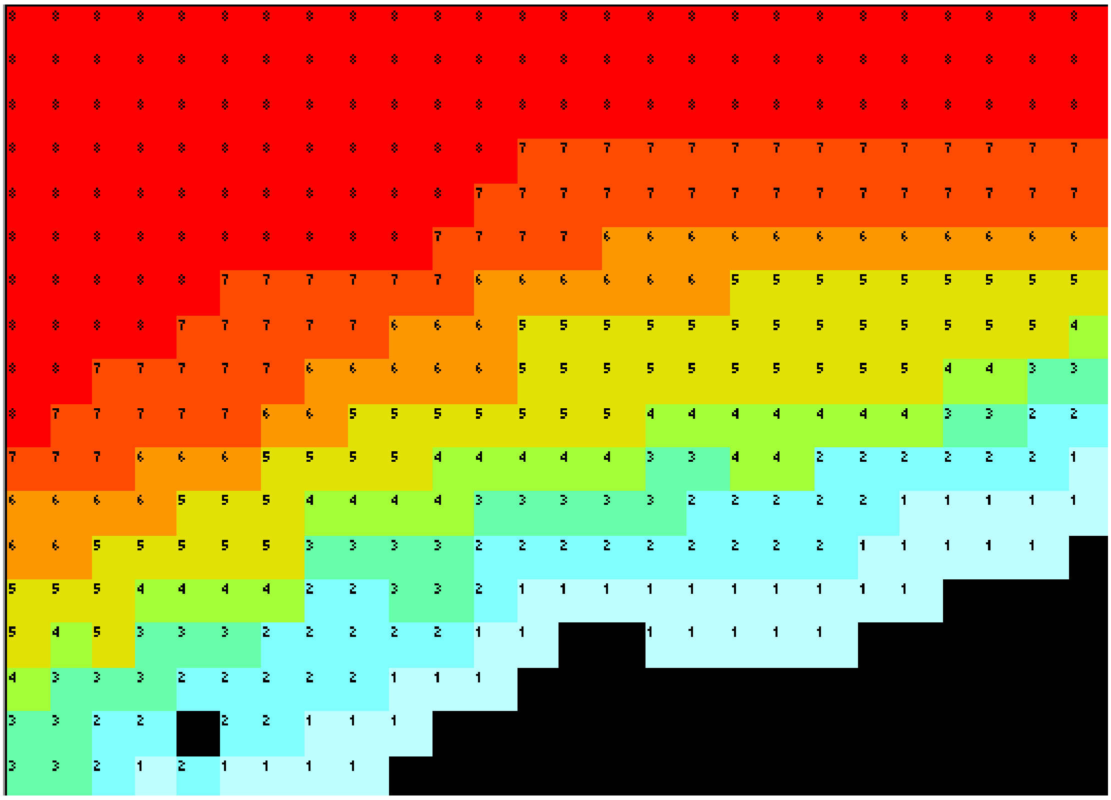
9.1 Habitat designation and species assignation

The study area was apportioned into habitats according to depth and benthos coverage (table 9.1.1; figure 9.1.1). Benthos coverage was determined by Althaus et al. (2006) from photographic surveys as the proportion of the bottom covered with benthos.

Table 9.1.1: Descriptions of depth and benthos coverage for each habitat defined in *Ecospace* model. The inner shelf and outer shelf habitats are outside the study boundaries.

Habitat	Description	Fraction of total area
0	All habitats (e.g. pelagic)	1.000
1	Inner shelf (<20 m)	0.096
2	20-50 m depth and 50% benthos coverage	0.101
3	50-120 m and 0-20% benthos coverage	0.066
4	50-120 m and 20-35% benthos coverage	0.066
5	50-120 m and 35-50% benthos coverage	0.138
6	50-120 m and >50% benthos coverage	0.091
7	120-200 m (<30% benthos coverage)	0.140
8	Off shelf (>200 m)	0.302

Species or species groups were assigned to habitats based on their occurrence from survey data and Althaus et al. (2006) (table 9.1.2). Species were assigned to a habitat if more than 10% of the total abundance occurred in that habitat. The inner and outer shelf habitats were outside the study boundaries and so species were not specifically allocated to them. However, this allows some dispersal into those areas even though they were not preferred types. Dispersal rate, predation and foraging outside preferred habitats were left as default values in *Ecospace*.



8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
8	8	8	8	8	8	8	8	8	8	8	8	7	7	7	7	7	7	7	7	7	7	7	7	7	7
8	8	8	8	8	8	8	8	8	8	8	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
8	8	8	8	8	8	8	8	8	8	7	7	7	7	6	6	6	6	6	6	6	6	6	6	6	6
8	8	8	8	8	7	7	7	7	7	7	6	6	6	6	6	6	5	5	5	5	5	5	5	5	5
8	8	8	8	7	7	7	7	7	6	6	6	5	5	5	5	5	5	5	5	5	5	5	5	5	4
8	8	7	7	7	7	7	6	6	6	6	6	5	5	5	5	5	5	5	5	5	5	4	4	3	3
8	7	7	7	7	7	6	6	5	5	5	5	5	5	5	4	4	4	4	4	4	4	3	3	2	2
7	7	7	6	6	6	5	5	5	5	4	4	4	4	4	3	3	4	4	2	2	2	2	2	2	1
6	6	6	6	5	5	5	4	4	4	4	3	3	3	3	3	2	2	2	2	2	1	1	1	1	1
6	6	5	5	5	5	5	3	3	3	3	2	2	2	2	2	2	2	2	2	1	1	1	1	1	
5	5	5	4	4	4	4	2	2	3	3	2	1	1	1	1	1	1	1	1	1	1				
5	4	5	3	3	3	2	2	2	2	2	1	1			1	1	1	1	1						
4	3	3	3	2	2	2	2	2	1	1	1														
3	3	2	2		2	2	1	1	1																
3	3	2	1	2	1	1	1	1																	

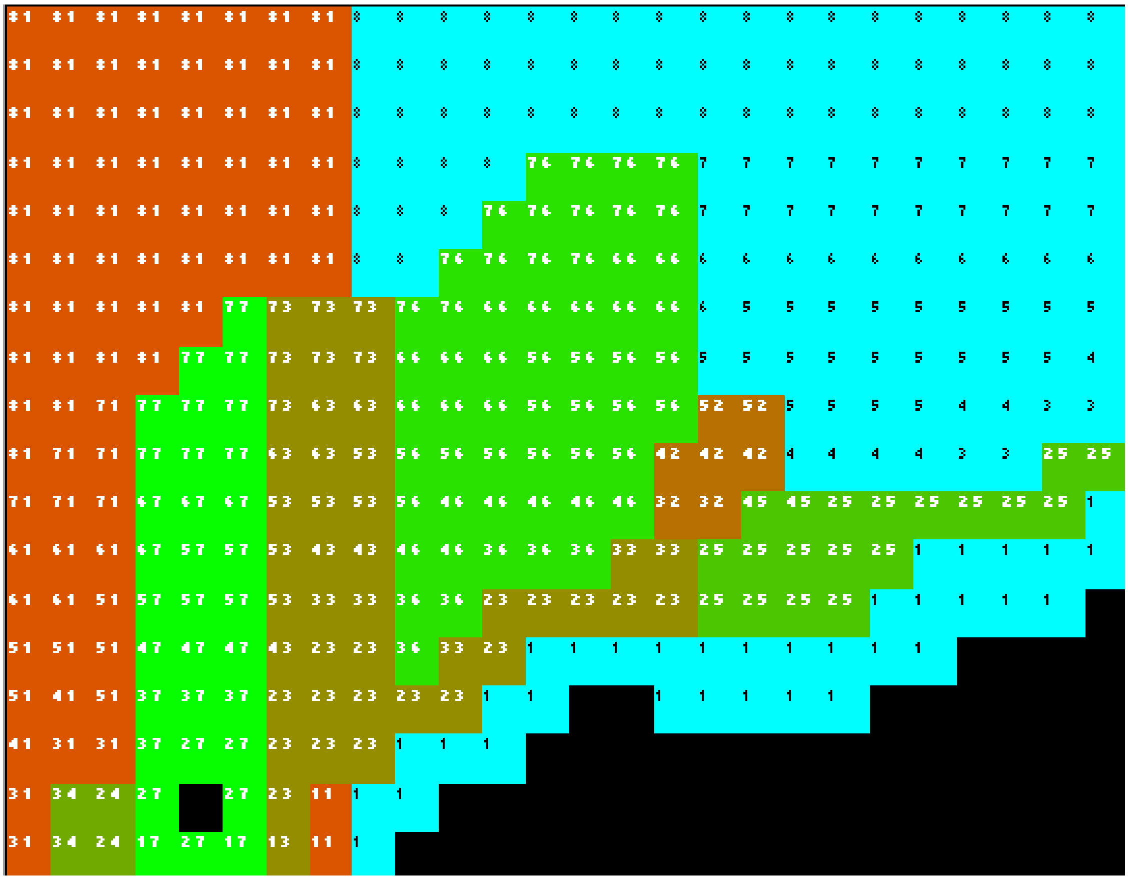
Figure 9.1.1: Distribution of habitats within North West Shelf study area. The black regions are land. Habitats are based on Althaus et al. (2006) and are described in table 9.1.1.

Table 9.1.2: Habitat assignations to functional groups in *Ecospace* model. Habitats are described in Table 9.1.1. Habitats 1 and 8 are outside study boundaries and do not have species assigned.

Group\Habitat #	1	2	3	4	5	6	7	8	Eco-space area	Eco-path area
Coastal sharks		+	+	+	+	+	+		0.609	1.0
Rays		+	+	+	+	+	+		0.609	1.0
Small tunas			+	+	+	+	+		0.501	1.0
Shallow lethrinids		+	+	+	+	+			0.469	1.0
Red emperor		+	+	+	+	+			0.469	1.0
Shallow lutjanids		+	+	+	+	+	+		0.609	1.0
Shallow nemipterids		+	+	+	+	+			0.469	1.0
Deep nemipterids							+		0.140	1.0
Shallow serranids		+	+	+	+	+			0.469	1.0
Frypan bream		+	+	+	+	+	+		0.609	1.0
Juvenile carangids		+	+	+	+				0.378	1.0
Adult carangids						+	+		0.231	1.0
Small pelagic fish		+	+	+	+	+	+		0.609	1.0
Shallow lizardfish		+	+	+	+		+		0.518	1.0
Deep lizardfish					+	+			0.229	1.0
Shallow mullids			+		+	+	+		0.435	1.0
Deep mullids						+	+		0.231	1.0
Trigger fish		+		+	+	+			0.401	1.0
Sweetlips			+	+	+				0.270	1.0
Pony fish						+	+		0.231	1.0
Shallow small fish			+	+	+				0.270	1.0
Deep small fish						+	+		0.231	1.0
Shallow medium fish		+	+	+	+				0.378	1.0
Deep medium fish						+	+		0.231	1.0
Shallow large fish		+	+	+					0.241	1.0
Deep large fish						+	+		0.231	1.0
Sessile epibenthos		+	+	+	+	+	+		0.609	1.0
Megabenthos		+	+	+	+	+	+		0.609	1.0
Macrofauna		+	+	+	+	+	+		0.609	1.0
Commercial prawns		+	+	+	+	+	+		0.609	1.0
Squid		+	+	+	+	+	+		0.609	1.0
Large zooplankton		+	+	+	+	+	+		0.609	1.0
Small zooplankton		+	+	+	+	+	+		0.609	1.0
Pelagic phytoplankton		+	+	+	+	+	+		0.609	1.0
Benthic phytoplankton		+	+	+	+				0.378	1.0
Microphytobenthos						+	+		0.231	1.0
Detritus		+	+	+	+	+	+		0.609	1.0
Habitat area	0.09	0.11	0.07	0.07	0.14	0.09	0.14	0.30	-	-

9.2 Fishery area closures

A series of fishery closures and sector allocations has evolved in the North West Shelf fishery. These were represented by allocating certain fisheries to specified areas (called MPAs in the model). In all, seven MPAs were defined to allow for differences in spatial and temporal ranges of the fisheries. In 1985 the foreign fleet was excluded from waters west of 116°E but by 1987, this exclusion zone was extended to areas west of 117.5°E. This was designated MPA1 where the foreign fleet was not allowed to fish. The domestic trawl fishery now operates within Zone 2 in the east of the Pilbara Fish Trawl Interim Managed Fishery (PTF), between 116 and 120°E, and between the 50 and 200 m isobath (see Stephenson & Chidlow, 2003, figure 2.1.1 for details). A small area in the zone, Area 3, is closed to all trap and trawl fishing (MPA2 in figure 9.2.1). Trapping is permitted in all areas of the PTF between 114 and 120°E, and between the 30 and 200 m isobath, except Area 3 (MPA2). Longlining is not restricted and is allowed in all MPAs and habitats. The prawn fishery operates largely inshore, and is subject to seasonal closures in various nursery areas which are not within the study area. Prawn trawling was therefore assigned to MPAs in shallower waters (MPA1, MPA3, and MPA4). Although these management zones have evolved over time, for this investigation, it was assumed they all were operating from 1987.



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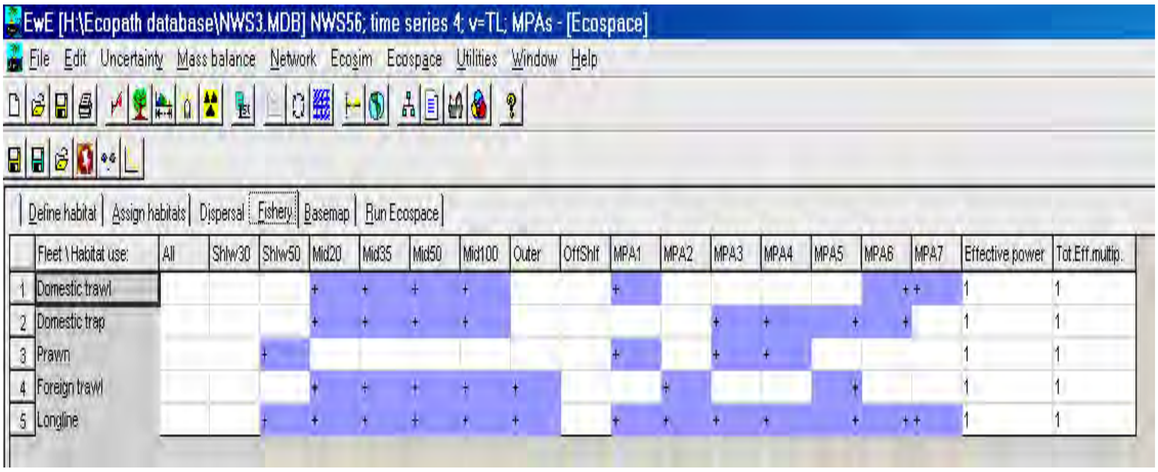
81	81	81	81	81	81	81	81	8	8	76	76	76	76	66	66	6	6	6	6	6	6	6	6	6	6
81	81	81	81	81	77	73	73	73	76	76	66	66	66	66	66	6	5	5	5	5	5	5	5	5	5
81	81	81	81	77	77	73	73	73	66	66	66	56	56	56	56	5	5	5	5	5	5	5	5	5	4
81	81	71	77	77	77	73	63	63	66	66	66	56	56	56	56	52	52	5	5	5	5	4	4	3	3
81	71	71	77	77	77	63	63	53	56	56	56	56	56	56	42	42	42	4	4	4	4	3	3	25	25
71	71	71	67	67	67	53	53	53	56	46	46	46	46	46	32	32	45	45	25	25	25	25	25	25	1
61	61	61	67	57	57	53	43	43	46	46	36	36	36	33	33	25	25	25	25	25	1	1	1	1	1
61	61	51	57	57	57	53	33	33	36	36	23	23	23	23	23	25	25	25	25	1	1	1	1	1	
51	51	51	47	47	47	43	23	23	36	33	23	1	1	1	1	1	1	1	1	1	1				
51	41	51	37	37	37	23	23	23	23	23	1	1			1	1	1	1	1						
41	31	31	37	27	27	23	23	23	1	1	1														
31	34	24	27		27	23	11	1	1																
31	34	24	17	27	17	13	11	1																	

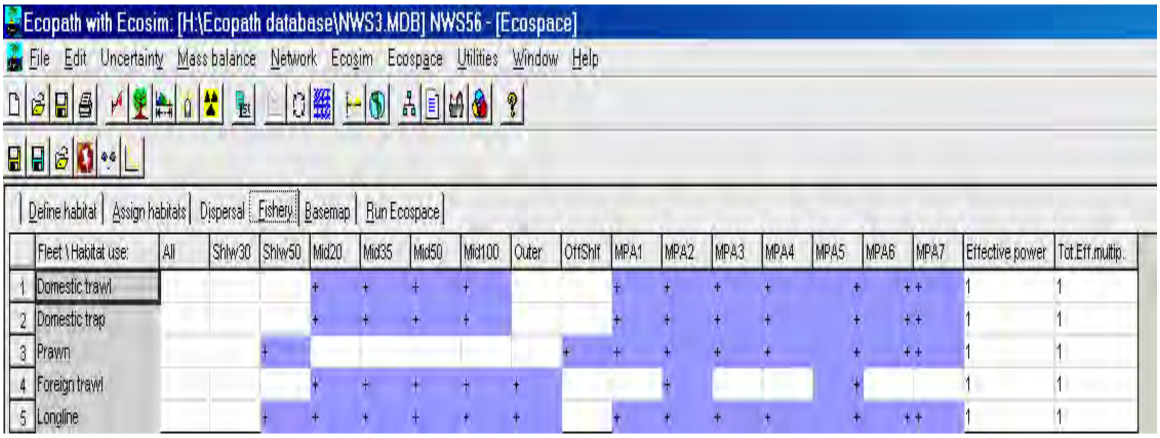
Figure 9.2.1: Distribution of protected areas and fishery closures operating in the NWS spatial model. See figure 9.4.1 for specific area closures for each fishing fleet operating in area. The first numbers are the habitat types underlying the MPAs (the first nine columns in figure 9.4.1) while the second numbers indicate the MPA (the next 7 columns in figure 9.4.1).

(a)



	Fleet \ Habitat use:	All	Shlw30	Shlw50	Mid20	Mid35	Mid50	Mid100	Outer	OffShlf	MPA1	MPA2	MPA3	MPA4	MPA5	MPA6	MPA7	Effective power	Tot.Eff.multip.
1	Domestic trawl				+	+	+	+			+					+	+	1	1
2	Domestic trap				+	+	+	+					+	+	+	+		1	1
3	Prawn			+							+		+	+				1	1
4	Foreign trawl				+	+	+	+	+			+			+			1	1
5	Longline			+	+	+	+	+	+		+	+	+	+	+	+	+	1	1

(b)

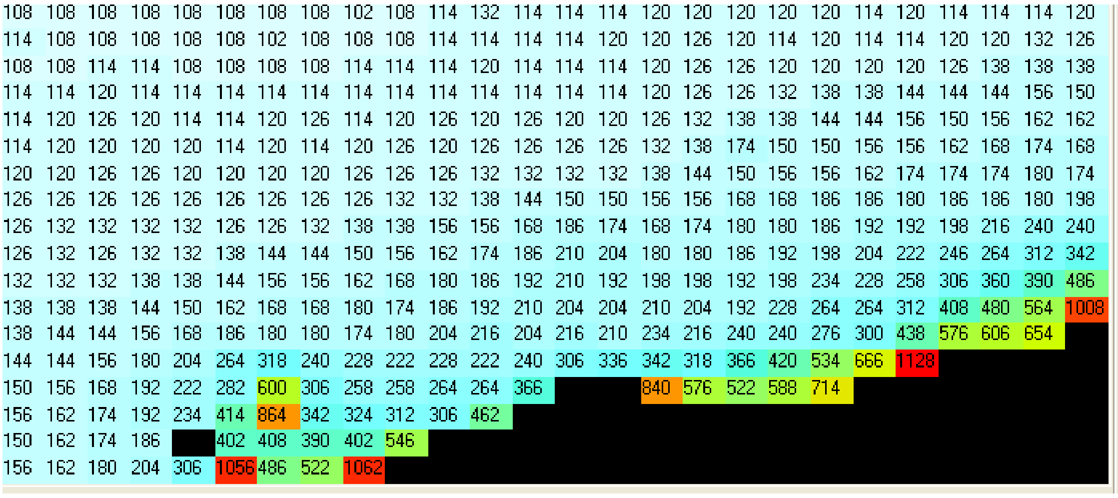


	Fleet \ Habitat use:	All	Shlw30	Shlw50	Mid20	Mid35	Mid50	Mid100	Outer	OffShlf	MPA1	MPA2	MPA3	MPA4	MPA5	MPA6	MPA7	Effective power	Tot.Eff.multip.
1	Domestic trawl				+	+	+	+			+	+	+	+	+	+	+	1	1
2	Domestic trap				+	+	+	+			+	+	+	+	+	+	+	1	1
3	Prawn			+						+	+	+	+	+	+	+	+	1	1
4	Foreign trawl				+	+	+	+	+			+			+			1	1
5	Longline			+	+	+	+	+	+		+	+	+	+	+	+	+	1	1

Figure 9.4.1: Habitat and restricted area assignations for fisheries on the North West Shelf in (a) spatial management scenarios and (b) in scenarios assuming no spatial management apart from exclusion of the foreign fleet.

9.3 Primary production

The primary production estimates for the North West Shelf area were downloaded from a database of global SeaWIFS data held at the Fisheries Centre, University of British Columbia. The base map was imported into the NWS *Ecospace* model.



108	108	108	108	108	108	108	108	102	108	114	132	114	114	114	120	120	120	120	120	114	120	114	114	114	120
114	108	108	108	108	108	102	108	108	108	114	114	114	114	120	120	126	120	114	120	114	114	120	120	132	126
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114	114	120	114	114	114	114	114	114	114	114	114	114	114	114	120	126	126	132	138	138	144	144	144	156	150
114	120	126	120	114	114	120	126	114	120	126	120	126	120	120	126	132	138	138	144	144	156	150	156	162	162
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120	120	126	126	120	120	120	120	126	126	126	132	132	132	132	138	144	150	156	156	162	174	174	174	180	174
126	126	126	126	126	126	126	126	126	132	132	138	144	150	150	156	156	168	168	186	186	180	186	186	180	198
126	132	132	132	132	126	126	132	138	138	156	156	168	186	174	168	174	180	180	186	192	192	198	216	240	240
126	132	126	132	132	138	144	144	150	156	162	174	186	210	204	180	180	186	192	198	204	222	246	264	312	342
132	132	132	138	138	144	156	156	162	168	180	186	192	210	192	198	198	192	198	234	228	258	306	360	390	486
138	138	138	144	150	162	168	168	180	174	186	192	210	204	204	210	204	192	228	264	264	312	408	480	564	1008
138	144	144	156	168	186	180	180	174	180	204	216	204	216	210	234	216	240	240	276	300	438	576	606	654	
144	144	156	180	204	264	318	240	228	222	228	222	240	306	336	342	318	366	420	534	666	1128				
150	156	168	192	222	282	600	306	258	258	264	264	366			840	576	522	588	714						
156	162	174	192	234	414	864	342	324	312	306	462														
150	162	174	186		402	408	390	402	546																
156	162	180	204	306	1056	486	522	1062																	

Figure 9.3.1. Primary production basemap imported from SeaWiFS global database (Fisheries Centre, UBC).

9.4 Scenarios

Eight fishing management scenarios, combining current spatial management and the fishing rate scenarios described in the previous section, were simulated over a 30 year period for the North West Shelf fishery:

1. No spatial management zones and closures (figure 9.4.1 (b)) and continuation of fishing effort as in 1987 including the foreign fishery. This represents a hypothetical scenario of the outcome of only limiting the effort of the foreign fishery to about 10% of its maximum effort and with no further growth of the domestic fishery.

2. No spatial management zones or closures and with fishing rates as calculated for 1987 to 2001, and the 2001 fishing rate maintained until the end of the simulation as in figure 8.1 (a), representing a hypothetical scenario where there had been minimal management apart from the exclusion of the foreign fishing fleets from the EEZ, but growth in the domestic trawl fishery.

3. No spatial management zones or closures with the “enhanced management strategy” fishing rate as described in Little et al. (2006), where fishing rates increased to 25% above 2001 rates over five years and then declined to 50% below the 2001 rate over the next 10 years (figure 8.1 (b)), representing a regulated fishing effort scenario after a period of minimal management apart from exclusion of foreign fleets,

4. No spatial management zones or closures with a reduction in fishing rate to 50% below the 2001 rate over last 15 years management apart from exclusion of foreign fleets (figure 8.1 (c)),

5. Spatial management and closures as described in the previous sections (figure 9.4.1 (a)) and the continuation of the 1987 fishing efforts,
6. Spatial management zones and fisheries closures, with fishing rates as calculated for 1987 to 2002, and the 2002 fishing rate applied until the end of the simulation, representing the "status quo" scenario,
7. Spatial management zones and closures as above with the "enhanced management strategy" fishing rate where fishing rates increased to 25% above 2001 rates over five years and then declined to 50% below the 2001 rate over the next 10 years, representing an "enhanced management" scenario,
8. Spatial management zones and fisheries closures as described in the previous sections and with a reduction in fishing rate to 50% below the 2001 rate over last 15 years management apart from exclusion of foreign fleets.

9.5 Comparisons of scenarios

The most obvious result from the comparison of the non-spatially managed and the spatially managed scenarios was that there were no discernible differences in the overall outcomes for the species (figures 9.5.1 and 9.5.2). By far the most influential factor affecting stocks were the fishing rates. However, apart from if fishing rate had not altered since 1987, there was little difference in outcomes between the current fishing rate, the "enhanced management" rates and a straight 50% reduction in fishing over 15 years (figure 9.5.3). The *Ecospace* predictions for each trophic group were generally similar to that in figure 9.5.4.

Many of the major commercial species continued to decline under all management scenarios; however declines were less severe under the enhanced management scenarios for sharks, rays, nemipterids, and large deep fish. For tunas, red emperors, carangids, deep lizardfish, sweetlips, shallow small fish and small pelagic fishes the decline was more severe under enhanced management strategies. For several species there was no discernible difference between fishing rate strategy: shallow nemipterids, juvenile or small carangids, or frypan bream.

Shallow lizardfish increased in all scenarios which is consistent with the trends of the estimated biomass from the surveys. Lethrinids, serranids, mullids and medium-sized fish also increased more under enhanced management options. Ponyfish and lutjanids increased more under the 2001 fishing rates.

Triggerfish would have fared better if fishing rates had continued at the 1987 rates. This happened because initially there was no apparent catch or discard of this species in the foreign fishery but as the domestic fishery grew, so did the discard rates and a lower rate of increase. This situation occurred in several other species, where fish, not initially targeted, were increasingly discarded from the growing domestic fishery. Since most teleost fishes have a low survival rate, discarding of non-target fish could have serious consequences for some species. Rays were increasingly discarded from the growing domestic trawl fishery. However, the discard rates were reduced to 10% of the reported rate to account for their high apparent survival (Stephenson & Chidlow, 2003). Despite this reduction, rays would have declined slightly less under the 1987 rates.

The *Ecospace* predictions (figure 9.5.4) matched reasonably closely the trends in biomass and CPUE time series, given the limitations of the data. It was not possible to get an exact replication of the CPUE and biomass patterns in the *Ecosim* simulations, and in case of the unreliability of parts of the CPUE data it was not expected to, but in most cases the trends agreed. Where the *Ecosim* predictions differed from the observed data, this was usually rectified in *Ecospace* simulations. However, there were two differences of note. The time series trends for lethrinids indicated a probable decline, while both the *Ecosim* and *Ecospace* simulations predicted an overall increase in biomass (figure 9.5.4). A reason for this might be the multi-species nature of this group. There are several lethrinids in the group which are apparently declining whereas others are not. The averaging of their production and consumption parameters and vulnerabilities may therefore not give an accurate representation of these species. More appropriate splitting of species in this group might result in an improvement in prediction for these species. The second difference was the serranid biomass, which was predicted to increase while the time series indicated a decline. This might be rectified by changing production and consumption parameters, or other parameters such as vulnerability.

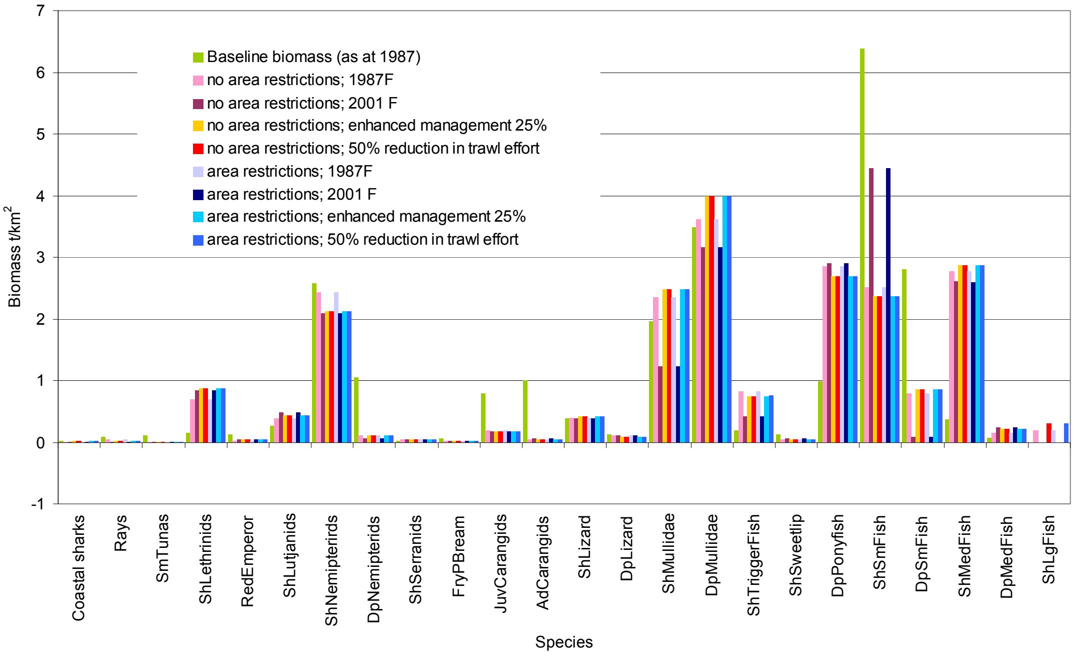


Figure 9.5.1: Predicted biomass of major fish functional groups after 30 year simulation under scenarios 1 to 4. Within each species category, the first column is the baseline biomasses in 1987 (green), the next four columns (warm colours) represent non-spatially managed scenarios and the last four columns (cool colours) represent the spatially managed scenarios.

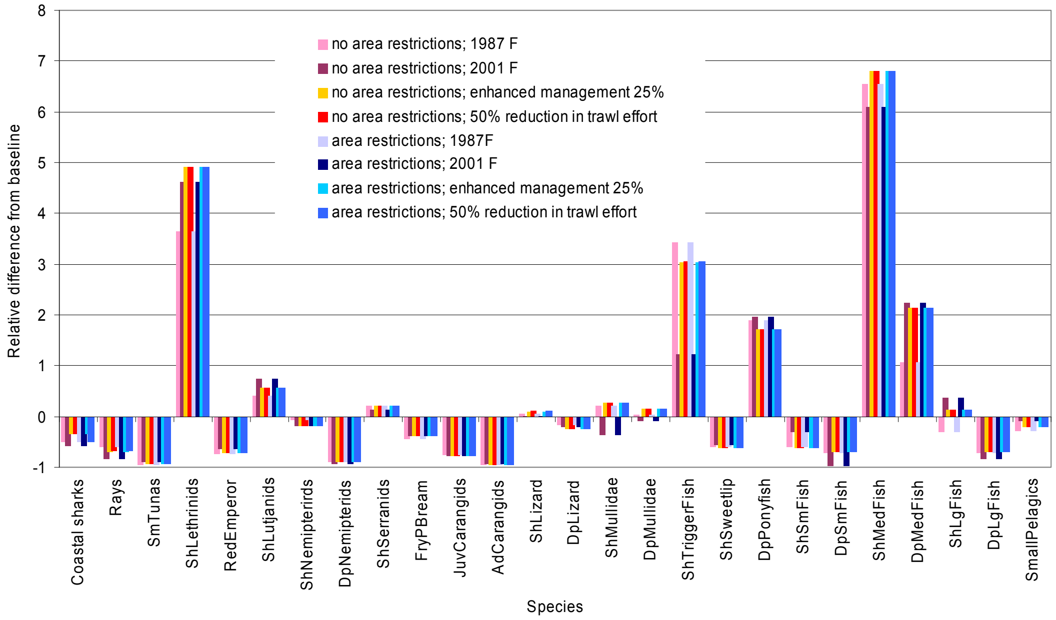


Figure 9.5.2: Predicted relative changes in biomass of major fish functional groups after 25 year simulation under scenarios 1 to 4.

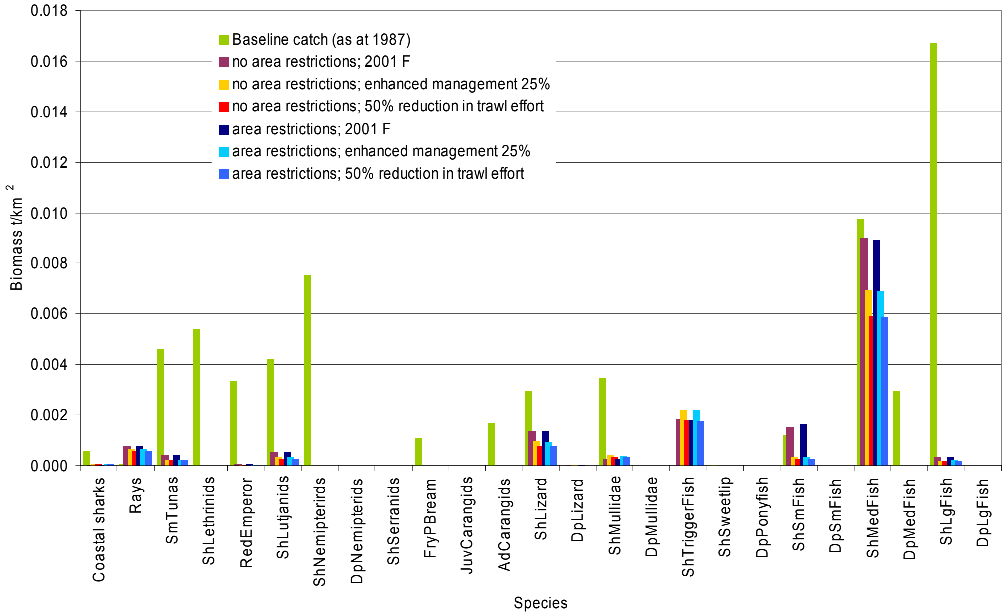
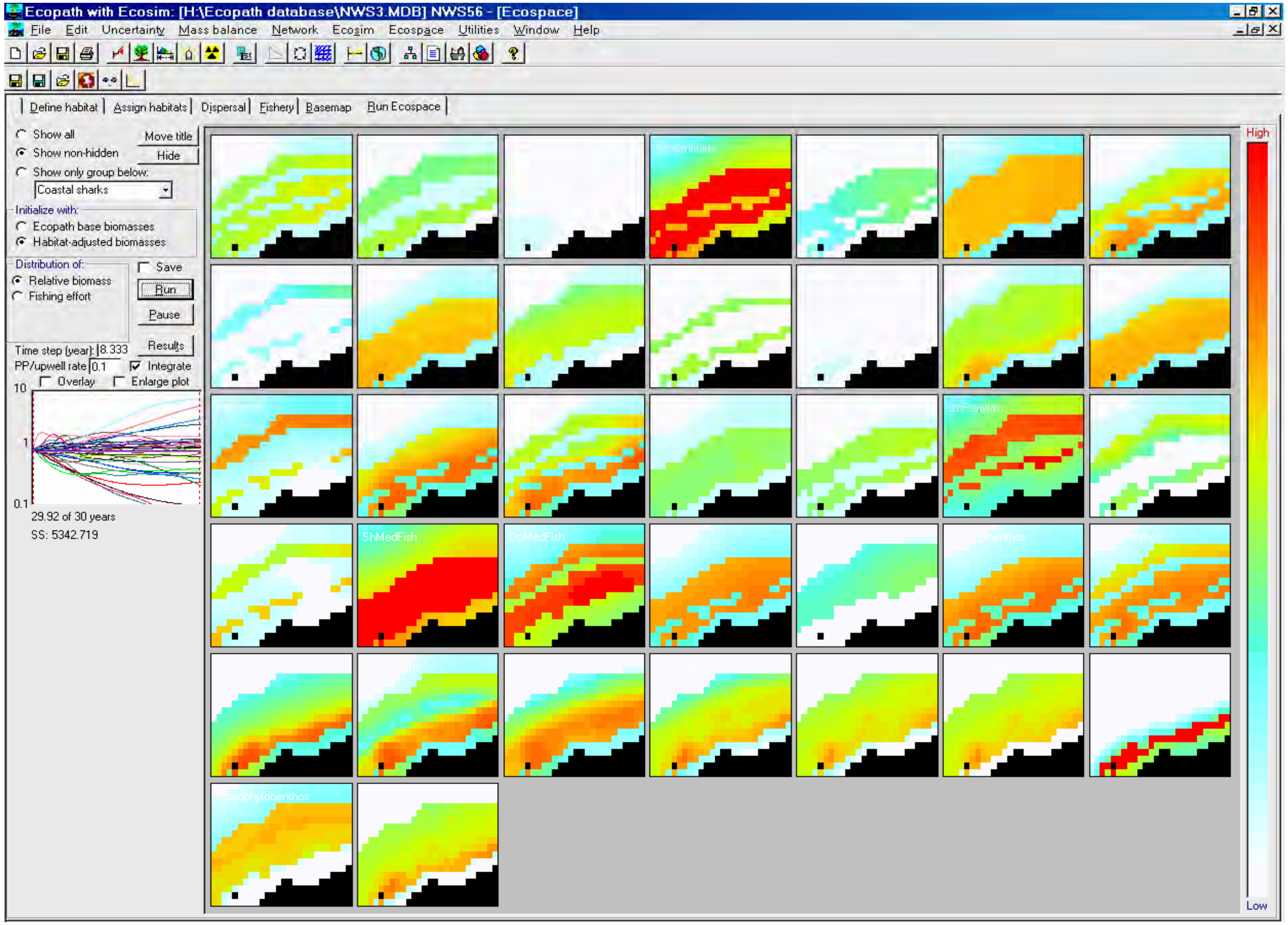


Figure 9.5.3: Predicted catches of major fish functional groups after 25 years of simulation under scenarios 1 to 4.

Given the uncertainties in the dietary data, and the fishery statistics, the model agreed reasonably well with observed data. As this was a preliminary spatial model, there were many parameters which were left at default values in the absence of the necessary data. Further development of this model would therefore involve specifying these parameters, e.g. foraging time, dispersal rates and advection rates, thus improving the fit and value of the model.



Ecopath with Ecosim: [H:\Ecopath database\NWS3.MDB] NWS56 - [Ecospace]

○ Show all
● Show non-hidden
○ Show only group below:
Coastal sharks

Initialize with:
○ Ecopath base biomasses
● Habitat-adjusted biomasses

Distribution of:
● Relative biomass
○ Fishing effort

☐ Save

Time step (year): 8.333
PP/upwell rate 0.1
☑ Integrate
☐ Overlay
☐ Enlarge plot

29.92 of 30 years
SS: 5342.719

Legend

Row 1: (L-R) Coastal sharks, Rays, Small tunas, Shallow lethrinids, Red emperor, Shallow lutjanids, Shallow nemipterids

Row 2: Deep nemipterids, Shallow serranids, Frypan bream, Juvenile carangids, Adult carangids, Small pelagic fish, Shallow lizardfish

Row 3: Deep lizardfish, Shallow mullids, Deep mullids, Trigger fish, Sweetlips, Pony fish, Shallow small fish

Row 4: Deep small fish, Shallow medium fish, Deep medium fish, Shallow large fish, Deep large fish, Sessile epibenthos, Megabenthos, Macrofauna

Row 5: Commercial prawns, squid, large zooplankton, small zooplankton, pelagic phytoplankton, benthic phytoplankton,

Row 6: Microphytobenthos, detritus

Figure 9.5.4: Spatial prediction of biomass in *Ecospace* after 30 years with spatial management. The small windows represent the biomass of each trophic group of the model. Biomass is colour-coded from high biomass being red to low being white (colour scale on right side of screen). The window on the left shows the average relative biomass per group similar to the *Ecosim* simulations.

10. SUMMARY

This model describes the trophic interactions of the major species occurring in the North West Shelf fishery between 30 and 200 m depth. It is based on the best available knowledge of those interactions but are annual averages and do not account for seasonal differences. No short or long-term environmental forcing, or any advection or migration processes, was imposed. It was assumed that the system was in decline at the beginning of the model period and allowed negative accumulation terms. It was also assumed that the vulnerabilities of the species were proportional to their trophic level in most cases. It was also assumed that habitat was not modified further than the state at the beginning of the model period. Removal of benthos creates the more open habitats favoured by lizardfish, and is considered an important factor in the increase of lizardfish in the present system.

The system statistics for the NWS system are consistent with a system that has lost maturity, in this case through exploitation from fishing. While the connectance and omnivory indices suggest a complex web structure indicative of a mature system, other statistics derived from primary production and biomass indicate an “immature” system, i.e. where primary production exceeds biomass and consequently respiration. The ambiguity might be explained by the nature of the NWS ecosystem. The pelagic sub-system is quite dominant in terms of biomass and has extensive links to the demersal system, which was heavily exploited by the foreign trawl fishery prior to the beginning of the model period.

Despite the constraints of the data and the assumptions, the spatial model appears to represent the NWS system reasonably well by predicting nearly all trends in biomass of fish species similar to those of the time series. The major inconsistency, the prediction of the lethrinids to increase where the times series suggests decline, would most likely be improved by aggregating the lethrinids more appropriately. A fundamental requirement of aggregating species in these models is that they are functionally similar and have similar production and consumption rates. If different species of lethrinids are subject to very different fishing pressures, it would not be possible to model the group sensibly as a whole. Further improvement to the model could be made by investigating parameters such as dispersal in bad habitats, non-feeding interactions, e.g. between species and their associated habitat structures, and feeding behaviour parameters such as feeding time adjustment rates, for which data was unavailable.

Assuming the model to be a reasonable representation of the system, it could be inferred from the spatial simulation results that any effects of spatial management on the North West Shelf are far outweighed by the effects of managing the effort applied in the fishery. Reducing fishing rates over the latter 15 year period of the 30 year simulation had beneficial effects for nearly all species either by reducing their rates of decline or by enhancing their rates of increase. Continuation for another 30 years resulted in the loss of the tunas and adult carangids, however both of these groups could be influenced by non-trophic factors such as environmental conditions and migration patterns not modelled here, and abundances of neither could be accurately estimated. This spatial model could be used to investigate other spatial and effort strategies and, with the appropriate economic data, policy optimisation.

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APPENDIX A: ECOPATH WITH ECOSIM MODEL

A.1 Ecopath

Ecopath was based on the approach developed by Polovina (1984) where biomass and food consumption of the various groups are estimated using mass-balance principles, and combined with an analysis of the flows between the groups by Ulanowicz (1986). The model describes an average state, rather than a steady state. Once the model is parameterised, it can be used in the temporal and spatial components, *Ecosim* and *Ecospace*.

The ecosystem is ccompartmentalised into groups of either single species, or of many species, grouped functionally based on taxonomy or ecology of the species. There are two master equations describing production and energy balance for each group.

Production = catches + predation mortality + biomass accumulation + net migration + other mortality. This can be expressed mathematically as:

$$P = Y_i + B_i M2_i + E_i + BA_i + P_i(1 - EE_i) \qquad \text{(A.1)}$$

where, for group *i*, P_i is the total production; Y_i is the total fishery catch; $M2_i$ is the total predation mortality on group i, and $M2_i = \sum_{j=1}^{n} Q_j DC_{ji}$; Q_j is consumption of predator *j*; B_i is the biomass; E_i is the net migration (emigration-immigration); BA_i is the biomass accumulation rate; and $P_i(1\text{-}EE_i)$ = other mortality rate, $M0_i$, and where *EE*, the ecotrophic efficiency, is the proportion of production of *i* that is utilised in the system. This can be re-expressed as:

$$B_i(PB^{-1})_i EE_i - \sum_{j=1}^{n} B_j(QB^{-1})_j DC_{ij} - Y_i - E_i - BA_i = 0 \qquad \text{(A.2)}$$

where PB^{-1} is production/biomass ratio and can generally be input as total mortality rate *Z* estimated in stock assessment models , QB^{-1} is consumption/biomass ratio, and DC_{ij} is the fraction of prey *i* in the diet of predator *j*. For a system of n groups this gives n linear equations that can be solved simultaneously

$$a_{1,1}X_1 + a_{1,2}X_2 + \ldots a_{1m}X_m = Q_1$$

:

:

$$a_{n1}X_1 + a_{n2}X_2 + \ldots a_{nm}X_m = Q_n \qquad \text{(A.3)}$$

where *n* is the number of equations and m is the number of unknowns. In matrix notation this is

$$[A]_{nm}[X]_m = [Q]_m \qquad \text{(A.4)}$$

and

$$[X]_m = [Q]_m\left[A^{-1}\right]_{nm} \qquad \text{(A.5)}$$

The series of simultaneous equations is solved by a generalised inverse method. If the equations are over-determined, i.e. there are more equations than unknowns and the equations are not consistent with each other, a least squares estimate will minimise the discrepancies. If they are under-determined, i.e. number of equations is less than the number of unknowns, non-unique solutions consistent with the data are found.

In the *Ecopath* model, the energy input and output of each box is balanced. The second master equation balances production with other flows so that:

consumption = production + respiration + unassimilated food.

This is based on the Winberg (1956) concept of the sum of somatic and gonadal growth, metabolism and waste. However, the *Ecopath* function differs in that it estimates losses and doesn't explicitly include gonadal growth, which is included in the predation mortality term. Respiration is determined by the difference between consumption, and production and unassimilated food, however it can be input. Energy is the currency used in all three programs but nutrients can also be used in *Ecopath*.

To parameterise the model three of the four terms, B, P/B, Q/B or EE, must be supplied. If all four of the terms are entered, the program will ask if biomass accumulation or net migration is to be estimated. Also required are diet composition DC, assimilation rate, net migration E, catch Y, and biomass accumulation BA, the last three of which may be zero.

Uncertainty within parameters can be addressed in *Ecopath* by using the EcoRanger module. This allows entry of a mean and range for basic parameters and random input variables are drawn from a frequency distribution. The best model from a range of models is chosen based on a criterion such as the minimum residual. This therefore allows for a statistically based approach to fitting models within given constraints.

A.2 Ecosim

Ecosim was developed by incorporation of coupled differential and difference equations into *Ecopath*, to allow for dynamic simulations (Walters et al. 1997). Biomass flux rates are expressed as a function of time varying biomass and harvest rates (Christensen et al. 2000). Predator-prey interactions can be varied to emulate top-down or bottom-up control (Walters et al. 2000; Bundy, 2001). Time series data on biomass, catch rates, fishing effort etc. can be fitted and makes this program useful to explore options for management policies.

The basic equation modified from the basic *Ecopath* equation A.2 is:

$$dB_i / dt = g_i \sum_i Q_{ij} - \sum_j Q_{ij} + I_i - (M_i + F_i + e_i) B_i \tag{A.6}$$

where dB_i/dt is the growth rate of group i in biomass, g_i is the net growth efficiency or production/consumption ratio, Q_{ij} is the consumption of prey j by predator i, M_i is the other mortality, F_i is the fishing rate, e_i is emigration rate, and I_i is the immigration rate. The first summation is the total consumption by group i and the second is the total consumption on group i. The biomasses of groups are split into vulnerable and invulnerable and it is the transfer rate, v_{ij}, between them that determines the type of control over the interactions, i.e. bottom-up donor driven or top-down Lotka-Volterra type. Mixed control is also possible.

The Lotka-Volterra assumption has usually been used to predict flows, $c_{ij}(B_i, B_j)$, so that:

$$c_{ij}(B_i, B_j) = a_{ij} B_i B_j \tag{A.7}$$

where a_{ij} is the instantaneous rate of mortality on i by j and c_{ij} (formerly Q_{ij} in *Ecopath*) is consumption. The problems with this equation are that satiation by a predator is not accounted for, but is thought to be minor, and that the vulnerability of prey to predators, determined by behavioural factors or physical factors such as habitat. For example, diel vertical migration of mesopelagic fishes might make them unavailable to predator fishes for part of the day. This is a critical concept in *Ecosim* (Walters et al. 1999) and in *Ecosim* it is possible to vary the amount of biomass of prey i available to predator j. Consumption rate, c_{ij}, is then derived by;

$$c_{ij} = v_{ij} a_{ij} B_j B_i / (2v_{ij} + a_{ij} B_j) \tag{A.8}$$

The available biomass, V_{ij} , exchanges with the unavailable biomass B_i-V_{ij} according to:

$$dV_{ij} / dt = v_{ij}(B_i - V_{ij}) - v_{ij}V_{ij} - a_{ij}V_{ij}B_j \tag{A.9}$$

The available biomass is added to from the unavailable pool at the rate of v_{ij}, and biomass is returned at the rate $v_{ij}V_{ij}$. Biomass is also being removed from the available biomass by predators at the rate, $a_{ij}V_{ij}B_j$, the mass-action encounter rate (Walters et al. 1997). Low values of v_{ij} and high values of a_{ij} imply a ratio-independent interaction leading to bottom-up control, whereas high values imply a mass-action interaction leading to top-down control (Walters et al. 1997).

Functions also exist for computing flows between split-pools, i.e. between juveniles and adults, each group having their own parameters, but stock recruitment relationships are accounted for by using delay-difference equations. Functions for either computing flows where prey or predator biomass levels increase to high levels and for handling detritus are also added. The differential equations are solved using an Adams-Basforth integration routine or a Runge-Kutta 4th order routine.

Failures of the *Ecosim* model to predict flows when there are large changes in prey or predator biomass could occur due to predator satiation during high abundance of prey, prey-switching when prey abundance is low or when predation risk increases due to changes of behaviour or vulnerability.

A.3 Ecospace

Ecospace uses a defined rectangular grid of cells for which a differential equation system of equations based on equations A.6 and A.8 and delay-difference equations for split pools. The cells are assigned either land or water and a habitat type. Movement is allowed across the face of the cells but not land or diagonally. Areas or cells of higher primary productivity, and restricted or closed fishing areas, can be assigned.

Immigration I_i for each cell is made up of four components, the emigration flows across each face of the cell from the surrounding cells (except on the boundary). These flows are represented by:

$$e_i = m_i B_i \tag{A.10}$$

where m_i is the instantaneous movement rate. The rate will be affected by the way in which the organism is transported i.e. by itself or reliant on advective process; whether an organism prefers specific habitats thus increasing the emigration rate from non-preferred habitat type cells; and the response of the organism to predator risk relative to prey abundance. Emigration rate is calculated from the average speed of movement of the organism and is proportional to the speed and inversely proportional to the cell size. A problem with this is that the organism's movements are likely to be made up of two types: many short movements within a home range and a few longer movements such as migrations. Most movements are non-random but the Eulerian approach does not allow a history to be attached. Cells on boundaries are therefore vulnerable to exploitation. Another problem is the fact that organisms might have preferred habitats thus the probability of moving in the direction of that habitat is increased. Feeding efficiencies and predation risk are likely to be affected also.

Fishing mortality for each cell can be separated by gear where a variety of gear is used. This allows for situations where effort might be higher such as on the boundary of an MPA. For each gear in the initial *Ecopath* analysis, a gravity model represents spatial distribution of fishing mortality. The proportion of total effort *E* is proportional to the sum over all groups of biomass x catchability x price of target groups. If there are *N* cells, each gear *k* can exert a total mortality rate NF_k over the whole grid. This rate is distributed over cells c in proportion to gravity weights G_{kc}:

$$G_{kc} = O_{kc} U_{kc} (P_{ki} q_{ki} B_{ic}) \tag{A.11}$$

where O_{kc} is 1 if open to the fleet or 0 if not, U_{kc} is 1 if gear *k* can fish the habitat type assigned to the cell, p_{kc} is relative price, q_{kc} is catchability, *B* is the current biomass, and *c* is the relative cost of fishing in the cell. Total mortality NF_k is distributed among cells by:

$$F_{kc} = Nf_{kc} G_{kc} / \sum G_{kc} \tag{A.12}$$

The differential equations of *Ecosim*/*Ecospace* have a structure that is exploited to develop efficient algorithms. For any *B*, i.e. in any cell at any time *t*:

$$dB/dt = (I + gC) - (Z + E)B \tag{A.13}$$

where *I* is total immigration rate and *E* is total instantaneous emigration rate. If the rate components were constant over time, *B* would move towards equilibrium,

$$B_e = (I + gC)/(Z + E) \tag{A.14}$$

along a time trajectory,

$$B_{t+\Delta t} = W_t B_t + (1 - W_t) B_e \tag{A.15}$$

where the exponential weight, $W_t = e^{-(Z+E)\Delta t}$. Therefore, *W* is pre-computed for each group by using movement parameters m and mortality rates *Z*. For each time step, equilibrium biomass B_e is calculated for each group, before updating the biomass estimates for the next time interval. Walters et al. (1999) found that by splitting the fast, e.g. phytoplankton, and slow, such as fish and marine mammals, variables, computation was sped up enormously. They found that fast variables generally tracked the moving equilibria of slow variables. However, the speed of computation has been facilitated at the expense of being able to incorporate seasonal variation in system "forcing" i.e. physical mixing and plankton, and dispersal-migration behaviours, which were available in *Ecosim*. In addition, the preservation of persistent time lag structure might dampen or lose the cyclical behaviour of predator-prey interactions (Walters et al. 1999).

Ecospace is therefore capable of providing general indications of biomass responses to MPAs and should not be expected to provide more. Walters et al. (1999) suggested that it is as a useful tool to synthesize information, to design better management experiments and monitoring programs to evaluate policies rather than for providing the quantitative predictions about the policies.

APPENDIX B: MESH SELECTIVITIES

B.1 Nemipterids

[Note: the taxonomy of the nemipterids was changed so that what was called *N celebicus* became name *N peronii*, and what had been called *N peronii* got the name *N furcosus* (Sainsbury et al. 1990)].

To generate a generic selectivity curve, the data for *Nemipterus furcosus* was used, for which there was good ageing data. A theoretical population structure was recreated from the mortality equation of Sainsbury and Whitelaw (1984),

$$LnN = 10.95\text{-}1.85T \qquad \text{(B.1)}$$

where N = numbers and T = age in years, and the von Bertalanffy growth curve parameters, $L_\infty = 41.9$cm, $K = 0.25$, $M = 0.85$ and $t_0 = -0.74$. A proportion of the population less than age two in Sainsbury and Whitelaw's figure 9, was not fully recruited. This proportion was estimated by fitting a line through the points indicated as not fully recruited. The line was forced through the y-value of 6.4, the result of equation B.1 at the age = 2. The equation of that line was then:

$$LnT = 2.4+2*T \qquad \text{(B.2)}$$

and for each age less than 2, the "actual" numbers were estimated. The ratio of the "actual" numbers and the expected numbers was the mesh selectivity index, s. The length at age 2 was 16.5 cm.

To determine the proportion of the population of *N. furcosus* not sampled, the reconstructed age-frequency distributions, expected and actual, were converted to length-frequency distributions, by estimating length at age T from:

$$L_T = L_\infty * (1\text{-}e^{-KT}) \qquad \text{(B.3)}$$

The length-frequency distributions, actual and expected, were converted to total biomass. Biomass at each length class was calculated by calculating the weight, W, from the length-weight relationship (Sainsbury & Whitelaw, 1984):

$$W = 0.157 * L^{3.029} \qquad \text{(B.4)}$$

and then multiplying by actual or expected numbers. The proportion of the population sampled, estimated as the ratio of the total biomass of the "actual "population to that of the expected, was 37.5%.

However the s derived from this data was possibly unsuitable for this survey data for other nemipterids. The length frequency distributions of *Nemipterus furcosus* of Sainsbury and Whitelaw (1984) whose data were collected during the late 1970s were noticeably different to those from the surveys during the years for which the abundances were being estimated, 1986 to 1991. *N. peronii* was far less abundant than *N. furcosus*, which was the most abundant fish during the survey period. Changes in mortality were suspected due to the impact of heavy fishing and its subsequent decline. Significant recruitment variability was also suspected.

Analysis of the cohorts of *N. furcosus* provided an alternative way to determine size selectivity relevant to this survey data. Length frequency data was converted to age frequency distributions by converting length to age:

$$T = \frac{Ln(1 - \frac{L_T}{L_\infty})}{-K} \tag{B.5}$$

and accumulating the numbers within an age group. These numbers were transformed to natural log. Each cohort was plotted year by year from 1982 to 1995 (figure B.1.1), except in years when surveys were not conducted.

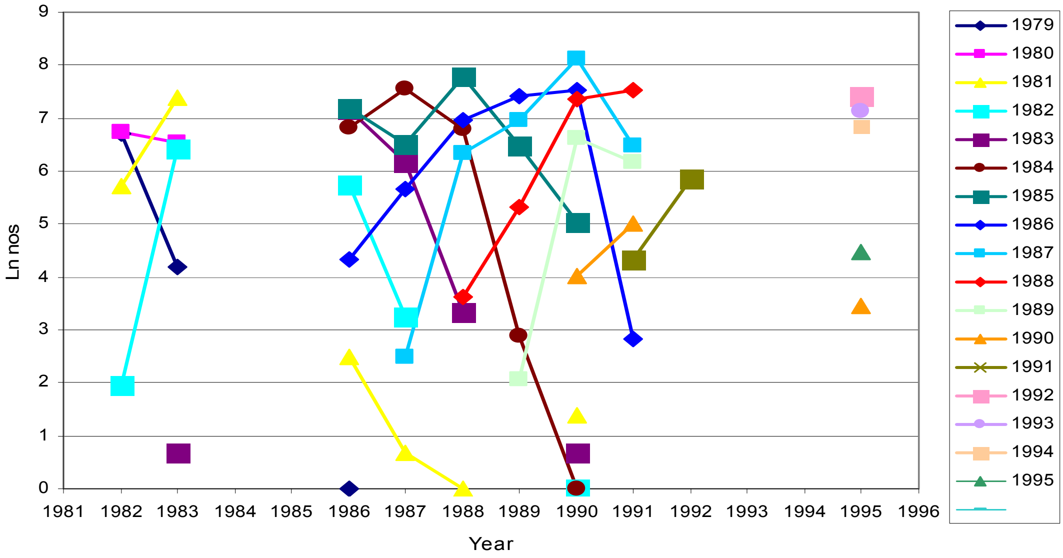

Figure B.1.1: Cohort analysis for *Nemipterus furcosus*.

From this plot of numbers per cohort by year, the age at which fish from these surveys were fully-selected was probably about three. A regression through all data points age three or greater gave another estimate of mortality relevant to the population during the years 1983 to 1995:

$$LnN = 13.62 - 1.97T \tag{B.6}$$

The equation through the points less than three when the fish were not fully-recruited was estimated by fitting a power curve using the Solver routine in Excel. The line was forced through the age three value of equation B.6 and 0 (figure B.1.2):

$$LnN = 2.12LnT + 5.3656 \tag{B.7}$$

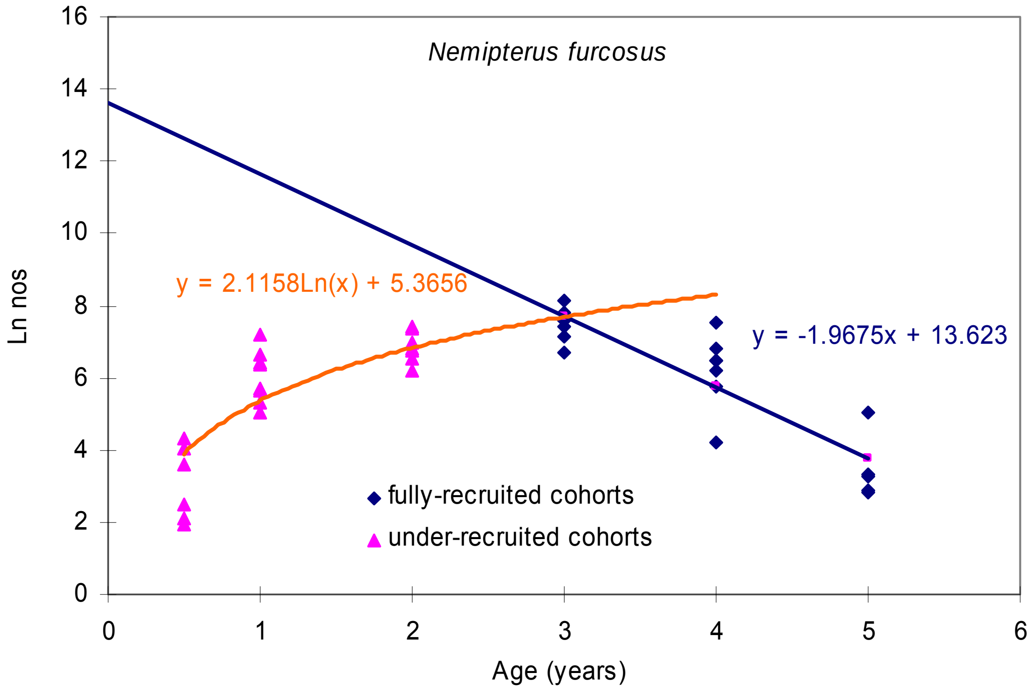

Figure B.1.2: Catch at age curves for *Nemipterus furcosus*.

The ratio of the "actual" numbers and the expected numbers was the mesh selectivity index, s, (figure B.1.3). The fully-recruited length at age 3 was 23 cm.

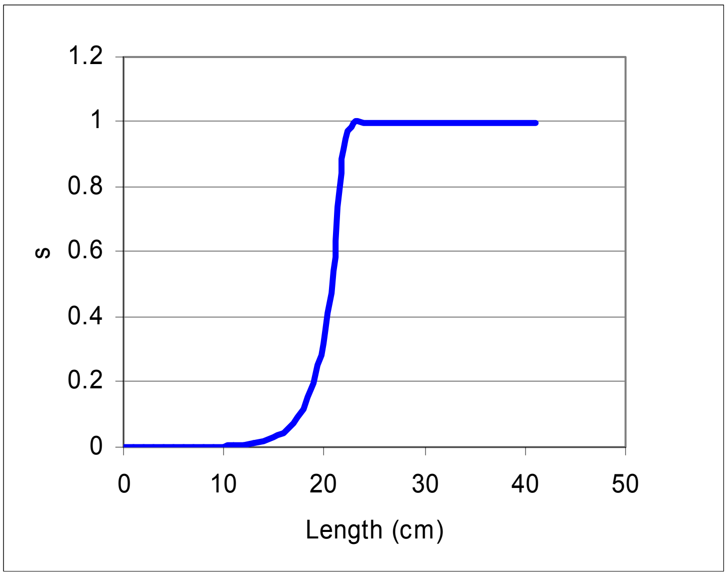

Figure B.1.3: Size selectivity curve derived from survey data of *Nemipterus furcosus*.

To determine the proportion of the population of *N. furcosus* sampled the same procedure as for *N. furcosus* was followed. The reconstructed age-frequency distributions, expected and actual, were converted to length-frequency distributions, by estimating length at age *T* from equation B.3. The length-frequency distributions, actual and expected, were converted to total biomass. Biomass at each length class was calculated by calculating the weight-at-length, *W*, from the length-weight relationship equation B.4 and multiplying by actual or expected numbers. The proportion of the population sampled, estimated by the ratio of the total biomass of the "actual" population and that of the expected, was 17.6%.

The resulting table of length-specific *s* was applied to the length frequency distributions of other nemipterids (table B.1.1), and for most other small species for which specific selectivity indices could not be calculated. The indices for the smallest lengths were nonsensically small indicating that very small fishes were very poorly sampled. Using either specific length-weight relationships or a generic one where a specific one was not available, the length frequency distributions of each species were converted to biomass. The proportions of the populations sampled were calculated and this proportion was used to scale up the swept-area abundances. Because of the limitation of the selectivity index, a lower limit of 5% sampled was always used.

Table B.1.1: Estimated proportion of populations of *Nemipterus* species sampled based on generic *Nemipterus s* index.

Species	Proportion of population sampled
Nemipterus furcosus	0.375
Nemipterus peronii	0.176
Nemipterus celebicus	0.008
Nemipterus bathybius	0.007
Nemipterus virgatus	0.047
Scolopsis monogramma	0.603

B.2 Lutjanids

The lutjanids have a different profile from nemipterids and were suspected of reaching a different size to the nemipterids when fully selected. A specific *s* was determined for *Lutjanus vittus* using the data of Davis and West (1992) and following the same procedure as for the nemipterids. Length frequency data was converted to age frequency distributions by converting length to age (equation B.3), accumulating the numbers within each age group and transforming to natural log. Each annual cohort was traced individually from 1982 to 1995, except in years when surveys were not conducted, by plotting the numbers in each cohort per year (figure B.2.1). From this plot, the age at which fish from these surveys were fully-selected was probably about three. A regression through all data points age three or greater gave another estimate of mortality relevant to the population during the years 1983 to 1995:

$$LnN = 10.64 - 1.35T \qquad \text{(B.8)}$$

The equation through the points less than three when the fish were not fully-recruited was estimated by fitting a power curve using the Solver routine in Excel. The line was forced through the age three value of equation B.8, and 0 (figure B.2.2):

$$\mathrm{Ln}N = 2.34\mathrm{Ln}T + 4.02 \qquad \text{(B.9)}$$

The ratio of the "actual" numbers and the expected numbers was the mesh selectivity index, *s*. The length at which the fish appeared to be fully-selected was 20 cm.

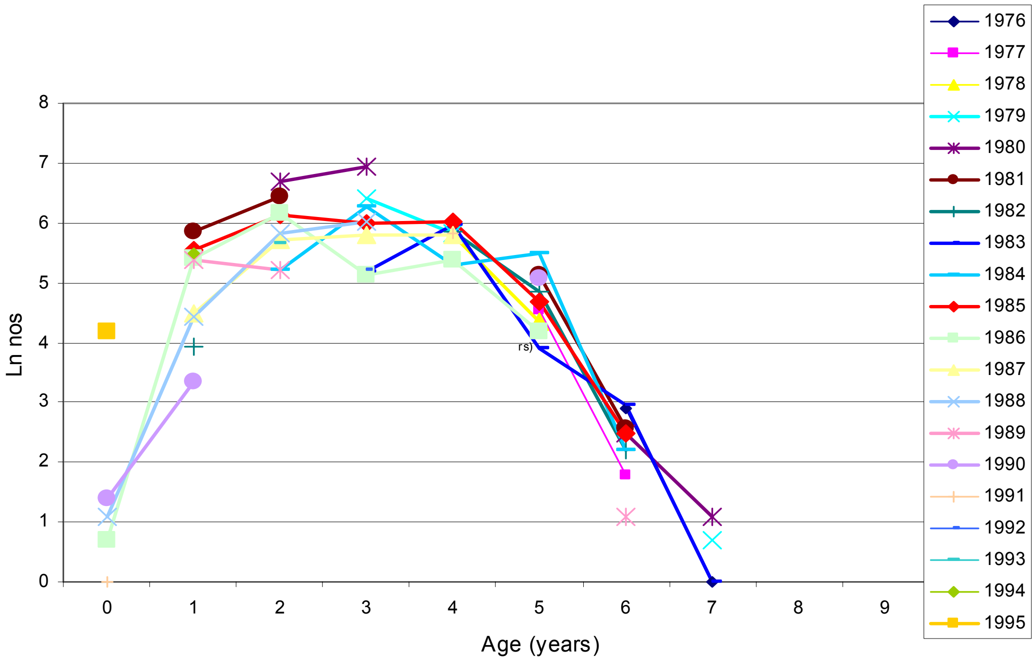

Figure B.2.1: Catch at age by cohort.

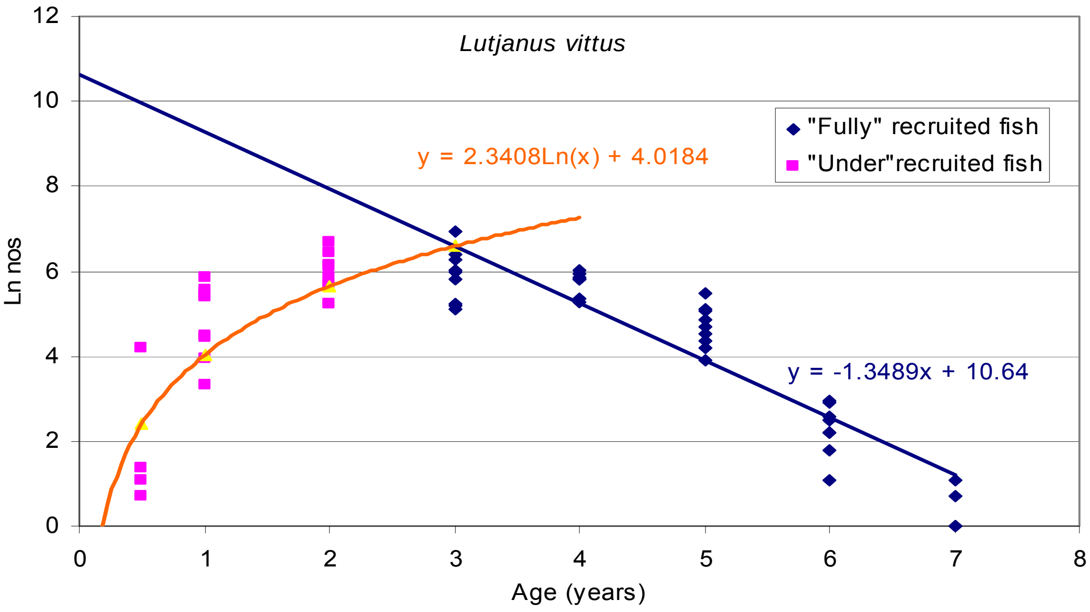

Figure B.2.2: Catch at age curve for *L. vittus*.

To determine the proportion of the population of *L. vittus* sampled the same procedure as for N. furcosus was followed. The reconstructed age-frequency distributions, expected and actual, were converted to length-frequency distributions, by estimating length at age T from equation B.3, and the von Bertalanffy growth curve parameters, l = 40.3 cm, K = 0.325 and M = 1.04 (Davis & West, 1992). The length-frequency distributions, actual and expected, were converted to total biomass. Biomass at each length class was calculated by calculating the weight-at-length, W, from the length-weight relationship equation B.4 and multiplying by actual or expected numbers. The proportion of the population sampled, estimated by the ratio of the total biomass of the "actual" population and that of the expected, was 53.8% (table 7.4.1).

The lutjanid table of length-specific *s* was applied to the length frequency distributions of other lutjanids for which specific selectivity indices could not be calculated.

Table B.2.1: Estimated proportion of population of lutjanids species sampled.

Species	**Proportion of population sampled**
Lutjanus vittus	0.5385
L. erythropterus	0.9963
L. malabaricus	0.9905
Pristipomoides multidens	0.8775
L. typus	0.85
L. sebae	0.95
L. lutjanus	0.1207
Pterocaesio chrysozona	0.9750
L. carponotatus	0.9578
Dipterygonotus balteatus	0.7466
Lutjanus sp. (in Yearsley, Last and Ward, 1999)	0.9993

B.3 Carangids

The carangids presented yet another problem besides under-estimation of smaller size classes. Large adult carangids become unavailable to capture by trawl after reaching maturity. A similar procedure as above was used to determine the proportion unavailable beyond maturity, in addition to that unavailable due to mesh selectivity. This was applied only to the larger species of carangids.

Assuming von Bertalanffy growth curve parameters of K = 0.16 and M = 0.36, estimated from the length-frequency routine on *FishBase*, and forcing the line through the age two and 21 values, the equation describing the predicted catch at age curve (figure B.3.1) was:

$$LnN = 7.63 - 0.36T \qquad \text{(B.10)}$$

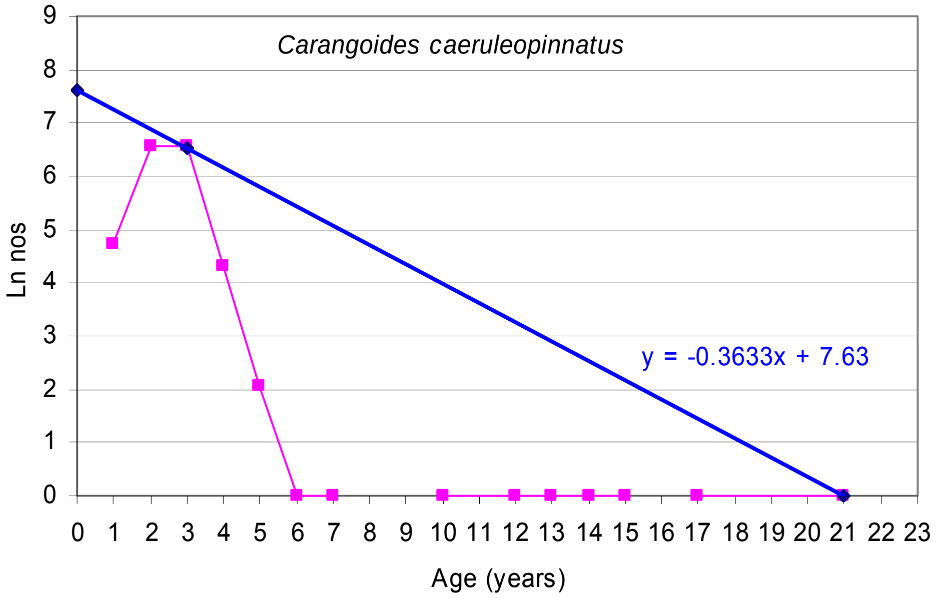

Figure B.3.1: Catch at age plot for *Carangoides caeruleopinnatus* based on data from 1983 to 1995 (pink), and the predicted catch-at-age curve (blue).

Converting the numbers at age curve into a length-frequency distribution and then a biomass structure using the procedures as for the previous species and the formula for weight (biomass):

$$W = W_{\infty}(1\text{-}e^{-KT})^3 \qquad \text{(B.11)}$$

and where W_{∞} is 4,709g. The proportion of population caught was estimated to be 10% (table B.3.1). The length at which the species appeared to be fully selected at about 23 cm slightly smaller than the nemipterids probably due to their higher morphometric profile. However, the generic *s* table of the nemipterids was applied to account for the unsampled small fish, which may over-estimate the under-sampled proportion.

For *C. chrysophrys* only fish greater than 15 cm were sampled (figure B.3.2). The length frequency distribution was converted to age, assuming L_{∞} of 74.4 cm from *FishBase* and K = 0.16 similar to *C. caeruleopinnatus.* A regression through the descending point of this catch-at-age structure showed little evidence of age selectivity in this population. However, assuming size selectivity for fish less than age two, and using the generic size-selectivity table, it was estimated that 61% of the population of this population had been sampled (table B.3.1).

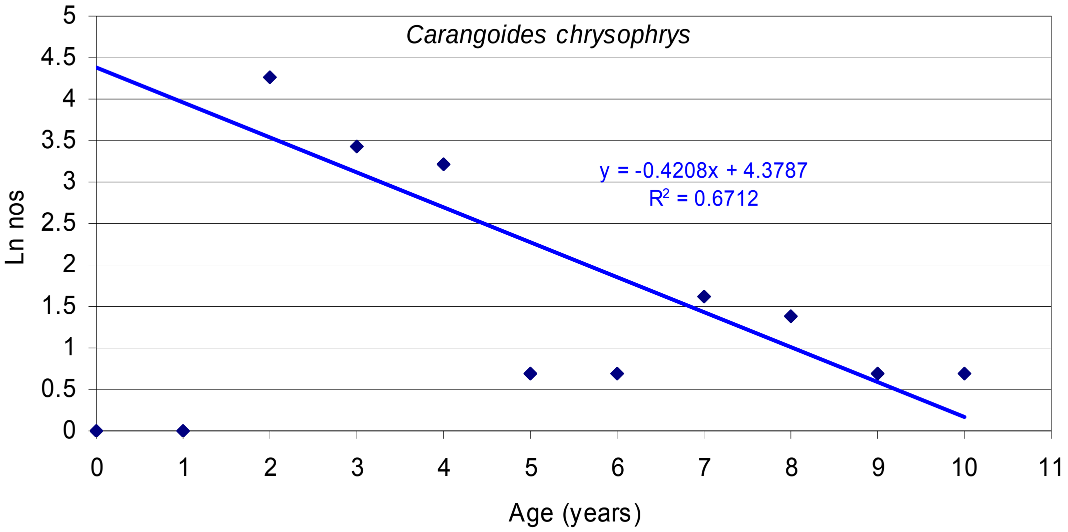

Figure B.3.2: Catch-at-age plot of sampled *Carangoides chrysophrys* population. The equation line is fitted through the descending points.

For the other small carangid species, *C. malabaricus* and *C. equula*, the size selectivity factor was also applied to account for the small fish. The maximum lengths of these two species were less than 30 cm and so the age-selection factor was applied. Only small *C. gymnostethus* were collected although maximum size for this species is reported to be 90 cm. The size selectivity factor was applied, but ignored age selectivity for this species also.

Table B.3.1: Estimated proportions of the carangid populations sampled and the proportion of the sample <30 cm. This length is assumed to be the length at which age the larger carangids mature.

Species	Proportion of population sampled	Proportion of sample <30 cm
Carangoides caeruleopinnatus	0.10	0.88
C. malabaricus	0.06	1
C. equula	0.05	1
C. chrysophrys	0.61	0.23
C. gymnostethus	0.34	0.93

The carangids were split into two stanzas: a juvenile stanza less than 30 cm and an adult stanza >30 cm. This split was intended to represent the majority of the carangid population which was dominated by *C. caeruleopinnatus*. *C. malabaricus* was the second most abundant carangid but the whole sample was <26 cm and was represented in the "juvenile" stanza. The reported max length for this species was 60 cm therefore this may have been underestimated for this species. To estimate the abundance of the juvenile stanza of carangids, the swept-area abundances of the five carangid species in table B.3.1 were scaled by their respective proportions of the population sampled and their proportions of the sample that was <30 cm, and totalled. A total of 0.73 t km^{-2} was estimated as the juvenile carangid biomass. This biomass was entered as the lead stanza biomass.

For both stanzas, diet composition and mortality was entered but for the lead stanza, in this case the juveniles, Q/B and biomass were also entered. The Q/B and biomass for the "adult" stanza is calculated by *Ecopath* using a generic length-weight relationship and assuming a stable mortality and recruitment rate. A von Bertalanffy K of 0.16 and Z of 0.6 was entered and it was assumed that the "juvenile" stanza consisted of fish less up to four years. This gave a population curve structure similar to the reconstructed *C. caeruleopinnatus* except that the larger age classes were included.

B.4 Synodontidae

For *Saurida filamentosa* the deep-water saurid, data from selected research cruises only were used because of problems with identification of the species of *Saurida* in earlier cruises. The remaining length frequency distribution was converted to a catch at age distribution. Data from selected research cruises only were used because of problems with identification of the species of *Saurida* in earlier cruises. Fish at about age five, corresponding to a length of about 20 cm, appear to be fully selectable by the net. Von Bertalanffy growth curve parameters of K = 0.12 and L_∞ of 47.9 cm were estimated from the length-frequency routine in *FishBase*, the equation of the line describing the fully-selected lengths from the catch at age curve (figure B.4.1) was:

$$LnN = 7.6482 - 0.3181T \tag{B.12}$$

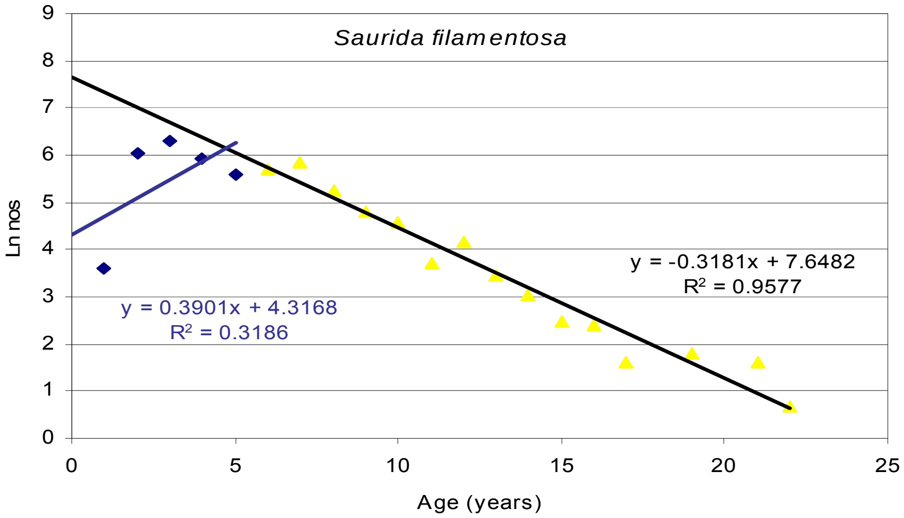

Figure B.4.1: *Saurida filamentosa* catch-at-age curve. The falling line represents fully-selected fish while the rising line represents the under-selected fish.

Converting the numbers at age curve into a length-frequency distribution and then into biomass using the procedures as for the previous species and the formula:

$$W=aL^b \tag{B.13}$$

where $a = 0.014$ and $b=2.84$ (Wen et al. 1987). The proportion of population caught was estimated to be 90% (table B.4.1).

In addition, the selectivity curves were compared for Wen et al. (1991) and Liu et al. (1985) with the values derived from length frequency data of this study. Wen et al. (1991) and Liu et al. (1985) derived selectivity measures for a range of mesh sizes. Because the research surveys used a mesh size of 45 mm, the 40 and 51mm mesh curves of Wen et al. (1991) and Liu et al. (1985) were used, and an average curve was derived by eye (figure B.4.2). The three different selectivity curves used to reconstruct the theoretical population length frequency distributions were then converted to biomass distribution using the length-weight conversion factors above (equation B.7). The size-selectivity table was constructed and applied to the length frequency distribution of *S. undosquamis*, *S. grandisquamis* and *Saurida* sp. 2. The proportions of the saurid populations sampled were then calculated (table B.4.1).

Table B.4.1: Estimated proportions of saurid species sampled by net using the different mesh selectivity indices, *s*, as indicated.

Species	Wen *s*	Liu *s*	Survey *s*
S. undosquamis	0.77	0.84	0.90
S. grandisquamis	0.19	0.26	0.37
S. longimanus	0.26	0.32	0.45
S. filamentosa	0.78	0.79	0.90

B.5 Lethrinidae

The three lethrinids for which length frequency data was available had distinct size ranges: *Lethrinus genivittatus* was the smallest with a length range largely from 10 to 25 cm; *Lethrinus* sp. (Carpenter pers. comm.) had a length range largely between 20 to 35 cm and *L. nebulosus* was the largest of the three with a length range from 35 to 60 cm.

Converting the length frequency of *L. genivittatus* to catch-at-age using $K = 0.31$ and $L_\infty = 33$ cm, the equation of the descending tail of the plot was fitted to the points considered as fully-selected (figure B.4.2). The expected numbers of the under-sampled size classes were calculated using the equation:

$$LnN = 10.31 - 1.8318T \tag{B.14}$$

The biomass of the expected and actual populations were estimated by converting lengths to weight using the length-weight relationship where a = 0.0204 and b = 2.975, and compared to determine the proportion of the population sampled. The result was 88% of the population had been sampled.

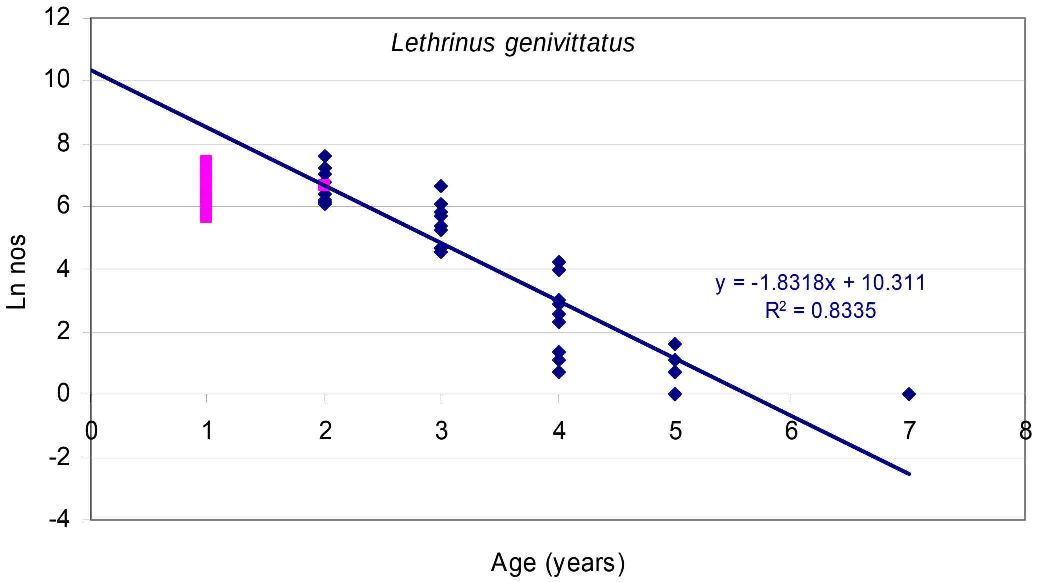

Figure B.4.2: Catch-at-age structure for *Lethrinus genivittatus*.

The *Lethrinus* sp (=*choerorhynchus*) population was mostly in the fully-selected range although the length frequency plot suggested the size selectivity range might be slightly bigger and that older fish might be unavailable as for *Carangoides caeruleopinnatus*. However, this species has not been validated and there is no specific ageing data upon which it could be determined what proportion of older fish might be missing. Therefore the generic size selectivity factors were used to the length frequency data to estimate that about 96% of the *Lethrinus* sp. population had been sampled.

Of the *L. nebulosus* population, only large (>27 cm) fish were caught. Smaller fish are apparently not in the area (K. Sainsbury CSIRO, pers. comm.). Although it was unnecessary to determine the proportion of small fish that were missing because they were all larger than the fully-selected generic size the length frequency distribution was very flat. Suspecting a recruitment variability to be causing it, the cohorts were plotted (figure B.5.1). Rather than show a consistent age at which numbers peaked as would be expected if juveniles were fully-recruiting at that age, the peaks were very variable.

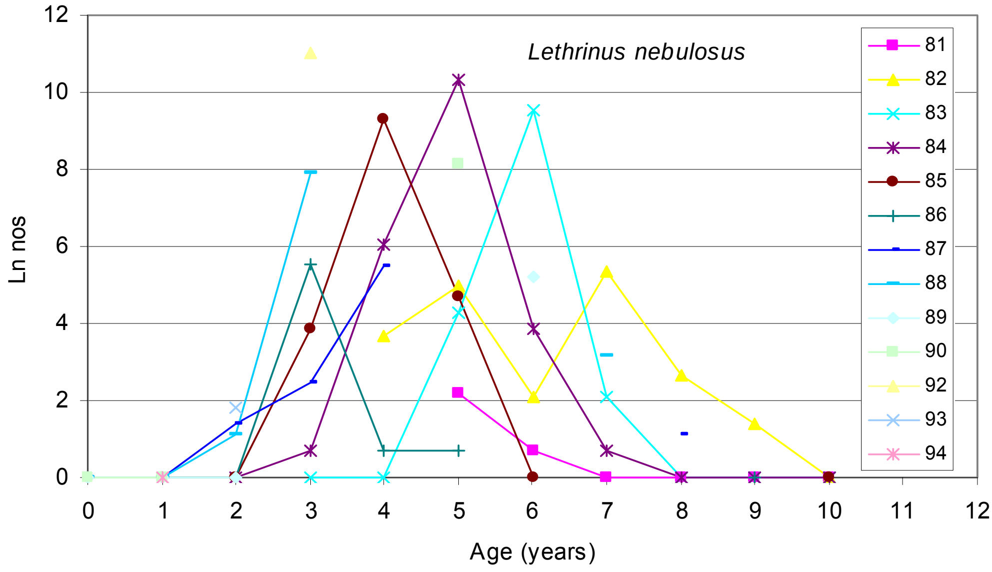

Figure B.5.1: Cohort analysis of *Lethrinus nebulosus*.

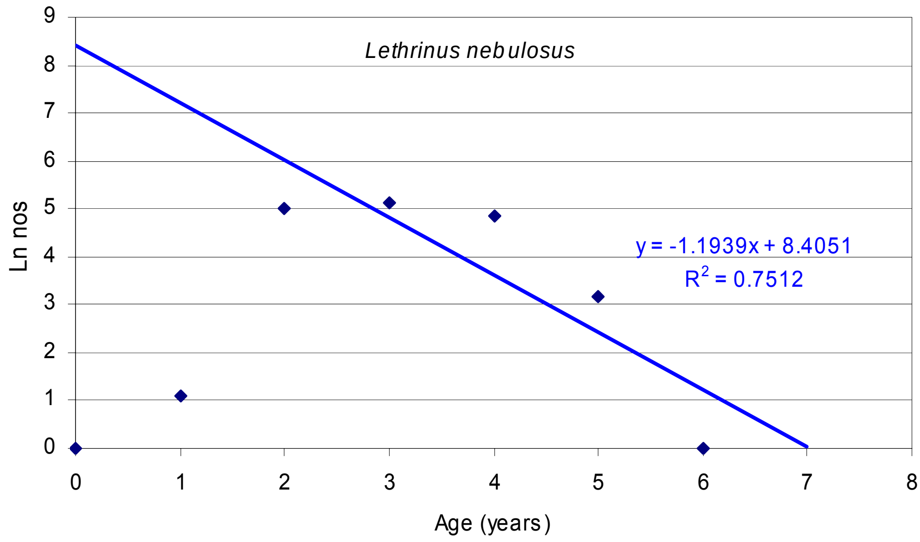

Figure B.5.2: Catch-at-age curve for *Lethrinus nebulosus*.

The fit to the catch-at-age curve (figure B.5.2), derived from K = 0.16 and L_∞ = 87 cm, was not good, which supported the possibility of age-selection variability. Any further estimation using this method was futile and so this species was considered to be fully size-selected.

The large uncertainty of these species' data because of apparently "missing" sections of the populations lessened the reliability of the proportions estimated so that a more conservative value of 0.5 by which to scale up the abundances was taken. This value was smaller than any of the estimates but would allow for some small fish if the assumption that juveniles were never in the area was wrong.

B.6 Mullidae

For three species of Mullidae, *Upeneus moluccensis, Parupeneus heptacanthus* and *Upeneus* sp. the generic size selectivity table for nemipterids was applied as for the previous species. These species are typically very small and the corrections at the lower end of the table are extremely dubious. The resulting proportions of the populations being sampled were very small and also dubious. For these small species, and for other small fishes in general, the lower limit of 5% of the population sampled was assumed.

B.7 Other small species

For all other species designated as “small” (less than 30 cm) the proportion of the populations sampled was assumed to be 5%, similar to that estimated for small species for which data was available. The swept-area abundances were then scaled up accordingly.

The same procedure was followed where von Bertalanffy growth parameters could be found or estimated. By using the length-frequency tool on *FishBase*, or estimating regression through the declining peaks of length frequency distributions, von Bertalanffy parameters could be estimated for each species. Species-specific mesh selectivity indices were calculated. In some species, large annual differences in recruitment masked the natural mortality rate. By differentiating and tracking cohorts, individual mortality rates could be estimated and then averaged.

The size at which species became fully selected varied. These differences might be due to morphological differences. For example, lutjanids might have been selected at a smaller size than nemipterids because their profiles are more humped and spiny, thus catching on the meshes of the trawl net. *Saurida filamentosa* a much more streamlined species than either lutjanids or nemipterids, and presumably able to pass through the meshes more easily, appeared to be fully-selected at greater than 30 cm.

B.8 Small tunas

Estimates of biomass of small tunas could not be properly estimated by the swept-area method therefore, to estimate tuna biomass an approximation method, was devised (M. Basson & R. Campbell, CSIRO). Of the tuna species for which there was any stock assessment information at all, only bigeye tuna *Thunnus obesus* and yellowfin tuna *Thunnus albacares* were likely to be in the study area. The stock assessments available for these species are for the whole Indian Ocean and so estimates of the proportions of the biomass of these fish in this study were made. Longline CPUE data over the period 1986 to 1991 were used as an estimate for the population density. The CPUE per km^{-2} in three 5 degree grid squares, in which the study area sits, was calculated and summed. This CPUE per km^{-2} was divided by the total CPUE per km^{-2} of the whole Indian Ocean as an estimate of the proportion of the biomass in the relevant grid squares. This proportion was multiplied by the IOTC stock assessments for each species averaged over 1986 to 1991. The resulting biomass was area corrected for the grid squares. The estimates for bigeye biomass were 0.007 to 0.009 t km^{-2}, or about 0.16 to 0.22 individuals km^{-2}, assuming an adult fish weighed 40 kg; and for yellowfin 0.056 to 0.315 t km^{-2}, or about 1.6 to 9 individuals km^{-2}, assuming an adult fish weighed about 35 kg. The average values were summed to give 0.097 t km^{-2}.

It must be emphasised that because the tuna assessment is very uncertain, the approximation method used here increases the uncertainty of this estimate, and doesn't include other small tuna species. This must lead to a very conservative estimate of this group in the study area but the impact of these species was thought to be small if they are highly mobile, migratory and particularly if they feed outside of the study area.

B.9 Catchability factor from *Lutjanus sebae* stock assessment

The swept-area abundances from the survey data were scaled up according to the size-selectivity calculated in the previous sections and then by another catchability factor derived from the stock assessment of *Lutjanus sebae* compared to the rescaled swept-area abundance. *L. sebae* was estimated to be about 95% sampled. It was assumed no size-selectivity thus the swept-area abundance was estimated at 0.052 t km^{-2}. This biomass was then compared to that derived from stock assessments. Spawning biomass for the areas relevant to this study area (areas 0 to 4) were summed and multiplied by three to account for non-spawning stock (Stephenson & King, 2000; P. Stephenson pers. comm.). This biomass was obtained for the depth range 50 to 120 m, that in relation to this study area would be about 60% of this study area, or about 42000 km^2. This resulted in an estimated abundance of 0.119 t km^{-2}in the stock assessment area. Based on the assumption assumed that this abundance was the same throughout this larger study area, the swept-area abundance was 0.44 of the assessment abundance. Consequently, abundances for most trawl-caught species were scaled up according to this catchability factor. Alternatively, it was considered that the population was not sampled throughout its entire depth range for the stock assessment 50 to 120 m because about 24% of the red emperor catches were from habitats that were shallower and deeper. Consequently, the total tonnage of red emperor from the stock assessment surveys was scaled up by 24% and divided by the total study area. The swept-area abundance of the scientific surveys was then 0.63 of the rescaled stock assessment abundance. Another alternative is that if on survey catches from exactly the same depth range of the stock assessment range were compared, out abundances were 0.36 of the stock assessment abundance. The 0.44 factor was chosen because it was mid-range of the alternatives and similar to the catchability factor of 0.5 usually applied in stock assessments. This probably would result in higher estimates for many fish species.

Sharks and tunas which were largely caught by non-trawl methods, and then aggregated according to their designated trophic groups and no catchability factors were applied to these groups (table 4.4.1) *Ecopath*. Catchability was not applied to rays because they were considered large and benthic in habit and likely not to be readily caught compared to other fishes.

APPENDIX C: CATCH PER UNIT EFFORT

Table C.1: Annual catch per unit effort (CPUE) t h^{-1} km^{-2} yr^{-1} estimated only across the trawl-based fisheries: foreign, domestic and prawn and scaled relative to the first year of the simulation (1987).

Trophic group	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
1	1	1.72	0.74	0.53	0.63	1.10	1.33	6.39	11.83	9.76	9.02	13.72	12.52	7.66	10.32
3	1	0.44	9.53	2.76	0.85	1.13	1.47	3.89	5.39	5.42	3.62	5.12	2.73	2.06	4.57
4	1	0.36	0.26	0.15	0.13	1.12	1.60	1.85	5.66	2.63	0.70	0.91	0.79	0.68	0.23
5	1	0.57	1.86	2.37	0.69	1.54	2.19	3.00	7.69	5.33	3.61	3.50	3.03	2.81	2.42
6	1	0.44	1.51	1.03	0.77	5.29	9.11	13.64	37.46	19.82	19.28	36.81	22.18	20.07	20.81
7	1	0.60	0.42	0.15	0.09	1.50	3.47	4.59	4.83	7.18	5.08	9.72	6.39	4.23	4.03
9	-	-	1	1.28	8.02	104.86	139.94	271.83	1118.59	737.10	364.84	330.85	487.63	374.06	295.85
10	1	0.53	1.49	1.38	0.92	4.11	11.39	18.12	31.56	19.30	14.80	19.91	10.92	7.84	5.58
12	1	0.67	0.59	1.18	1.11	2.58	6.84	11.91	21.36	10.49	9.01	22.05	15.00	10.20	9.09
13	1	0.92	0.62	0	0.16	0	0.03	0	0	0.01	0	0	0	0	0
14	1	0.40	0.04	0	0	0	0	0	0	0	0	0	0	0	0
16	1	0.05	0.23	0.10	0.10	1.01	1.77	2.68	5.27	1.86	3.00	6.58	3.48	2.50	2.75
19	1	2.21	2.43	0	0	0	0	0	0	0	0	0	0	0	0
21	1	1.40	2.74	3.61	2.63	2.20	3.55	2.18	5.56	3.48	2.67	2.90	3.34	2.01	1.53
23	1	1.03	1.05	0.77	0.32	0.41	0.66	1.37	2.19	1.94	1.51	2.54	1.71	0.95	0.88
24	1	0.40	0.06	0.04	0.09	0.09	0.64	0.70	1.46	1.25	1.14	3.28	2.90	2.21	1.25
25	1	0.61	0.75	0.62	0.23	1.59	4.22	5.70	15.69	9.98	5.44	10.11	7.75	4.79	3.40
26	1	2.30	1.40	0.02	0.28	0.00	0.10	0	16.53	0.06	8.91	1.14	1.12	1.73	6.35
27	-	-	-	-	-	1.00	0	0	0.06	63.06	0	0	0	0	0
28	1	6.54	1.82	3.18	3.05	1.65	2.38	1.52	2.64	2.60	1.90	2.08	2.54	2.19	2.71
30	1	0.62	0.87	1.38	0.94	1.00	1.14	1.66	1.49	1.32	1.31	1.67	2.36	1.83	0.91
31	1	0.52	1.27	0.53	0.84	2.02	3.12	5.62	6.28	4.89	6.45	8.61	5.09	3.49	7.79

APPENDIX D: TROPHIC GROUP SPECIFICATIONS

Table D.1: Trophic groups and major representative species (not full listing), biological parameters and swept area abundances from scientific surveys. * Values not used in model.

Trophic group no.	Group name	Representative species in group	Common Name	CAAB Code	Rank by catch in 1986-91	P/B	Q/B	Swept-area abundances of trophic group		
								1986-91	1995	1997
1	Coastal sharks	*Sphyrna mokarran*	Great hammerhead	37019002	-	0.12	1.80	0.0229	0.0890	0.0230
		Galeocerdo cuvieri	Tiger shark	37018022	292	0.12	1.60			
		Carcharhinus plumbeus	Sandbar shark	37018007	126	0.12	2.10			
		Carcharhinus sorrah	Spot-tail shark	37018013	370	0.52	7.40			
		Hemigaleus microstoma	Weasel shark	37018020	71	0.39	5.60			
		Loxodon macrorhinus	Sliteye shark	37018005	88	0.43	5.00			
2	Rays	Dasyatididae	Rays	37035000	39			0.1288	0.0809	0.1983
		Dasyatis thetidis	Black stingray	37035002	11	0.16	2.00			
		Himantura toshi	Back-spotted whipray	37035020	89	0.28	5.70			
		Himantura uarnak	Reticulate whipray	37035003	25	0.14	2.50			
		Rhynchobatus djiddensis	White-spotted guitarfish	37026001	32	0.19	2.80			
		Taeniura meyeni	Blotched fantail ray	37035017	29	0.18	2.20			
		Aetobatus narinari	White-spotted eagle ray	37039003	539	0.18	2.40			
3	Small tunas	*Thunnus obesus*	Bigeye tuna	37441011		0.37	8.30	0.0004*	0.0000*	0.0008*
		Scomberomorus commerson	Narrowbanded Spanish mackerel	37441007	381	0.39	9.20			
		Euthynnus affinis		37441010		0.70	9.80			
		Katsuwonus pelamis		37441003		0.94	24.00			
4	Shallow Lethrinids	*Lethrinus* sp. 1	Lesser spangled emperor	37351001	3	0.47	6.30	0.1388	0.6858	0.0887

Trophic group no.	Group name	Representative species in group	Common Name	CAAB Code	Rank by catch in 1986-91	P/B	Q/B	Swept-area abundances of trophic group		
								1986-91	1995	1997
		Lethrinus nebulosus	Spangled emperor	37351008	33	0.47	6.30			
5	Red Emperor	*Lutjanus sebae*	Red emperor	37346004	6	0.43	4.40	0.1191	0.2061	0.1759
6	Shallow Lutjanids	*Lutjanus malabaricus*	Saddle tail seaperch	37346007	23	0.30	4.20	0.2651	0.4601	0.7818
		Lutjanus vittus	Brownband seaperch	37346003	10	0.56	7.30			
		Lutjanus erythropterus	Crimson seaperch	37346005	57	0.72	6.65			
		Pristipomoides multidens	Jobfish	37346002	12	0.52	5.10			
		Pristipomoides typus	Jobfish	37346019	85	0.51	5.80			
7	Shallow Nemipterids	*Nemipterus furcosus*	Rosy threadfin bream	37347005	1	0.83	10.40	2.4342	3.1755	4.7282
		Nemipterus celebicus	Striped threadfin bream	37347004	34	0.92	12.70			
		Scolopsis monogramma	Rainbow monocle bream	37347006	17	0.80	10.30			
8	Deep Nemipterids	*Nemipterus bathybius*	Yellow belly threadfin bream	37347001	30	0.92	9.30	0.9733	1.0524	2.3758
		Nemipterus virgatus	Yellow-lipped threadfin bream	37347009	50	0.85	9.00			
9	Shallow Serranids	*Epinephalus multinotatus*	Rankins cod	37311010	35	0.44	5.00	0.0289	0.1233	0.0348
10	Frypan bream	*Argyrops spinifer*	Frypan bream	37353006	16	0.37	6.10	0.0491	0.1037	0.1135
11	Shallow carangidae (juvenile)	*Carangoides caeruleopinnatus*	Coastal trevally	37337021	31	0.80	6.80	0.7989	0.8268	0.9551
		Carangoides chrysophrys	Longnose trevally	37337011	68	0.51	5.00			
		Carangoides gymnostethus	Bludger	37337022	55	0.45	4.50			
		Seriolina nigrofasciata	Black-banded kingfish	37337014	81	0.54	5.70			
		Carangoides malabaricus		37337005	83	0.60	4.60			
12	Deep carangidae (adult)	*Carangoides caeruleopinnatus*	Coastal trevally	37337021	31	0.80	6.80	0.1911	0.3037	0.1977

Trophic group no.	Group name	Representative species in group	Common Name	CAAB Code	Rank by catch in 1986-91	P/B	Q/B	Swept-area abundances of trophic group		
								1986-91	1995	1997
		Carangoides chrysophrys	Longnose trevally	37337011	68	0.51	5.00			
		Carangoides gymnostethus	Bludger	37337022	55	0.45	4.50			
		Seriolina nigrofasciata	Black-banded kingfish	37337014	81	0.54	5.70			
		Carangoides malabaricus		37337005	83	0.60	4.60			
		Carangoides equula		37337013	58	0.84	8.20			
13	Small pelagic fishes	*Sardinella albella*	gold-stripe sardine	37085014		2.98	35.60	1.8032	0.5313	1.8268
		Herklotsichthys koningsbergeri	large-spotted herring	37085007	0	1.60	34.40			
		Decapterus russelli	Indian scad	37337023	84	1.14	8.40			
		Auxis thazard		37441009		1.44	6.10			
14	Shallow lizardfish	*Saurida undosquamis*	Brushtooth Lizardfish	37118001	2	1.09	8.20	0.7787	0.7247	1.2268
15	Deep lizardfish	*Saurida filamentosa*	White-spot lizardfish	37118006	8	1.18	11.40	0.2442	0.2348	0.3277
16	Shallow mullidae	*Parupeneus heptacanthus*	Red spot goatfish	37355004	13	0.86	9.00	1.8433	1.9024	3.3017
17	Deep mullidae	*Upeneus moluccensis*	Gold-band goatfish	37355003	5	1.88	9.80	3.2967	0.8043	5.2948
18	Shallow Triggerfish	*Abalistes stellaris*	Triggerfish	37465011	4	0.60	5.60	0.1748	0.3413	0.3481
19	Shallow Sweetlip	*Diagramma labiosum*	Painted sweetlip	37350003	7	0.45	10.70	0.1110	0.1617	0.1369
20	Deep Ponyfish	*Leiognathus bindus*	Orange tipped ponyfish	37341002	28	1.98	28.40	0.8166	0.3344	2.5799
21	Shallow small fish	small fish (<30)						5.9746	5.4797	8.4010
22	Deep small fish	small fish (<30)						2.3426	0.5336	2.4845
23	Shallow medium fish	medium fish (30-50)						0.3480	0.4477	0.7389
24	Deep medium fish	medium fish (30-50)						0.0679	0.1864	0.0741
25	Shallow large fish	large fish (>50)						0.2432	0.2824	0.8857
26	Deep large fish	large fish (>50)								
27	Sessile epibenthos	Sessile epibenthos sponges, corals				1.0	12.00	-		
28	Megabenthos	large mobile invertebrates				3.10	20.00	-		

Trophic group no.	Group name	Representative species in group	Common Name	CAAB Code	Rank by catch in 1986-91	P/B	Q/B	Swept-area abundances of trophic group		
								1986-91	1995	1997
		incl. octopus, bivalves, crabs, prawns) >20 mm								
29	Macrofauna	infauna (polychaetes) & small epifauna <20 mm (benthic copepods) & meiofauna				2.90	10.00	-		
30	Prawns	commercial prawns; bananas, tiger, king				7.57	37.90	-		
31	Cephalopods	squids				4.59	17.55	-		
32	Large zooplankton	zooplankton >20 mm, carnivorous jellies, ichthyoplankton				20	40	-		
33	Small zooplankton	zooplankton <20 mm including pelagic copepods				40	80	30		
34	Pelagic phytoplankton					240	-	35		
35	Benthic phytoplankton					20	-	40		
36	Microphytobenthos					24	-	24		
37	Detritus							100		

APPENDIX E: ANNUAL CATCHES

Table E.1: Annual catch, Y, (t km^{-2}) per trophic group combined across all fisheries.

Trophic group	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
1	0.0007	0.0004	0.0005	0.00004	0.00005	0.0001	0.0001	0.0006	0.0008	0.0009	0.0012	0.0011	0.0010	0.0009	0.0011
3	0.0002	0.0001	0.0003	0.0001	0.00002	0.00002	0.00002	0.0001	0.0002	0.0001	0.0002	0.0001	0.0001	0.0001	0.0002
4	0.0057	0.0033	0.0025	0.00005	0.00005	0.0003	0.0005	0.0005	0.0011	0.0010	0.0003	0.0003	0.0003	0.0003	0.0002
5	0.0031	0.0021	0.0078	0.0006	0.0002	0.0005	0.0011	0.0014	0.0022	0.0024	0.0022	0.0014	0.0013	0.0013	0.0013
6	0.0050	0.0043	0.0109	0.0003	0.0003	0.0013	0.0032	0.0051	0.0065	0.0084	0.0103	0.0104	0.0092	0.0094	0.0125
7	0.0080	0.0078	0.0048	0.00005	0.00004	0.0004	0.0018	0.0024	0.0016	0.0040	0.0036	0.0041	0.0032	0.0029	0.0034
9			0.000001	0.000002	0.00002	0.0001	0.0003	0.0005	0.0012	0.0012	0.0007	0.0005	0.0007	0.0006	0.0005
10	0.0011	0.0009	0.0020	0.0001	0.0001	0.0002	0.0008	0.0012	0.0012	0.0015	0.0014	0.0010	0.0008	0.0007	0.0006
12	0.0021	0.0004	0.0004	0.0001	0.0001	0.0002	0.0011	0.0015	0.0013	0.0018	0.0019	0.0028	0.0025	0.0021	0.0023
13	0.00003	0.00005	0.00003		0.0000005		0.0000001			0.00000002					
14	0.0030	0.0019	0.0002												
16	0.0032	0.0003	0.0008	0.00001	0.00002	0.0001	0.0004	0.0006	0.0006	0.0005	0.0010	0.0011	0.0008	0.0008	0.0010
19	0.0001	0.0002	0.0002												
21	0.0024	0.0021	0.0059	0.0015	0.0017	0.0008	0.0024	0.0011	0.0018	0.0020	0.0016	0.0015	0.0019	0.0013	0.0014
23	0.0099	0.0073	0.0092	0.0004	0.0002	0.0003	0.0007	0.0014	0.0013	0.0016	0.0019	0.0019	0.0016	0.0013	0.0018
24	0.0030	0.0019	0.0002	0.00001	0.00001	0.00001	0.0001	0.0002	0.0002	0.0003	0.0003	0.0006	0.0006	0.0005	0.0004
25	0.0156	0.0112	0.0145	0.0005	0.0002	0.0010	0.0053	0.0064	0.0093	0.0128	0.0086	0.0094	0.0089	0.0073	0.0063
26	0.00001	0.00001	0.000005	0.0000003	0.0000003	0.0000001	0.000001		0.0003	0.000001	0.0002	0.00002	0.00001	0.00002	0.0001
27						0.00001			0.000001	0.0005					
28	0.0003	0.0018	0.0007	0.0009	0.0010	0.0007	0.0008	0.0007	0.0011	0.0011	0.0008	0.0009	0.0009	0.0008	0.0008
30	0.0053	0.0026	0.0046	0.0083	0.0066	0.0066	0.0053	0.0123	0.0103	0.0075	0.0086	0.0091	0.0135	0.0082	0.0058
31	0.0012	0.0010	0.0017	0.0001	0.0001	0.0001	0.0003	0.0006	0.0004	0.0005	0.0009	0.0008	0.0005	0.0004	0.0011

APPENDIX F: FISHING MORTALITIES

Table F.1: Fishing mortalities used in *Ecosim* time series fitting.

Trophic group	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
1	0.0261	0.0179	0.0231	0.0055	0.0083	0.0095	0.0064	0.0651	0.0774	0.1122	0.1577	0.1751	0.2033	0.2154	0.3633
3	0.0008	0.0005	0.0029	0.0042	0.0061	0.0060	0.0058	0.0096	0.0120	0.0134	0.0142	0.0135	0.0126	0.0113	0.0139
4	0.0038	0.0034	0.0094	0.0025	0.0017	0.0013	0.0011	0.0092	0.0056	0.0076	0.0077	0.0058	0.0039	0.0033	0.0111
5	0.0434	0.0265	0.0209	0.0008	0.0008	0.0046	0.0055	0.0055	0.0119	0.0102	0.0027	0.0035	0.0039	0.0032	0.0016
6	0.0293	0.0196	0.0760	0.0118	0.0042	0.0104	0.0131	0.0166	0.0265	0.0309	0.0279	0.0190	0.0186	0.0194	0.0200
7	0.0199	0.0171	0.0449	0.0028	0.0032	0.0156	0.0208	0.0337	0.0441	0.0593	0.0777	0.0850	0.0831	0.0927	0.1361
9	0.0033	0.0033	0.0020	0.0000	0.0000	0.0004	0.0009	0.0012	0.0008	0.0020	0.0018	0.0020	0.0016	0.0014	0.0017
10	0.0054	0.0039	0.0052	0.0002	0.0020	0.0115	0.0145	0.0268	0.0700	0.0736	0.0462	0.0373	0.0541	0.0455	0.0386
12	0.0927	0.0747	0.1312	0.0059	0.0052	0.0173	0.0397	0.0619	0.0635	0.0826	0.0865	0.0688	0.0592	0.0503	0.0521
13	0.0023	0.0004	0.0005	0.0003	0.0003	0.0006	0.0016	0.0024	0.0020	0.0028	0.0030	0.0043	0.0039	0.0033	0.0036
14	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
16	0.0086	0.0056	0.0015	0.0025	0.0036	0.0068	0.0130	0.0168	0.0217	0.0288	0.0276	0.0290	0.0264	0.0240	0.0281
19	0.0000	0.0000	0.0003	0.0008	0.0012	0.0022	0.0042	0.0054	0.0069	0.0090	0.0085	0.0088	0.0078	0.0070	0.0080
21	0.0018	0.0002	0.0004	0.0000	0.0000	0.0003	0.0004	0.0006	0.0006	0.0005	0.0011	0.0012	0.0009	0.0009	0.0011
23	0.0001	0.0000	0.0011	0.0031	0.0045	0.0085	0.0163	0.0212	0.0274	0.0366	0.0354	0.0375	0.0344	0.0316	0.0373
24	0.0005	0.0017	0.0019	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
25	0.0005	0.0004	0.0013	0.0007	0.0010	0.0005	0.0008	0.0004	0.0006	0.0007	0.0006	0.0005	0.0006	0.0005	0.0005
26	0.0305	0.0242	0.0307	0.0030	0.0016	0.0033	0.0046	0.0091	0.0084	0.0107	0.0129	0.0127	0.0114	0.0099	0.0138
27	0.0483	0.0334	0.0039	0.0004	0.0011	0.0010	0.0056	0.0087	0.0096	0.0172	0.0186	0.0343	0.0376	0.0314	0.0255
28	0.0703	0.0548	0.0754	0.0072	0.0042	0.0210	0.0607	0.0775	0.1231	0.1923	0.1604	0.2092	0.2484	0.2795	0.3302
30	0.0079	0.0134	0.0045	0.0003	0.0003	0.0001	0.0013	0.0000	0.1721	0.0005	0.1165	0.0166	0.0091	0.0159	0.1042
31	0.0000	0.0000	0.0005	0.0008	0.0011	0.0011	0.0010	0.0017	0.0021	0.0025	0.0024	0.0023	0.0021	0.0019	0.0023

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