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Neil R. Loneragan, Russell C. Babcock,

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Neil R. Loneragan[1], Russell C. Babcock[2], Hector Lozano-Montes[3] and Jeffrey M. Dambacher[4]

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[1]Centre for Fish and Fisheries Research, School of Biological Sciences and Biotechnology, Murdoch University, South Street, Murdoch, Western Australia 6150, Australia;
E-MAIL: n.loneragan@murdoch.edu.au

[2]CSIRO Marine and Atmospheric Research, PO Box 120, Cleveland, Queensland 4163, Australia;

[3]CSIRO Marine and Atmospheric Research, Underwood Avenue, Floreat, Western Australia 6014, Australia;

[4]CSIRO Mathematics, Informatics and Statistics, GPO Box 1538, Hobart 7001, Tasmania, Australia.

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2006/038 Evaluating how food webs and the fisheries they support are affected by fishing closures in Jurien Bay, temperate Western Australia

PRINCIPAL INVESTIGATOR: Prof. Neil R. Loneragan
ADDRESS: Centre for Fish and Fisheries Research, School of Biological Sciences and Biotechnology, Murdoch University, South Street, Murdoch, Western Australia 6150, Australia

OBJECTIVES:

1. Evaluate how food webs and the fisheries they support are likely to be influenced by fishing closures in the Jurien region.
2. Investigate how past and future changes in abundance of key fished species (e.g. Western Rock Lobster, Pink Snapper, Wrasse, Dhufish) are likely to influence other species.
3. Investigate the effectiveness of area closures and alternative management approaches for conserving food webs and fisheries.
4. Identify useful indicators of ecosystem response to changes in the environment and management systems.

During the course of the project, however, several complementary studies were undertaken to improve the understanding of the interaction between environmental and biological components. These include the effect of climate change on the ecosystem of Jurien Bay.

NON TECHNICAL SUMMARY

OUTCOMES ACHIEVED TO DATE

This project built on collaborative research in the Jurien Bay Marine Park to develop quantitative models of the ecosystem in this region (Ecopath, Ecosim and Ecospace) and qualitative models of different parts of the ecosystem. These models were used to evaluate the effects of different management options, such as controls on fishing effort and different spatial closures, on fished species (e.g. Western Rock Lobster, Dhufish, Pink Snapper) and the trophic interactions in the ecosystem. In addition to evaluating different management options, the process of developing the model through a series of workshops provided a mechanism for integrating research from previous studies and building understanding about the ecosystem and model among researchers, managers, fishers. The Ecopath model consisted of 80 functional groups (more than 200 species), including 31 fish groups, 26 invertebrates, 11 primary producers, two marine mammals, two seabirds and eight non-living groups. The Advisory group for the project, which had representatives from the Department of Fisheries WA, Department of Environment and Conservation, RecFishWest, RLIAC, and WAFIC, provided directions for developing the management scenarios for evaluation by the quantitative models, including recent changes to fishing regulations in the West Coast region. The final stage of the model can address key ecological questions in the system and explore the dynamics of target species such as Western Rock Lobster and top predators under different fishing regimes. The benefits from the spatial closures, evaluated by Ecospace, vary greatly between species – they were much more effective for relatively sedentary species such as Dhufish and Pink Snapper than migratory species such as sharks.

This project was developed to synthesise the ecosystem understanding gained from previous, comprehensive empirical studies of the Jurien Bay marine ecosystem, and build models of the food web in the Jurien Bay ecosystem to evaluate different management options for fisheries and closed areas in the region. Quantitative (Ecopath with Ecosim – EwE) and qualitative models (signed digraphs) were developed for the ecosystem of the Jurien Bay Marine Park (~30° S) through a series of workshops with researchers, managers, fishers and fishing

industry representatives and consultation with a Steering Committee, comprised of representatives from the Department of Fisheries, Department of Environment and Conservation, WAFIC and RecFishWest and the project team.

Objective 1: Food webs, fisheries and fishing closures
The Ecopath with Ecosim model, a biomass-based dynamic model, was used to investigate the impact and role of Western Rock Lobster and finfish e.g. Pink Snapper (*Pagrus auratus*), Wrasses (Labridae), Dhufish, Baldchin Grouper (*Choerodon rubescens*) in the shallow waters of this marine park (depths from 0-40 m) and to evaluate their response to changes in fishing closures. The estimated total catches in the marine park for both commercial (340 tonnes in 2006) and recreational fisheries (56 tonnes), were dominated by Western Rock Lobster (*Panulirus cygnus*) (~70% of total catches). The Ecopath model had 80 functional groups and included eight commercial and six recreational fishing gears. Ecopath and Ecosim simulations showed that Jurien Bay is a dynamic system, with low rates of recycling and dominated by the benthic community. A simulated closure of the entire park to all fishing activity introduced over three years, lead after 20 years, to a large predicted increase in biomass (400-700%) of some top-predators, such as Pink Snapper and large sharks, and a smaller 20% increase in lobster biomass, probably because of the recovery of lobster predator populations that are able to consume a greater biomass of lobsters. These results suggest that bottom-up processes have a greater influence than top-down processes on ecosystem function in this system i.e. benthic primary production is a major limiting factor.

Three groups of qualitative models were developed during the first two workshops of the project and focussed on: 1) the overall ecosystem structure, 2) interactions among predatory fish, and 3) fisheries interactions with rock lobsters and their predators. The model of the overall system was relatively stable, largely due to predator prey relations within subsystems (e.g. reef, seagrass, plankton). Many groups in the system responded strongly to algal wracks (floating accumulations of detached macroalgae and seagrass), which are a major pathway of energy flow through the food web. The model of interactions among predatory fish suggested that interactions between large (Dhufish, Snapper, Baldchin Grouper, Breaksea Cod) and small predators (Wrasses, Western Foxfish) could be significantly affected by fishing pressure – e.g. high levels of fishing on the large predators could reduce their biomass and push the system into an alternative state where the small predators dominate and large predators are not able to recover because the small predators prey on their larvae and juvenile stages. The model of fishery interactions identified a number of relatively weak effects including a negative effect of the fishery on adult rock lobster and a positive effect on large predatory fish and cephalopods (through a decrease in their sea lion predators). Ecosystem interactions with the rock lobster fishery were relatively uncertain, and overall there appears to be little chance that increasing fishing facilitates octopus predation on lobsters.

The Ecopath model of Jurien Bay was also used to explore possible fishing strategies to optimize social, economic and ecological objectives. The overall results of these exploratory analyses confirm that fishing and conservation could be compatible in the marine park. However, the low number of scenarios with this 'win-win' characteristic suggests that this would be difficult to achieve for some exploited species such as Rock Lobster, Pink Snapper and Dhufish. These analyses should be regarded as preliminary and providing some indication of how fishing effort should be modified in order to achieve conservation and sustainable fisheries.

Objective 2: Evaluation of past and future changes in abundance of fished species
The results from Ecosim simulations of different scenarios for fishing pressure suggest that a reduction in fishing mortality on the Western Rock Lobster is unlikely to produce major

trophic cascades in the marine park, possibly because the prey of lobster are highly productive and have short life cycles (i.e. small invertebrates and algae). Rock lobster also feed on a wide range of functional groups across many trophic levels, which results in numerous, relatively weak trophic linkages throughout the system. The results of the Ecosim model also found that fishing indirectly affects primary producers by removing the predators of grazing benthic invertebrates. In contrast, to the weak response of the system to changes in lobster biomass, the model predicts much larger responses (> 60% change in biomass) from changes in the biomass of benthic primary production by macrophytes. A simulated 50% reduction in fishing mortality over three years for commercial finfish predicted that after 3 years, the total catch would decline by about 10%, but that the biomass of important fished species, Pink Snapper and Dhufish, would increase by up to 200% after twenty years. The biomass of adult lobster was predicted to increase by ~30% at the end of the run. This could be explained because the predicted increase in biomass of Pink Snapper increased the predation mortality on octopus, one of the main predators of adult rock lobsters. When a 50% increase in recreational fishing was simulated, significant reductions in the biomasses of target species (up to 30%) were predicted after 20 years. Species such as Pink Snapper and Baldchin Grouper were the most impacted (declining by 20-25% of their biomass), followed by lobster (a reduction of ~20%). No major changes in the total catch (<10%) were predicted by the model, which implies that the catch per unit effort will have declined significantly with the 50% increase in recreational fishing.

Another component of the Ecopath with Ecosim modelling of Jurien Bay was to integrate knowledge from ecological and social fields in attempting to reconstruct past stages of this ecosystem, using an approach that incorporate Local Fisher's Knowledge (LFK). The results from 20 interviews suggested that fishers perceive that most of the fishery resources in Jurien Bay have declined over the past 25 years (1980-2006). A few groups, such as sea lions, apparently have been increasing since the 1990s. The information gathered from LFK represents the only way to estimate past abundances for many non-commercial species (e.g. seabirds, marine mammals, fishes and invertebrates) in the region. Overall, this LFK material displays the potential value of LFK and social participation in the management of marine ecosystems.

Objective 3: Effectiveness of areal closures

An Ecospace model, using a 60 x 100 cell grid (grid size ≈ 2.25 km^2), was developed to investigate the potential impacts of spatial closures on key species and the food webs in the Jurien Bay Marine Park. The effectiveness of the closed areas was explored using five Ecospace scenarios. The results suggest that the introduction of the current management zones with 4% of the area in sanctuary zones produced a modest increase of ~5% in the biomass of Western Rock Lobster after 20 years, even with stable fishing effort. However, Western Rock Lobster biomass increased by ~20% when the sanctuary area covered 25% of the Park. Similar trends were observed for exploited fish species such as Pink Snapper, Dhufish, and small sharks with their biomasses predicted to increase by up to 30% as the area of sanctuary zones increase from 4% to 25%. When the sanctuary zones were removed, i.e. the area was opened to fishing and fishing effort was maintained at its current levels, significant declines in biomass were predicted for some species after 20 years. The biomass distribution predicted by the model is very sensitive to the movement rates of species, which are key parameters that are used in evaluating the potential effectiveness of closures. This highlights the need for further tagging studies to estimate the movement and dispersal rate of lobster and key fished species.

Objective 4: Indicators of ecosystem response

The different modelling approaches have identified some ecosystem indicators for the Jurien Bay marine ecosystem. They include the biomass and productivity of the macroalgae, the ratios of: benthic to primary productivity; pelagic to demersal fish biomass; and target to non-target species, and the biomass and productivity of small and large predatory fish. In addition, the trophic level of the catch and the distribution of the total system biomass and catch at different trophic levels of this ecosystem can be followed through time, providing a useful means of assessing the status of the Jurien Bay fished marine ecosystem.

Additional research: Effects of climate change
The Ecosim model was also used to understand the potential effects of climate change in the Jurien Bay region. The affects of climate change were evaluated by downscaling changes in primary productivity based on predicted environmental conditions for the region from the CSIRO Mark 3.5, General Circulation Model. This model predicted a relative change in pelagic primary production by 2100, or approximately 100 years, of an increase in production by about 11% ($\approx$ 0.11% year^{-1}). This predicted change in primary production was associated with a decline of ~4% (~50 tonnes km^{-2}) in the total biomass in the marine park and a decline of ~3% (12 tonnes km^{-2}) in the total catch. These results challenged some general predictions of the ocean-drive model Mk3.5 i.e. that the increased pelagic primary production will produce positive outcomes for fisheries catch. Our results highlight the need to develop small-scale coastal primary producer models that include benthic primary production on which coastal ecosystems in temperate Western Australia, such as Jurien Bay, are highly dependent. These models will provide more accurate predictions on the effects of climate change on marine ecosystems.

KEYWORDS: food web model, fisheries, ecological interactions, Western Rock Lobster, marine protected area, climate change

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1. BACKGROUND

This project addresses Challenges 1 (“Maintain and improve the management and use of aquatic natural resources to ensure their sustainability”) and 2 (“Resource access and allocation) of the FRDC Research and Development Plan (2005-2010), by investigating the influence of closed areas on food webs and the fisheries they support. It also addresses all four areas for investment in research and development identified in a recent FRDC funded review of ecosystem based fisheries management (Smith *et al.*, 2004), particularly areas 1 and 4 which focus on predicting the outcomes of spatial management and improving ecosystem-level performance assessment. The project proposal has been developed in consultation with a wide variety of groups through a workshop on the CSIRO Collaborative project on the Jurien region (see related projects).

Spatial closures have been used in fisheries management for many years, particularly to protect the juvenile habitat or small individuals of exploited species. They are also used to conserve marine biodiversity in the contexts of ecosystem-based management of human activities and regional marine planning. There is increasing scientific evidence demonstrating that the abundance, biomass and length of target fish species increase inside of closure areas to fishing (Babcock *et al.*, 1999; Russ *et al.*, 2005; Watson *et al.*, 2007). The effect of protection of no-take areas on targeted and non-targeted reef fish species in Western Australia has showed in some studies (e.g. Watson *et al.*, 2007) that the abundance inside closure areas was up to eight times greater than their abundance at fished locations, demonstrating that the removal of abundant targeted species from an ecosystem by fishing can indirectly impact non-fished species and alter the trophic structure of fish assemblages. In addition, the importance of fishing closures to the success of conservation efforts has become widely recognised and promoted (Mayfield *et al.*, 2005), where national and international laws call for broad protection of marine environment for fisheries, marine habitats, marine biodiversity and endangered and protected species.

The application of traditional fisheries management or spatial closures for conserving fisheries or biodiversity, and the question of which approach offers the greatest advantages for economic, ecological and social sustainability, has generated heated debate and conflict among sectors. The use of closed areas has gained greater attention recently for conservation and management plans due, in part, to some the historic fishery collapses. In most of these cases, these fisheries were managed by simple catch or effort regulations. Both catch and effort controls often suffer from implementation uncertainty, that is the inability of management to achieve the stated target because of the difficulty of fully monitoring and controlling catch and effort (Stefansson and Rosenberg, 2005). Furthermore, in effort control-based systems the increased technology and efficiency of the fleets resulted in higher catchability of the fleets with time. Protected areas address the concerns over broader ecosystem protections in some cases (Botsford *et al.*, 2003), preventing bycatch of non-targeted species, protecting habitat from fishing gear damage and providing refuge for a broad range of species in the ecosystem. However, the buffering effect of protected areas is complex to determine and it seems that the combination of substantial MPAs along with quota controls appears to have clear benefits for conservation and sustainability of fishery yields (Stefansson and Rosenberg, 2005). Simply, having a closed area without a measure that provides substantial restrictions of fishing will not help.

The Jurien region in the central West Coast of WA provides an ideal area in which to examine these issues. The region is located in Zone B of the Western Rock Lobster fishery, which accounts for about half of the total commercial Western Rock Lobster catch each year. Commercial and recreational fishing for finfish in the region (e.g. Dhufish, Pink Snapper, and Baldchin Grouper) is also a significant activity. The Jurien Marine Park, a multiple-use marine park extending over about 90 km of coastline and covering an area of about 800 km^2, was declared in August 2003. The park was established to achieve conservation goals but also has the potential to affect fishers, fish stocks and the wider ecosystem in unanticipated ways.

The general zones in the park consist of “no-take” sanctuary zones (~4% of the total area), scientific reference zones (~18%) that allow fishing for Western Rock Lobster and shoreline fishery, but no other forms of fishing, and general use zones (~78%) where all activities are allowed, as before. This means that over 20% of the park is no longer accessible to fishing for finfish and 4% is closed to lobster fishing and all other forms of fishing. The design of the different zones in the park allows the effects of finfishing to be partitioned from those of lobster fishing, and increases the inferential power that can be applied to any conclusions from comparative studies across the zones. From the perspective of the fisheries, the effects of these closures on both the value of fisheries production and the sustainability of the food webs need evaluation. There are many unanswered questions, such as: Will alternative, more traditional fisheries management measures have greater benefits to the fishery than a spatial management framework? Should spatial management be combined with more traditional fisheries management approaches?

Ecological research to describe the distribution and abundance of the flora and fauna of the region was initiated about 12 months after the declaration of the Jurien Marine Park through the Jurien Collaborative Projects (as part of the Strategic Research Fund for the Marine Environment - SRFME). This research, led by CSIRO, collected data on the abundance and biomass of many species in the region with the goal of describing the links and interactions among species and the structure and functions of the biological community. These studies therefore provide much of the basic understanding and inputs to develop fishery-ecosystem models for the region, which will considerably enhance our capability to develop and implement management and policies that optimise all values supported by the system. Previous research, close to the northern boundary of the Marine Park, provides information on components of the ecosystem for the mid-1970s and early to mid-1980s, particularly the inshore populations of Western Rock Lobster. In addition to these data, a time series of data are available for the commercial lobster and finfish fisheries in the area at a resolution of 30' grids. These data are ideal for the construction of ecosystem models. The potential answers to these questions are addressed in Section 5.3 of this report.

A range of ecological modelling approaches, including both qualitative models and Ecopath with Ecosim (EwE), were used to get a better understanding of the complex relationships between habitat structure, species composition, food webs, and multiple uses of marine ecosystems in the central west coast at Jurien. The historical data, ongoing intensive data collections and fisheries data allowed the models to be calibrated and validated. These data, combined with interviews with commercial and recreational fishers who have fished in the region over the past two decades allowed the past states of the system to be characterised. They also provide a means of reconstructing the fishery and evaluating ecological changes over time to create a robust tool for future projections of the state of fisheries and ecosystem and different planning options. In addition to being able to evaluate different management scenarios, the models provided a valuable mechanism for synthesising the current understanding of an area, identifying gaps and priorities for research, and building the capacity for ecosystem research and management.

2. NEED

The closures to fishing declared as part of the Jurien Bay Marine Park are administered by the WA Department of Conservation and Land Management and are intended to conserve marine biodiversity and ecosystem function. The potential effectiveness of these closures for protecting both fished and unfished species, relative to alternative, more traditional, fisheries management strategies, is very uncertain. We used food web linkages between important fish stocks and other biota in the Jurien region to evaluate how the food webs, and hence the fish stocks, respond to fishing closures. This research addressed two of the high priority research areas for the WA FRAB: evaluating the marine park planning (Priority 5); and developing an understanding of the knowledge requirements for cost-effective, ecosystem-based approaches to fisheries (Priority 6). In addition, it provides approaches to assess further the impact and role of Western Rock Lobsters and key finfish e.g. snapper, Wrasse, Dhufish, Baldchin Grouper, in the broader ecosystem. This is one of the questions identified explicitly for investigation by the Rock Lobster Ecosystem Scientific Reference Group and an essential element of strategies to address the ESD obligations of fisheries. Although initially focused on the Jurien region, the qualitative and quantitative modelling approaches increased the general understanding and developed knowledge that can be used to explore management options, including the design of protected areas, in other parts of temperate Western Australia. This project provides approaches to promote the ecologically sustainable use of natural fisheries resources along the temperate west coast, thus helping to meet the requirements for Fisheries under the EPBC Act.

3. OBJECTIVES

1. Evaluate how food webs and the fisheries they support are likely to be influenced by fishing closures in the Jurien region.

2. Investigate how past and future changes in abundance of key fished species (e.g. Western Rock Lobster, Pink Snapper, Wrasse, Dhufish) are likely to influence other species.

3. Investigate the effectiveness of area closures and alternative management approaches for conserving food webs and fisheries.

4. Identify useful indicators of ecosystem response to changes in the environment and management systems.

During the course of the project, however, several complementary studies were undertaken to improve the understanding of the interaction between environmental and biological components. These include the effect of climate change on the ecosystem of Jurien Bay.

4. METHODS

This project built on collaborative research in the Jurien Bay Marine Park to develop quantitative models of the ecosystem in this region (Ecopath, Ecosim and Ecospace) and qualitative models of different parts of the ecosystem. These models were used to evaluate the effects of different management options, such as controls on fishing effort and different spatial closures, on fished species (e.g. Western Rock Lobster, Dhufish, and Pink Snapper) and the trophic interactions in the ecosystem. In addition to evaluating different management options, the process of developing the model through a series of workshops provided a mechanism for integrating research from previous studies and building understanding about the ecosystem and model among researchers, managers, fishers. The Advisory group for the project, which had representatives from the Department of Fisheries WA, Department of Environment and Conservation, RecFishWest, RLIAC, and WAFIC, provided directions for developing the management scenarios for evaluation by the quantitative models, including recent changes to fishing regulations in the West Coast region.

In a series of facilitated workshops marine biologists (8–9 June 2005 and 8–9 November 2006), ecologists and fisheries managers came together to discuss the structure and function of marine ecosystems in Jurien Bay, Western Australia.

4.1 Qualitative modelling

Consensus elicited from the workshops was brought together in a series of qualitative models that addressed key components of the Jurien Bay ecosystem. The models fell into three main groups; 1) overall ecosystem structure, 2) predatory interactions among fish, and 3) fisheries interactions with rock lobsters and their predators. The variables and relationships used in the model were portrayed by sign-directed graphs, or signed digraphs (SDGs), where a link from one variable to another ending in an arrow (→) represents a positive direct effect, such as births produced by consumption of prey, and a link ending in a filled circle (—•) represents a negative direct effect, such as death from predation. All possible relationships can be described in this manner. Pairwise ecological relationships, for example, are portrayed in the following manner: predator-prey or parasitism (•→), mutualism (↔), commensalism (→), interference competition (•—•), and amensalism (—•). Self-effects are shown by links originating and ending in the same variable, and are typically negative (↻•), as in self-regulated variables, but can also be positive (↻) where variables are self-enhancing. Qualitative modelling can also be used to portray complex functional responses between variables, where a variable either enhances or suppresses a pairwise interactions. These *modified interactions* can be accounted for as direct effects between variables by taking the signed product of the interaction modification and the pairwise effects (Dambacher and Jiliberto, 2007). Methods for qualitative modelling can be found in the aforementioned references and in a brief synopsis in Appendix 4.

4.2 Quantitative ecosystem modelling – Ecopath with Ecosim

The quantitative ecosystem modelling of Jurien bay modelling involved a mass-balanced model developed with Ecopath with Ecosim (EwE) to characterise the trophic structure, ecosystem attributes and impact of fishing in the region (see appendix 5 for details of the study area). Using ecosystem-based models such as the food webs developed with EwE it is possible to quantify the interplay of predators, prey and fisheries and to evaluate their response to fishing closures. Ecopath mass-balance models account for trophic interactions among organisms within the defined ecosystem area, averaged over a pre-defined area and time period, at multiple trophic levels (Polovina, 1984; Christensen and Pauly, 1992; Christensen *et al*., 2000; 2004). Summarizing all ecosystem components into a small number of functional groups (i.e., species aggregated by trophic similarity), the box model describes the flux of matter and energy in and out of each group, and can represent human influence through fishery removals and by other means. Dynamic routines (named Ecosim and Ecospace) use the mass-balanced model generated by Ecopath to simulate changes that may include effects of human activities, including fisheries, other disturbances and stressors on the biological components in the system (Walters *et al*., 1997; 2000; Christensen and Walters, 2005), providing an effective tool for evaluating ecosystem impacts. Reviews and criticisms of the EwE approach are provided by Fulton *et al.,* 2003, Christensen and Walters, 2004; Plagányi and Butterworth, 2004 and Pitcher *et al*., 2005. More comprehensive descriptions of the basis, scope and pitfalls of Ecopath with Ecosim (EwE) can be found in Christensen and Walters (2004) and the freely distributed software is available at *www.ecopath.org*. Structure and estimation of model parameters is presented in Appendix 5.

Understanding the impacts of fishing on the trophic structure of ecosystems has become increasingly important because of the introduction of Ecosystem Based Fisheries Management and the legislative requirements of fisheries to demonstrate that fishing activities are not having a negative impact on other species in the environment. To evaluate the impact of fisheries, we developed an Ecosim model of Jurien Bay. It accounts for the biomass flux between groups using coupled differential equations derived from the first Ecopath master equation (Appendix 6). The principle innovation in Ecosim considers risk-dependant growth by attributing a specific vulnerability term for each predator-prey interaction (Walters *et al.*, 2000). The vulnerability parameter is directly related to the carrying capacity of the system, and it describes the maximum allowable increase in the rate of predation mortality on a given prey (Christensen and Walters, 2004). Variable speed splitting enables Ecosim to simulate the trophic dynamics of both slow and fast growing groups (e.g., whales/plankton) or multi-stanza pools such as the four stages of rock lobster considered in our model. In Ecosim, vulnerabilities (V) are assigned to individual predator/prey relationships, indicating whether the biomass of a group is controlled primarily by predators or prey. In Ecosim, vulnerabilities range from 1 to ∞; when V takes high values (’top down’), a high proportion of the biomass is vulnerable to predation. If V is closer to 1.0 (‘bottom up’), prey have the opportunity to find refuge from predators. Initially, the Vs during the fitting process were allocated from 1.0 to 10.0 and the final Vs of each group were set during the tuning of the model with time-series biomass data of rock lobster (see details in Appendix 6). Ecosim dynamic ecosystem simulations were carried out to explore the impact of fishing using different as proposed by the steering committee during past workshops (i.e. June, 2009; WA Fisheries’ Hillarys Laboratories). The four scenarios investigated were: 1) close all commercial fin-fisheries; 2) fishing closures for Dhufish, Pink Snapper and Baldchin Grouper by reducing their fishing mortality by 50% over 3 years; 3) Increasing recreational fishing by 50% over 20 years; and 4) closure of the rock lobster fisheries (commercial and recreational gears. The results of these scenarios were presented in a seminar/workshop discussion group at the Department of Fisheries, Research Laboratories on October 14th 2009. The purpose of the meeting was to gain feedback on the results of Ecosim scenarios developed from a meeting of the Steering Committee in July 2008. The discussions from the meeting were used to complete the final version of the model and its results presented in this report. Appendix 6 presents the calibration of the model and other routines of Ecosim (e.g. Mixed Trophic Impact and Network analysis) used to define the main ecological attributes of Jurien Bay ecosystem and compare it with other ecosystem models characterized by calcareous and limestone reefs with macroalgae assemblages.

4.3 Quantitative modelling – spatial dynamics (Ecospace)

Real ecosystems have spatial dynamics that make them far more complex than those represented in Ecosim (Appendix 6). In order to get a better representation of the basic features of Jurien Bay Marine Park, we implemented a dynamic, spatial version of the Ecopath model (Ecospace), incorporating all the key elements of Ecosim, including different vulnerabilities, rock lobster split pools and fishing mortalities as presented in Appendix 6. Ecospace is the spatial and temporal module of the Ecopath with Ecosim software package (www.ecopath.org; Christensen *et al*., 2005).We used a fully spatial ecosystem model of the Jurien Bay Marine Park that included scenarios with different levels of protection (provided by sanctuaries within the park) to explore the role of fishing closures in the structure and fisheries of this system.

This study is the first application of spatial (Ecospace) modeling in the Jurien region and it evaluates the effectiveness of different MPA configurations. One of the main goals of this project was to develop a biomass-based dynamic model of Jurien Bay Marine Park to investigate the effectiveness of fishing closure areas on both the Western Rock Lobster fishery and the overall functioning of this system. The Ecospace model used for the spatial modelling is presented is presented in Appendix 7. The map used for Ecospace simulations (latitude 31° N- 30° N; longitude 114.95° E – 115.05° E) was drawn on a grid of 6,000 cells (each approximately 2.25 km^2). The fishing pressure and landings were represented in the model using time series of effort per fleet per year that were defined in the Ecopath model (appendix 5). It should be noted that these fleets can be varied independently. The spatial distribution of this fishing effort is then controlled by a 'gravity' model, which allocates effort to each cell proportional to the relative profitability of fishing in each cell. The gravity model allows Ecospace to replicate realistic features of fisher behavior, such as concentration of fishing effort in particular habitats or along MPA boundaries, a factor that has been shown to be important for accurately predicting the effects of MPA establishment (CALM, 2005).

All Ecospace parameters were retained at default setting unless otherwise specified. Robust default estimation for these parameters based on life histories is built into Ecospace (Walters *et al.*, 1999; Christensen and Walters, 2004). It is important to mention that was the overall fishing effort remained the same on the Ecospace scenarios presented in this section and that the reduction of catch responds to a displaced effort to open areas out of the marine park.

The Ecospace habitat base map was designed on the detailed marine biological surveys carried by Burt and Anderton (1997) over 60 km of coastline off the central west coast of Western Australia, from Cervantes to Green Head. Using this comprehensive survey, it was possible to include the major habitat types and management zones of the park. The effectiveness of the closure areas was explored using five Ecospace scenarios (with a 20-year simulations each; and 2007 as baseline): (1) Sanctuary zones covering 4% of the total area; (2) Sanctuary zones increased to 25% of total area; (3) sanctuaries covering 33%; (4) Sanctuaries covering 50% and (5) No sanctuaries. Note that large demersal fish have a similar level of protection in the scientific and puerulus collection zones, where only recreational fishing from shore is allowed, to that in sanctuary areas.

The Ecospace Jurien model is structured on biomass pools, linked by trophic relationships (i.e. predator-prey as presented in Appendix 5), which migrate among the grids of cells of the marine park map. Movements of functional groups are driven by parameters such as foraging behavior, avoidance of predation, and dispersal rates that are linked to a range of defined habitats preferred by each functional group. We did a sensitivity analysis to explore which of these parameters have the strongest impact on the overall biomass predictions, an important step in the understanding of the modeling framework (Appendix 7). A discussion of the capabilities and limitations of Ecospace approach can be found in Christensen and Walters (2004). Results of the final simulations from the Ecospace models were presented to experts of the Department of Fisheries WA and members of the steering committee in October 14th, 2009 (Department of Fisheries, Hillarys, and WA). A summary of the presentation and feedback from this meeting is provided in Appendix 7 and they were used to guide the development of the final report for the project.

4.4 Past ecosystem states of Jurien Bay

As an attempt to reconstruct past stages of Jurien Bay ecosystem, we incorporated the perception, historical anecdotes and environmental knowledge from fisheries of Jurien Bay into the building and enhacement of trophic models of former states of this rich marine ecosystem during the past 20 years. The historical reconstruction of the Jurien Bay ecosystem for the period of 1985 involves an interdisciplinary methodology that integrates knowledge of ecological and social fields. As explained in Appendix 8, the approach uses Local Fisher's Knowledge (LFK) that provides information about the use of natural resources by the local people of the ecosystem (Pitcher *et al.*, 2005; Lozano-Montes *et al.*, 2009). The project is incorporating the perceptions, historical anecdotes and environmental knowledge of fishers from the Jurien Bay region through the data collected by means of twenty semi-structured interviews applied in the region of Jurien Bay (including Green Head and Cervantes). The questionnaire was designed to gain information about the resources, abundances, gear and fishing sites in the region, based on the memory of fishers of different age groups. Because the fishers' use of common names for fish, it was included a picture of the species/groups of the principal species of sea mammals, birds, commercial and non commercial fish, sharks and crustaceans reported to live in the area (see details in Appendix 8). The questionaire followed technical and ethical recomendations proposed by Bunce *et al.,* 2000 and it was approved (July, 2006) by the Human Research Ethics Committee of Murdoch University. The information provided by questionnaires along any additional comments was processed to ensure anonymity, according to the requirements of Human Research Ethics Committee of Murdoch University. This method promotes the participation of local residents from Jurien Bay and summarises their knowledge and understanding of changes of this ecosystem over the past twenty years. This interdisciplinary methodology may help to answer new questions about what this ecosystem was like two decades ago. The project is incorporating the perceptions, historical anecdotes and environmental knowledge of fishers from the Jurien Bay region through the data collected by means of twenty semi-structured interviews applied in the region of Jurien Bay (including Green Head and Cervantes). It is important to keep in mind that LFK is not a result of a systematic scientific study; its strength is in a lengthy series of local observations (Folke *et al*., 2003).

4.5 Evaluating ecological, economic and social objectives

Using the dynamic mass-balanced model of Jurien Bay (Appendix 6), we explore the effect of changes in mortalities imposed by fishing fleets (commercial and recreational) operating in the marine park to investigate possible optimum fishing strategies under specific economic, social and ecological objectives. Fifteen scenarios, categorized by economic, social and ecological criteria, were designed in this exploratory analysis of the optimization of the fisheries in Jurien Bay running from 2006-2016. The original goal of this exploratory analysis is not to incorporate the results from this bioeconomic model into future polices for management of the fisheries in Jurien Bay, instead the scenarios and results of this section only represent a preliminary stage and they must be taken as an exploration exercise which indicates which fishing efforts should be modified in order to achieve conservation under a sustainable fisheries. This modelling framework allows us to change the relative fishing mortalities using the multi-dimensional Davidson-Fletcher-Powell search algorithm included in the *Ecosim* 'policy search' routine (see Appendix 9 for details). This routine seeks an optimum solution based on the weighting assigned to the objectives of the scenario in question (Walters *et al.,* 2002; Christensen *et al*., 2004). The search iteratively changes the fishing mortality of all the gears employed (a total of eight included in the model) in the scenario. The fishing optimization presented in this report is an exploratory approach to maximize three of the critical 'objective functions' considered for management of marine ecosystems defined in Ecosim and recommended by Christensen *et al.,* (2004). These objectives are defined as follow: (1) maximize fisheries rent (The objective is to focus on the fishing efforts of the most lucrative species; e.g. Western Rock Lobster); (2) maximize social benefits, defined here as direct employment in the fisheries; and (3) maximize ecosystem structure or 'Ecological' value. Optimization for ecology often implies a reduction in the fishing effort for all gear types in order to maximize the biomass of the groups that receive a user-set weighting value (Christensen *et al.,* 2004). The search iteratively changes the fishing mortality of all the gears employed (fourteen for the Jurien Bay model) to maximize the objective specified (or a mix of the four objective) over a simulation of the 20 years. Basically, this optimum search maximizes the chosen objectives and provides a forecast of economic values, numbers of jobs, catches and biomasses at the end of the simulation. The catches, discards, fishing efforts data were provided by the Department of Fisheries, WA. Market prices were estimated from the local market in Jurien Bay, WA (April, 2008). This routine will maximize profits and they are calculated based on the catch (catch · price, by species) less the cost of fishing (fixed + variable cost). It is not expected that the Jurien model provide very precise estimates of optimum fishing mortality rates, but at least, the model is able to define prudent ranges of fishing mortalities and points out directions of changes.

4.6 Evaluating the effects of climate change

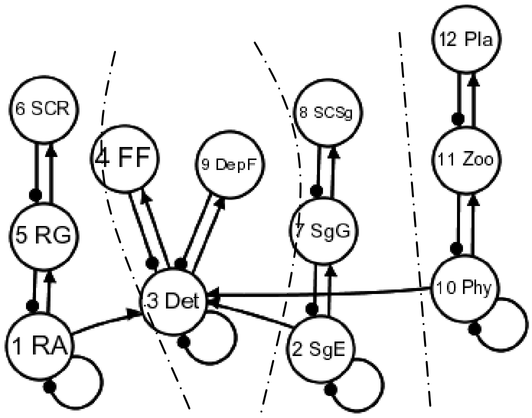
The last section of this report explores the effects of fishing and climate change on marine ecosystems. One of the major changes attributable to climate change on marine ecosystems is the rate and distribution of primary production (e.g. phytoplankton). This change is fundamental for the structure and functioning of marine food webs, resulting in change at higher tropic levels (Hunt and McKinnell, 2006; Shurin *et al.*, 2006). We use the mass-balanced ecosystem model of Jurien Bay presented in Appendix 5 as example of the potential responses of marine ecosystems in Western Australia to climate change (i.e. ocean warming). The effect of climate change on the food web of Jurien Bay was evaluated by downscaling changes in primary productivity. The environmental conditions for the pelagic primary production models were obtained from the Commonwealth Scientific and Industrial Research Organisation's (CSIRO) Mark 3.5 coupled atmosphere-ocean General Circulation Model (GCM, Hirst *et al.*, 2000, Gordon *et al.*, 2002). The relative change in pelagic primary production at 2100 predicted by this Mark 3.5 model for the Jurien Bay region (30°S) was an increase of about 11%. This change in pelagic primary production was used as a driver to run the dynamic food web model (Ecosim model; Appendix 6) of Jurien Bay (structure and input parameters of the model are presented in Appendix 5). Ecosim dynamic simulations were carried out to simulate the impact of increasing pelagic primary production by 11% over 100 years on both the secondary production and fisheries of Jurien Bay. This approach represents our first attempt to incorporate environmental factors into the food web of Jurien Bay in order to gain a better understanding of how changes in this primary production can influence small marine ecosystems in Western Australia.

5. RESULTS & DISCUSSION

5.1 RESULTS: Qualitative model

Nine qualitative models were developed during the two workshops (Figs 1–9). In the first workshop, discussions focused on the major transfers of primary production and detrital material between different types of reef or near-reef habitats (Models I-III). Model I (Fig. 1) details the main sources of primary production in the system, secondary consumers, and detrital flow. As expected, an increase in macroalgae was predicted to lead to an increase in reef grazers and secondary consumers which in turn led to an increase in grazing and consumption, essentially a stable subsystem. A similar scenario was found in the seagrass epiphyte and phytoplankton subsystems. Algal, epiphyte and phytoplankton production all fed into the detrital pool that supported filter feeders and deposit feeders which did not feed directly back into other subsystems. Further details of the output from the qualitative modelling for model I and also models II-IX are provided in Appendix 5.

Model I



Basal resource subsystems: Macroalgae Detritus Epiphytyes Phytoplankton

Figure 1: Signed digraph for Model I: 1 RA: reef macroalgae, 2 SgE: seagrass epiphytes, 3 Det: detritus, 4 FF: filter feeders, 5 RG: reef grazer, 6 SCR: secondary consumer (reef), 7 SgG:

seagrass grazer, 8 SCSg: secondary consumer (seagrass), 9 DepF: deposit feeder, 10 Phy: phytoplankton, 11 Zoo: zooplankton, 12 Pla: planktivore.

Models II and III (Figs. 2, 3) further elaborated the Jurien Bay ecosystem and embedded the various trophic sources and flows within pelagic, reef, sponge, and sand- and seagrass-bed habitats, which included general functional groups for invertebrates and fish. Model II elaborates the structure of the reef ecosystem to a greater extent, including corals and a range of fish and invertebrate consumers. In this model, there is reciprocal feedback between the different subsystems that results from consumption of secondary consumers from seagrass beds and small pelagic fishes by fish predators in the coral and rocky reef habitats. Model III has reduced biological detail in the reef subsystem, but includes reef substratum as a key habitat feature. Additionally, it includes separate piscivore variables in the seagrass and pelagic subsystems, and also includes a sand subsystem. Overall the models behaved similarly to one another. The reciprocal feedbacks between the various subsystems in models II and III produce conditions for stability, but these are relatively minor, and the predator-prey relationships within each subsystem act to maintain overall stability of each model system. A central feature of both models II and III is the transitory presence of algal and seagrass wracks, which constitute a major pathway of trophic flow, and which are subject to wave and current transport among the different habitats, and into and out of Jurien Bay (Figs. 2, 3). Analysis of the model showed strong positive reactions of many groups to an enhanced supply of wrack (i.e., positive response predictions in column 20 of Table 1). Some groups responded negatively, as in the case of grazers in seagrass beds, because of increased predation pressure from secondary consumers that benefit from enhanced trophic flow from increased abundance of wrack grazers. We can have a high level of confidence (>95%) in most of the responses in the model since they have weighted prediction values greater than 0.7 (Appendix 4, weighted predictions (W)).

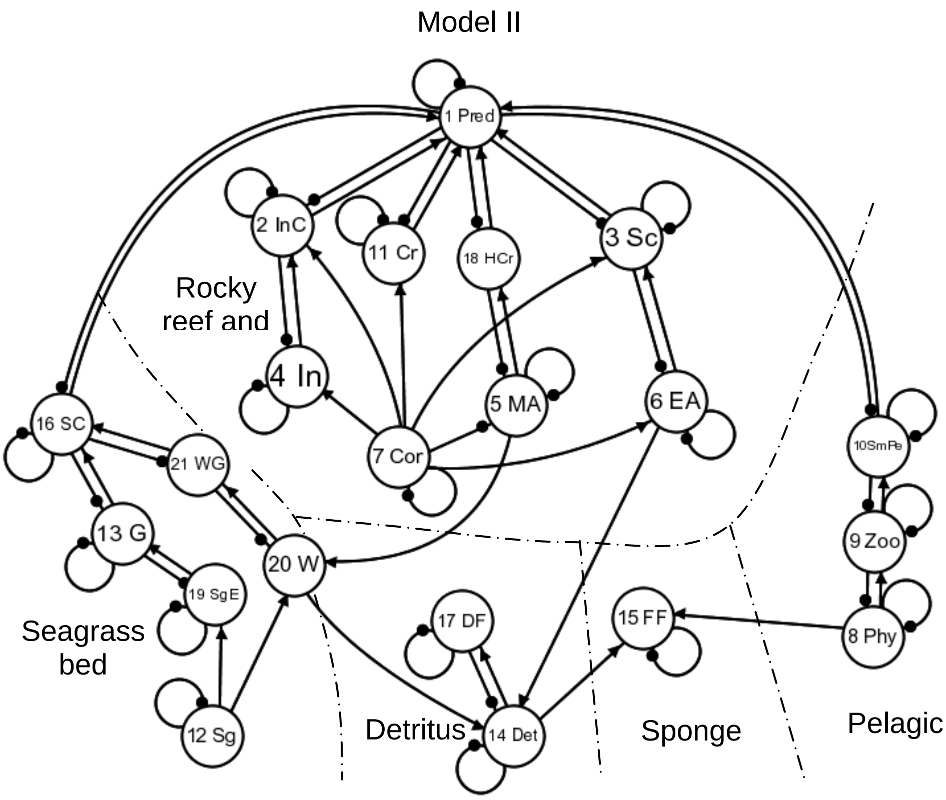


Figure 2. Signed digraph for Model II. 1 Pred: predator, 2 InC: invertebrate consumer, 3 Sc: scraper, 4 In: invertebrates, 5 MA: macroalgae, 6 EA: epiphytic algae, 7 Cor: coral, 8 Phy: phytoplankton, 9 Zoo: zooplankton, 10 SmPe: small pelagics, 11 Cr: croppers, 12 Sg: seagrass, 13 G: grazers, 14 Det: detritus, 15 FF: filter feeders, 16 SC: 2nd consumer, 17 DF: deposit

feeders, 18 HCr: herbivorous croppers, 19 SgE: seagrass epiphytes , 20 W: wracks, 21 WG: wrack grazer.

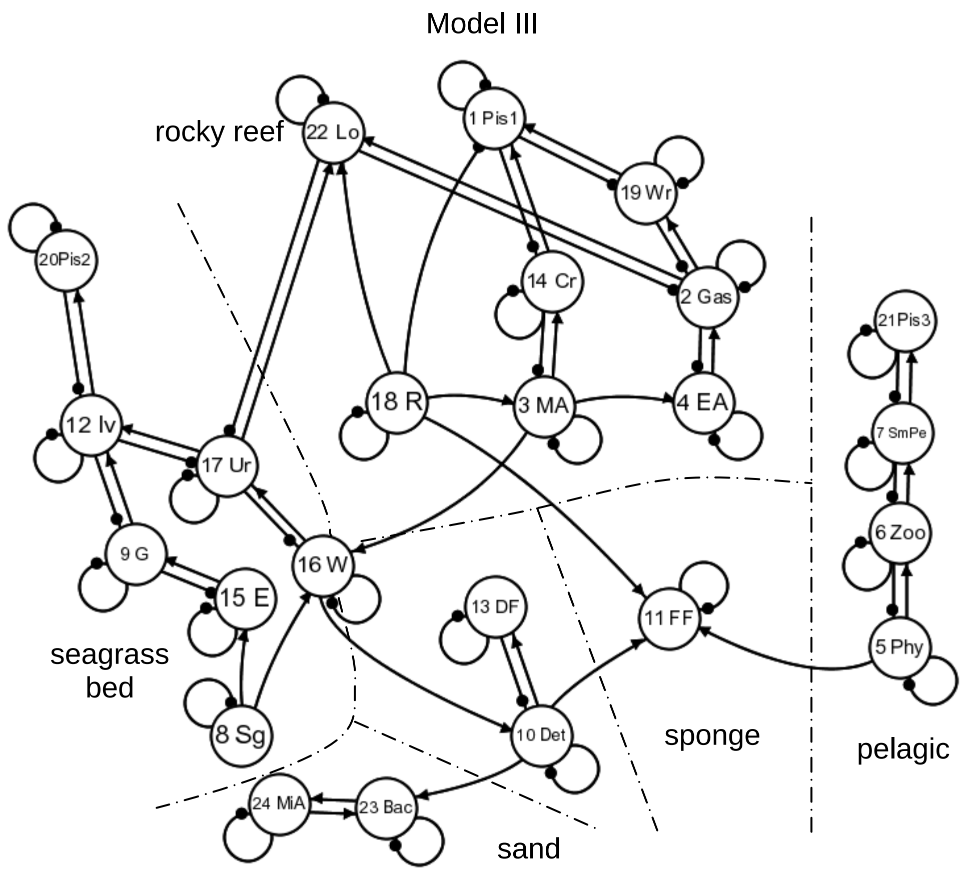


Figure 3. Signed digraph for Model III. 1 Pis1: piscivore 1, 2 Gas: gastropods, 3 MA: macroalgae, 4 EA: epiphytic algae, 5 Phy: phytoplankton, 6 Zoo: zooplankton, 7 SmPe: small pelagics, 8 Sg: seagrass, 9 G: grazers, 10 Det: detritus, 11 FF: filter feeders, 12 Iv: invertivores, 13 DF: deposit feeders, 14 Cr: croppers, 15 E: epiphytes , 16 W: wracks, 17 Ur: urchin, 18 R: reef, 19 Wr: wrasses, 20 Pis2: piscivore 2, 21 Pis3: piscivore 3, 22 Lb: lobster, 23 Bac: bacteria, 24 MiA: microalgae.

Table 1. Model II adjoint matrix (-A): values represent relative strength of reaction (rows) to positive press perturbations (columns) of the system.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1: predator	72	36	36	36	72	36	144	24	24	48	72	72	24	0	0	48	0	24	24	48	0
2: invert. consumer	-36	150	-18	150	-36	-18	264	-12	-12	-24	-36	-36	-12	0	0	-24	0	-12	-12	-24	0
3: scraper	-36	-18	150	-18	-36	150	264	-12	-12	-24	-36	-36	-12	0	0	-24	0	-12	-12	-24	0
4: invertebrates	36	-150	18	186	36	18	72	12	12	24	36	36	12	0	0	24	0	12	12	24	0
5: macroalgae	72	36	36	36	72	36	144	24	24	48	72	72	24	0	0	48	0	-312	24	48	0
6: epiphytic algae	36	18	-150	18	36	186	72	12	12	24	36	36	12	0	0	24	0	12	12	24	0
7: coral	0	0	0	0	0	0	336	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8: phytoplankton	-24	-12	-12	-12	-24	-12	-48	216	-120	96	-24	-24	-8	0	0	-16	0	-8	-8	-16	0
9: zooplankton	24	12	12	12	24	12	48	120	120	-96	24	24	8	0	0	16	0	8	8	16	0
10: small pelagics	-48	-24	-24	-24	-48	-24	-96	96	96	192	-48	-48	-16	0	0	-32	0	-16	-16	-32	0
11: croppers	-72	-36	-36	-36	-72	-36	192	-24	-24	-48	264	-72	-24	0	0	-48	0	-24	-24	-48	0
12: seagrass-epiphytes	0	0	0	0	0	0	0	0	0	0	0	336	0	0	0	0	0	0	0	0	0
13: grazers	0	0	0	0	0	0	0	0	0	0	0	0	112	0	0	-112	0	112	112	-112	0
14: detritus	18	9	-75	9	18	93	36	6	6	12	18	186	62	168	0	124	-168	-106	62	124	-168
15: filter feeders	-6	-3	-87	-3	-6	81	-12	222	-114	108	-6	162	54	168	336	108	-168	-114	54	108	-168
16: 2nd consumer	0	0	0	0	0	0	0	0	0	0	0	336	112	0	0	224	0	-224	112	224	0
17: deposit feeders	18	9	-75	9	18	93	36	6	6	12	18	186	62	168	0	124	168	-106	62	124	-168
18: herbiv. croppers	-72	-36	-36	-36	264	-36	-480	-24	-24	-48	-72	-72	-24	0	0	-48	0	312	-24	-48	0
19: epiphytes	0	0	0	0	0	0	0	0	0	0	0	336	-112	0	0	112	0	-112	224	112	0
20: wracks	0	0	0	0	0	0	0	0	0	0	0	336	112	0	0	224	0	-224	112	224	-336
21: w grazer	72	36	36	36	72	36	144	24	24	48	72	408	24	0	0	48	0	-312	24	384	0

In the second workshop, attention shifted toward developing models that addressed management of stocks of fish and rock lobster. Model IV (Fig. 4a) depicts interactions between species of large predatory fish (e.g., Pink Snapper, Baldchin Grouper, Breaksea Cod and Dhufish), small predatory fish (e.g., King Wrasse and Western Foxfish), and planktivorous fish. A key feature of this system is cannibalism in the large predatory fish, and the regulating effect of small predatory fish and planktivorous fish on large predatory fish via predation on large predatory fish larvae. The interspecific interactions form a set of positive feedback cycles (Fig. 4b), which, if strong, have the potential to create and maintain alternative system states. One possible state of this model system is where large predatory fish exist at a relatively high abundance and, through predation, control planktivorous and small predatory fish at a relatively low abundance. The alternative state is where planktivorous and small predatory fish are at a relatively high level of abundance, which effectively controls large predatory fish at a low abundance through predation pressure on their larval and juvenile life stages. These two alternative states are evident in the predicted responses of the system (Table 2), and appear to be most sensitive to input to the adult and juvenile life stages of adult predatory fish. Thus, input to either of these two variables is predicted to lead to a dramatic self-enhancing shift in the system's equilibrium. Weighted analysis of these predictions generally indicates a high level of predictability (i.e., W > 0.5, Appendix 4).

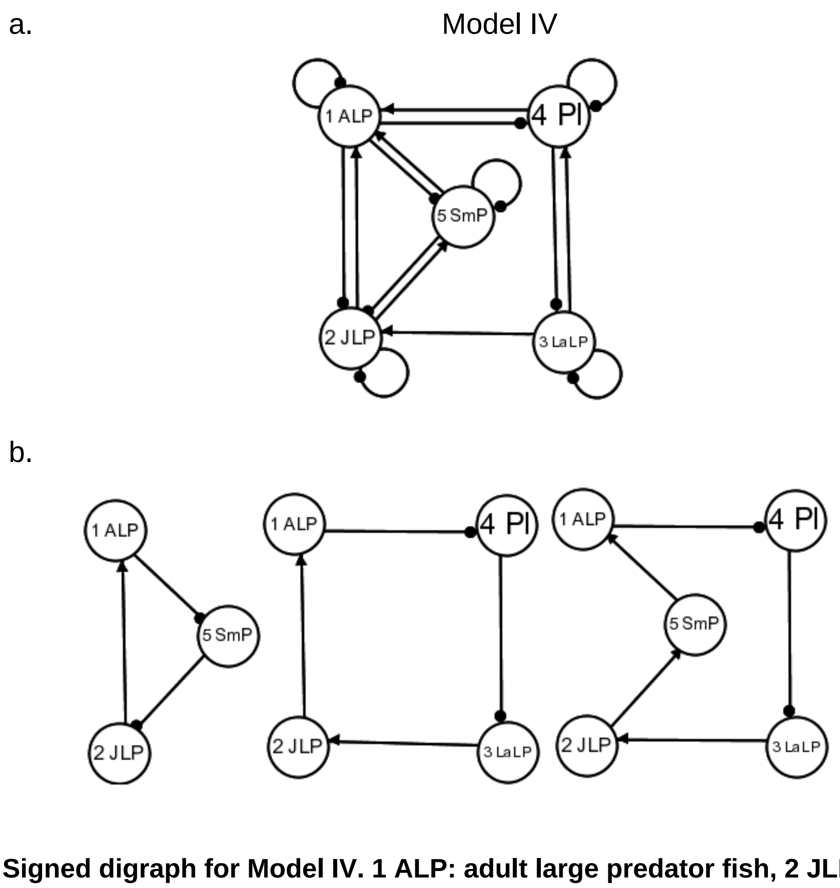


Figure 4. a) Signed digraph for Model IV. 1 ALP: adult large predator fish, 2 JLP: juvenile large predator fish, 3 LaLP: larvae large predator fish, 4 PI: planktivorous fish, 5 SmP: small predator fish. b. Positive feedback cycles of model IV system which contribute to alternative system states.

Table 2. Model IV adjoint matrix (-A): values represent relative strength of reaction (rows) to positive press perturbations (columns) of the system.

	1	2	3	4	5
1: Adult Large Predator	4	4	4	0	0
2: Juvenile Large Predator	1	5	3	-2	-4
3: Larval Large Predator	2	2	6	-4	0
4: Planktivore	-2	-2	2	4	0
5: Small Predator	-3	1	-1	-2	4

Models V and VI are variations on this theme, and include interactions with sharks (e.g., Bronze Whaler, Western Rock Lobster and three separate fisheries. In model V (Fig. 5), a line fishery on large predators (e.g., Dhufish) would release small predator and planktivore populations from predation, allowing their populations to increase, which in turn would inhibit the ability of large predator populations to replenish themselves and may even suppress them further. Potentially the shark fishery may relieve some of this pressure, if the reduction in the level of predation by sharks more than compensates for fisheries mortality. Interactions with the lobster fishery occur through predation by large predators on cephalopods (octopus), which are released from predation. The octopus' ability to prey on lobsters is enhanced by the traps used in the lobster fishery (the lobster fishery is depicted as having an overall positive effect on cephalopods since octopus catch in lobster traps is insignificant). There is therefore a potential negative indirect affect of the line fishery for large predators on lobster.

Model V

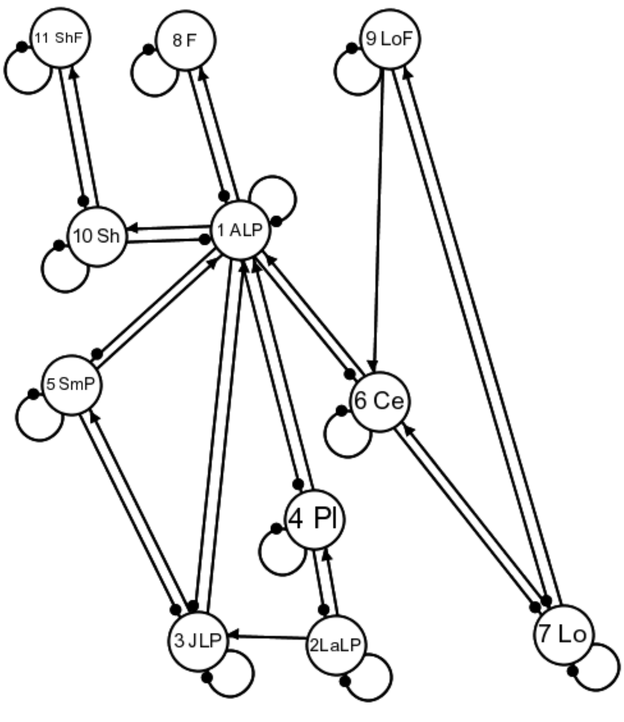


Figure 5. Signed digraph for Model V. 1 ALP: adult large predator fish, 2 LaLP: larvae large predator fish, 3 JLP: juvenile large predator fish, 4 Pl: planktivorous fish, 5 SmP: small predator fish, 6 Ce: cephalopods, 7 Lo: lobster, 8 F: fishery, 9 LoF: lobster fishery, 10 Sh: sharks, 11 ShF: shark fishery.

Model VI (Fig. 6) includes the possibility that small predators and planktivores also prey on puerulus and juvenile lobsters. If these effects are strong, then they would further amplify a negative indirect effect on lobster from the line fishery on large fish predators. In models IV, V and VI, there is no direct local recruitment of large predatory fish, which are presumed to gain recruits primarily from larvae supplied by a larger metapopulation persisting in reef habitats outside of Jurien Bay (i.e., an open population model).

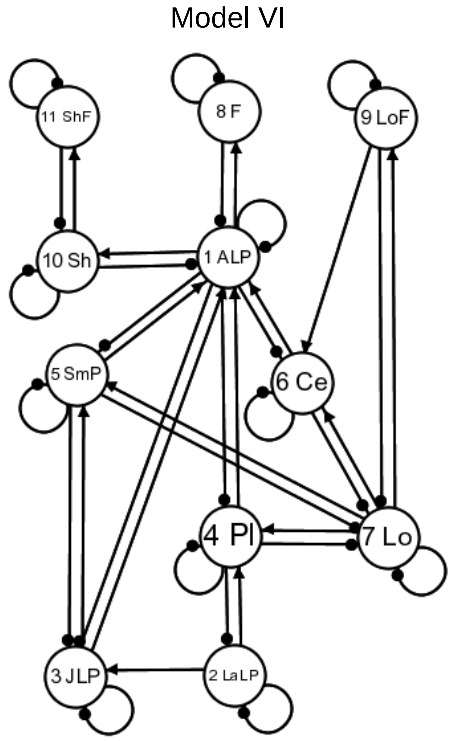


Figure 6. Signed digraph for Model VI. 1 ALP: adult large predator fish, 2 LaLP: larvae large predator fish, 3 JLP: juvenile large predator fish, 4 Pl: planktivorous fish, 5 SmP: small predator fish, 6 Ce: cephalopods, 7 Lo: lobster, 8 F: fishery, 9 LoF: lobster fishery, 10 Sh: sharks, 11 ShF: shark fishery.

Models VII–IX focus on Western Rock Lobster populations and their principle interactions with food resources, predators, and fisheries. Model VII (Fig. 7) depicts lobster using a single population variable, and as in previous models, the lobster fishery facilitates predation on lobsters by cephalopods. The model also includes additional relevant components such as direct predation on lobsters by fish predators as well as sea lions which potentially interact with the fishery indirectly through predation on cephalopods. This model demonstrates that there are a complex suite of components that may directly affect lobster populations, and that more than one of these additional components may be influenced by the fishery.

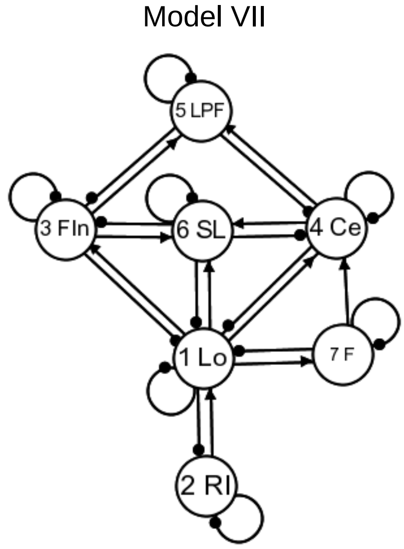


Figure 7. Signed digraph for Model VII. 1 Lo: lobster, 2 RIn: reef invertebrates, 3 FIn: fish invertevore, 4 Ce: cephalopod, 5 LFP: large fish predator, 6 SL: sea lions, 7 F: fishery.

The probability of any one of these groups interacting with lobsters, however, depends on the size or life history stage of lobsters. Consequently Model VIII (Fig. 8) includes six separate rock-lobster life-stages, with separate sources of mortality as well as food resources. Separate food resources were added within the model because lobster life history stages are differentially distributed across the shelf (i.e. juveniles tending to be inshore, adults tending to be offshore). In model VIII, food resources for a given life stage act to accelerate recruitment to the next life stage. Predation effects by invertebrate feeding fish are most important for post-puerulus and juvenile stages while cephalopods, sea lions and the fishery become increasingly important as lobsters mature (Fig. 8). In this model, and in Model IX below, there is no direct local recruitment of lobster larvae, and it is presumed larvae arrive in the system from a larger metapopulation from deep-water habitats along the west coast of Australia.

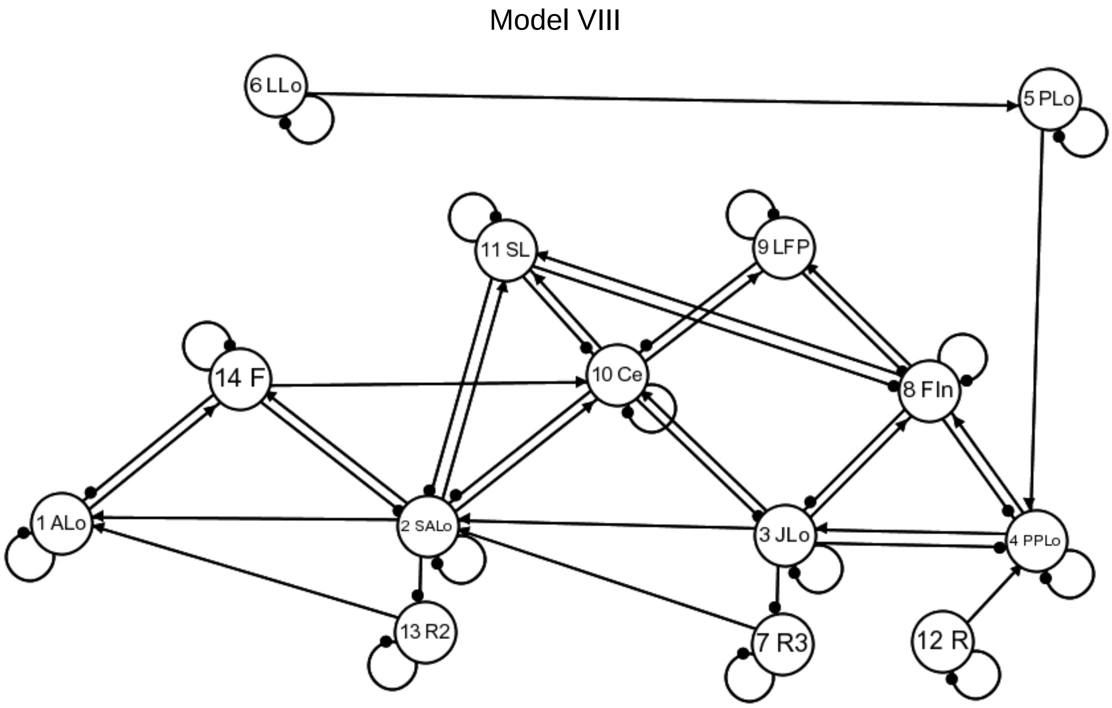


Figure 8. Signed digraph for Model VIII. 1 ALo: adult lobster, 2 SALo: subadult lobster, 3 JLo: juvenile lobster, 4 PPLo: post puerulus lobster, 5 PLo: puerulus lobster, 6 LLo: larval lobster, 7 R3: resource for 3, 8 FIn: fish invertivore, 9 LFP: large fish predator, 10 Ce: cephalopod, 11 SL: sea lions, 12 R: reef, 13 R2: resource for 2, 14 F: fishery.

In model IX (Fig. 9) the separate food resources for each lobster life stage are omitted for simplicity, which allows for a more straightforward analysis of feedbacks with lobster predators and life stage variables. Some unexpected interactions of the ecosystem with the rock lobster fishery are revealed through analysis of Model IX (Table 3). The first of these is that while the fishery obviously has a negative effect on adult rock lobster, it has a positive effect on post-puerulus stages of rock lobster as a consequence of reduced cannibalism by juvenile rock lobster. Large predatory fish and cephalopods were predicted to increase slightly due to the rock lobster fishery, because of a decrease in their sea lion predators which are negatively affected by the fishery. Interestingly, sea lions had a negative effect on all other components of the system, except for juvenile lobsters, which benefitted slightly because of negative effects of sea lions on larger lobsters and invertebrate fish predators (invertivores) which prey on juvenile lobsters. It should be emphasized, however, that because these responses are the product of multiple positive and negative indirect linkages, the strength of any conclusions based on this model are relatively weak (Weighted Analysis W<0.5; Appendix 5).

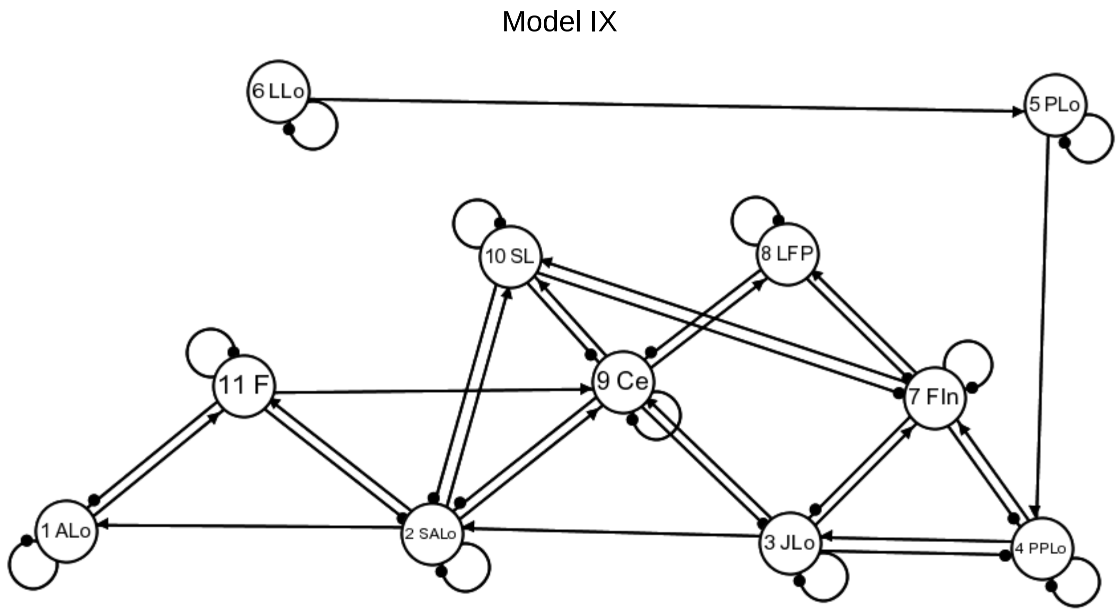


Figure 9. Signed digraph for Model IX. 1 ALo: adult lobster, 2 SALo: subadult lobster, 3 JLo: juvenile lobster, 4 PPLo: post puerulus lobster, 5 PLo: puerulus lobster, 6 LLo: larval lobster, 7 FIn: fish invertivore, 8 LFP: large fish predator, 9 Ce: cephalopod, 10 SL: sea lions, 11 F: fishery.

Table 3. Model IX adjoint matrix (-A): values represent relative strength of reaction (rows) to positive press perturbations (columns) of the system.

	1	2	3	4	5	6	7	8	9	10	11
1: Adult Lobster	61	0	0	0	0	0	0	0	0	0	-61
2: Sub-adult Lobster	-28	32	4	6	6	6	2	22	-24	-10	-28
3: Juvenile Lobster	-7	8	62	32	32	32	-30	36	-6	28	-7
4: Post-puerulus Lobster	3	14	-44	56	56	56	-22	2	20	-12	3
5: Puerulus Lobster	0	0	0	0	122	122	0	0	0	0	0
6: Larval Lobster	0	0	0	0	0	122	0	0	0	0	0
7: Fish Invertivore	4	-22	-18	34	34	34	52	-38	-14	-16	4
8: Large Fish Predator	10	6	16	24	24	24	8	88	26	-40	10
9: Cephalopods	6	28	34	-10	-10	-10	-44	4	40	-24	6
10: Sea lions	-18	38	20	30	30	30	10	-12	2	72	-18
11: Fishery	33	32	4	6	6	6	2	22	-24	-10	33

Discussion: Qualitative modelling

The nine models elicited from workshop participants have been used as a basis for developing the structure of the more detailed models in the Ecopath suite of programs with which to investigate the ecology and management of the Jurien Bay ecosystem. Analysis of models I – III which highlighted the importance of primary producer and detrital inputs as ecosystem drivers, a result mirrored in Ecopath analyses (Appendices B and C; Lozano-Montes *et al.,* 2010).

Some of the more novel conclusions of our modelling work relate to Models IV-VII, which indicate that fishing of large predatory fish could result in a phase shift to a stable community dominated by small predatory fish and planktivores. Such interactions, while complex, are not without precedent in the literature and are supported by some observations elsewhere in Western Australia. Offshore from Jurien Bay at the Abrolhos Islands, fished areas are dominated by small predators (wrasses such as *Coris* and *Thallasoma* spp), while targeted large predators were characteristic of adjacent unfished areas (Watson *et al.,* 2007). A similar trend between fished and unfished areas was evident at Rottnest Island near Perth, although it was weaker, perhaps due to the fact that such small predators are among a suite of fish now commonly targeted by recreational fishers (Kleczkowski *et al.,* 2008). At a larger scale, the same trend appears to be present with *Coris auricularis* relatively more abundant in heavily fished areas on the central west coast than in more lightly fished areas and on the south coast (De Lacy, 2008).

While these studies demonstrate that the relative dominance of large and small predators does vary in relation to fishing pressure, they do not establish the presence of negative feedback mechanisms. Experimental studies in other systems have, however, shown that small predators can suppress the recruitment of large predators (Stallings, 2009) and such feedbacks have also been implicated in large industrial fisheries (Koster and Molman, 2000). Our models, as well as simple quantitative models (Baskett *et al.,* 2006) strongly support the potential importance of such effects. Such interactions may be responsible for the lack of recovery seen in certain collapsed fisheries even after the cessation of fishing (Frank *et al.,* 2005); consequently it is important to determine whether such effects do in fact exist in western Australian coastal reef ecosystems. If they do, the recovery of depleted stocks may be a very lengthy process.

Ecosystem interactions with the rock lobster fishery were relatively uncertain, but there appears to be low-to-no risk that the fishery facilitates octopus predation on lobsters, thereby producing negative feedbacks on the lobster population. If however there is a depensatory mechanism present, similar to that described for Tasmanian *Jasus edwardsii* and *Octopus maorum* (Hunter *et al.,* 2005), where lobsters are increasingly vulnerable to octopus predation at low densities, it is possible that octopus predation could become a larger factor. Qualitative models such as those we have used are not able to deal with such quantitatively scaled interactions. With the introduction of seal lion exclusion devices (SLEDs) the interactions of sea lions with the fishery should now be minimized and consequently there are no sea-lion fishery interactions in the model. As an interesting observation, there are potential (but uncertain) benefits from the lobster fishery to large fish predators. This is mediated though the indirect benefits to octopus that result from the fishery because octopus are one of the prey of large fish predators such as Dhufish. Phase shifts between fish and invertebrate dominated systems, driven in part by the removal of large predatory fish, have been observed elsewhere (e.g. northwest Atlantic, Frank *et al.,* 2005), however such a phase shift seems unlikely in this system because the effects of large predatory fish are weak and uncertain, even though we can be more confident of cephalopod impacts on sub-adult lobsters (Table 3, Appendix 5).

5.2 RESULTS: Ecopath model

The final version of the model was used to calculate the trophic level aggregation for the 72 living groups considered. It was found that the system spans more than four trophic levels. The top predators were represented by large sharks (i.e. Port Jackson, Whiskery, Black Whaler, Grey Nurse, Long-Nose and Great White sharks) and Dhufish (*Glaucusoma hebraicum*) at a trophic level of 4.2. Most of the groups (around 70%) occur at a trophic level lower than 3.5, suggesting that Jurien Bay is dominated by lower trophic groups. Figure 10 shows the trophic aggregation of the 72 living groups (<250 species) in the model.

Using the size-shifted connectance analysis included in Ecopath 5.2 it was possible to explore quantitatively the trophic interactions among the 80 eco-groups considered in the model. The plot generated using this routine displays the three main trophic interactions in the system: predators, prey and fisheries (as another predator). The thickness of the bar represents their impact. This approach represents an easy way to capture the structure and interplay among the living and non-living components of Jurien Bay. Figure 11 shows an example of this routine where the trophic role of rock lobster (adult) is displayed. Its major predators are displayed in red bars and its prey in blue. Also, commercial and recreational fisheries have been included in the plot (green bars). The thickness of the bar represents its impact. This routine has the ability to put in the same plot the effect and impacts on lobster (or any other group) related to predators, prey and fisheries (recreational and commercial gears).

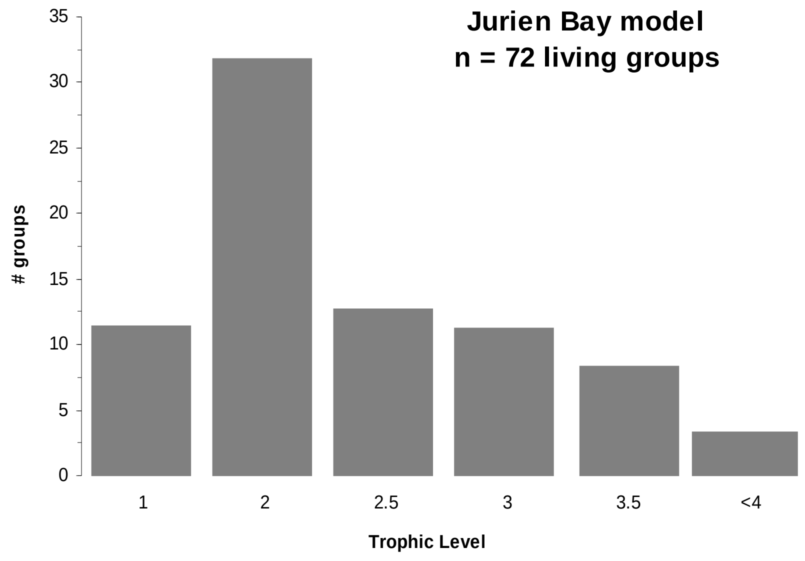


Figure 10. Trophic aggregation of the 72 living groups (>200 species) in the Jurien Bay model, show that the system is largely controlled by the lower trophic levels.

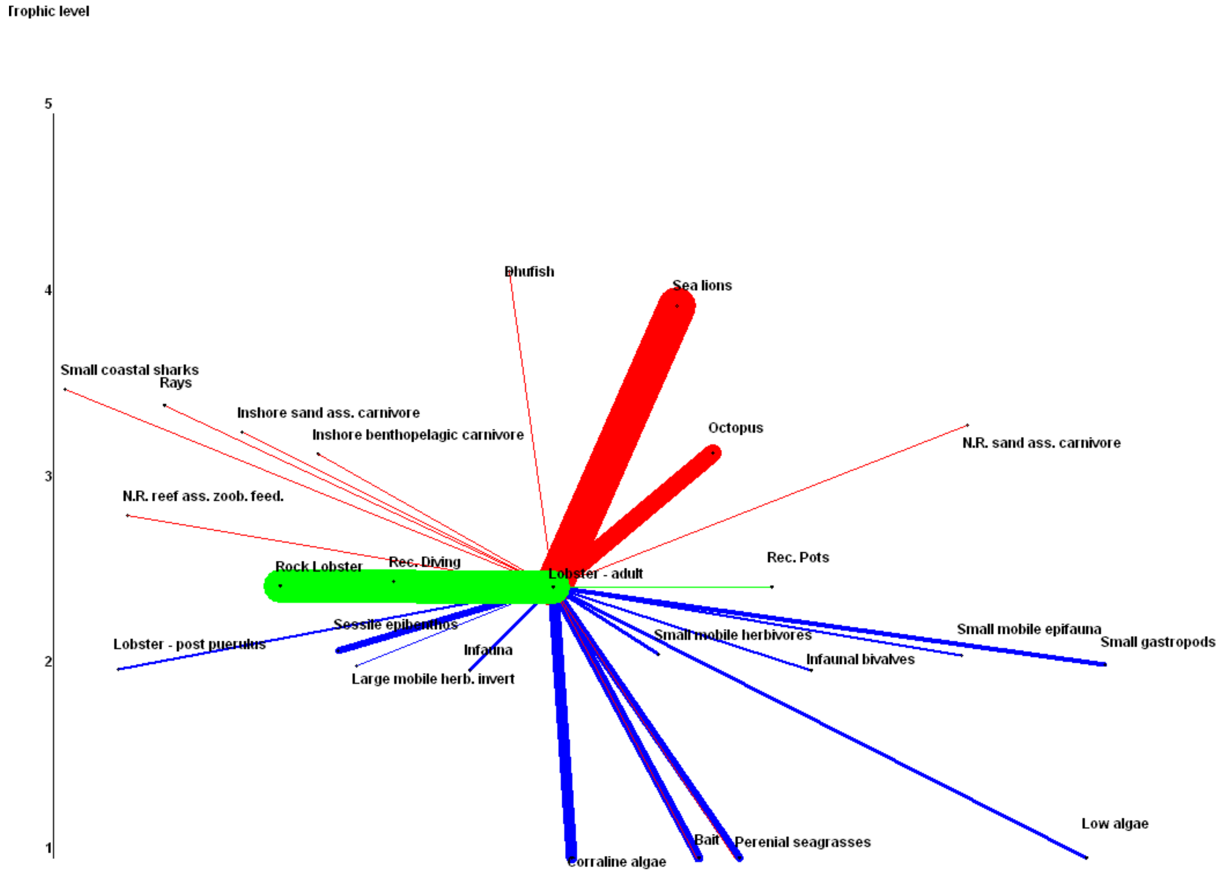


Figure 11. Size-shifted connectance plot for rock lobster, displaying its predators (red bars), prey (blue bars) and the effect of commercial and recreational fisheries (green bars). The thickness of the bar represents its impact on rock lobster. This plot was generated using a mass-balanced Ecopath model for Jurien Bay region.

Jurien Bay Ecosystem Structure and Attributes

Using some routines of the network analysis proposed by Ulanowics (1986); Ulanowics and Puccia (1990) it is possible to evaluate ecosystem attributes and functioning of Jurien Bay. Some of these attributes are related with the system development and recycling rates. In addition, results from the network analysis and its ecosystem attributes provide baselines of Jurien Bay for future comparisons. The network analysis built in Ecopath does not produce dynamic or quantitative results, and cannot predict how biomass will change with time or with fishing mortality. Such predictions are the product of Ecosim and Ecospace. However, it does provide valuable information about the structure of Jurien Bay, displaying, in a snapshot, which parts of this ecosystem play a major role. Table 4 describes emergent properties of Jurien Bay ecosystem obtained from the final version of the model and it compares these basic attributes with those obtained from Ecopath models of other marine ecosystems in Australia and a similar ecosystem of the West Florida shelf (USA).

Overall, values from Jurien Bay are within the range of these Ecopath ecosystem models, but with a relative low trophic level of the catch (2.71), explained by the high dominance of Western Rock Lobster in the total catch (around 70% of the total catch in the marine park is associated with rock lobster and much of the lobster diet is plant matter; Appendix 5). When rock lobster is removed from the catch, the trophic level of the total catch rises to 3.02. These values are ecosystem attributes that could be used as guidelines to detect potential overfishing in the system because it has been observed a decline of the mean trophic level of the catch is marine ecosystems with intense fishing. This trend is known as ‘fishing down marine food webs’ (Pauly *et al.,* 1998).

There are several ways to evaluate the structure and functioning of an ecosystem, but in general, they include the theoretical ecology proposed by Ulanowicz (1986) that quantifies attributes of the system such as flows to detritus and the impact of predation on the system. While this theory may be in need of revision (Christensen and Walters, 2004); it does represent a way to quantify Ecopath food webs and helps to consolidate knowledge vis-à-vis ecosystem function. Figure 12 shows the proportions of the major flows in the Jurien Bay system, where consumption (including fisheries) and respiration are the main energy flows in the system. Meanwhile, energy flows from the marine park to the deep water represent less than 5% of the total flows, suggesting that the production of Jurien Bay is mainly consumed within the marine park.

Table 4. Comparison of the main flow indices and ecosystem attributes of the Jurien Bay Ecopath model with those reported for other Ecopath model in Australia and a similar ecosystem in West Florida Shelf (USA).

Parameter	Rib Reef, GBR	GBR	West Florida shelf	**Jurien Bay**
	(Tudman, 2001)	(Gribble, 2005)	(Okey, 2004)	(May, 2008)
Sum of all consumption (t/km^2/year)	5,831	4,314	18,501	**11,790**
Sum of all respiratory flows (t/km^2/year)	3,446	1,732	5,977	**6,129**
Total system throughput (t/km^2/year)	17,267	11,205	42,656	**26,784**
Sum of all production (t/km^2/year)	6,50	3,920	14,071	**6,664**
Mean trophic level of the catch	3.5	2.5	3.5	**2.71**
Calculated total net primary production (t/km^2/year)	5,520	2,846	6,986	**4,152**
Total biomass (t/km^2)	521	289.9	717	**921**
Total catches (t/km^2/year)	0.8	8.5	0.4	**0.61**

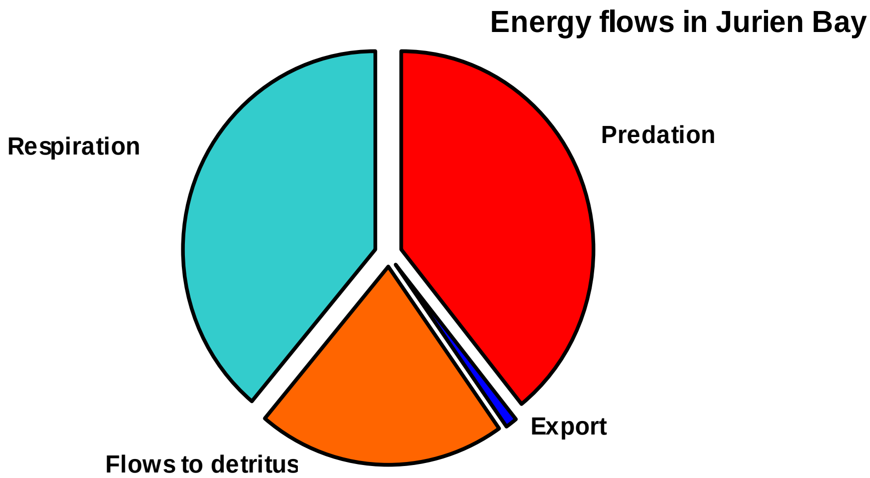


Figure 12. Proportion of the major flows in the Jurien Bay system in 2007.

Another important attribute of the system is the distribution of the total biomass by trophic level (TL) because it could be used as an indicator of changes to compare the present states of Jurien Bay (through other Ecopath models). This kind of comparison as been used in other marine ecosystems with the purpose of tracking changes in biomass through time, a key aspect of detecting loss of biomass in top predators (e.g. sharks) by intense fishing regimes (Lozano-Montes *et al.*, 2008; Pitcher *et al.*, 2005). Figure 13 presents the distribution of total biomass by trophic levels in Jurien Bay. More than 60% of the total biomass is located within the first two trophic levels (primary producers and herbivores), suggesting that Jurien Bay is dominated by lower trophic levels.

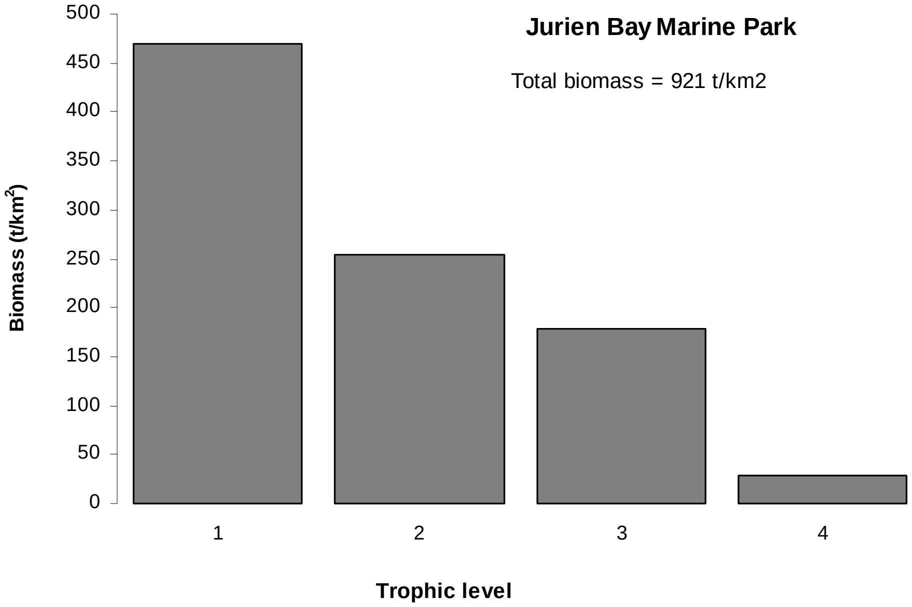


Figure 13. Distribution of the total biomass (t/km^2) by trophic level in Jurien Bay. Biomass of lower trophic levels dominates, suggesting that bottom-up forces control the system.

Discussion: Ecopath modelling

The first step in answering critical questions about the role of the fishing closures in the marine park was the construction of a dynamic Ecopath model of present-day conditions (2007). The collaborative construction of the model required four workshops, involving ecologists from CSIRO, Department of Fisheries, Edith Cowan University, Murdoch University and the Western Australian Museum. This participation builds intellectual capital of the model, increasing its trust. The model describes the interplay of predators, prey, and human fisheries using eighty functional groups (representing around 200 species) living in this marine ecosystem. The model synthesizes data for the region and it provides insight based on our current understanding, identifies gaps and assists in directing research needs. The results presented in this section show that Jurien Bay is dominated by lower trophic levels, but some minor top-down interactions were identified. Also, the model structure allows a representation of the basic features of Jurien Bay that can be summarizing as follow:

- Relatively complex system
- Medium to high relative productivity (Primary Production/Respiration = 1.23)
- Dynamic system, with low level of biomass accumulation (PP/Biomass = 1.6)
- Low rates of cycling (flows to detritus ~10%)
- Benthic groups dominate (biomass benthic/pelagic = 1.27)
- Trophic level of the catch including rock lobster is low (2.7; rock lobster dominated
- Ecosystem dominated by producer biomass

According to results from the size-shifted connectance analysis, adult lobster is likely to be preyed upon by larger species such octopus, Dhufish, sharks and sea lions. However, there is a paucity of dietary for these known and potential predators. From the existing data, no one species relies on Western Rock Lobster as its main food source, i.e. there does not appear to be one 'key' predator of the Western Rock Lobster in the southwest of Australia (MacArthur *et al.,* 2007). Several species of octopus are located within the range of the Western Rock Lobster but the most important predator of Western Rock Lobster is *Octopus tetricus* (Joll, 1983). This species may be an important predator in lobster pots as 182,794 octopus were caught in lobster pots at an average of 0.029 individuals per pot lift (de Lestang and Melville-Smith, 2006). However, no dietary data are available that show that this species is an important predator of lobster in the natural environment (MacArthur et al., 2007) Aquarium observations of octopus/lobster interactions indicate that Western Rock Lobster can easily evade *O tetricus*, whilst examination of food mounds around octopus shelters have not revealed rock lobster carapaces (Joll, 1983). More research is needed to establish a clearer link between the trophic interactions of octopus and lobsters.

Sensitivity analysis indicated that the model was sensitive to changes in the biomass of lower trophic levels (e.g. seagrass). Hence, obtaining more and better information of abundance for benthic producers is a critical aspect for the future. The model also highlights many of the uncertainties concerning the biological knowledge of the marine park. Understanding the process and interactions within this complex ecosystem, including the role of both low and high trophic level groups and the impact of fishing mortalities, can promote and support plans for conservation and management.

5.3 RESULTS: Ecosim model

Trophic levels and flows

The 80 functional groups and >200 species in the model span more than four trophic levels (TL) with the highest trophic level represented by large sharks (e.g. Port Jackson, Whiskery, Black whaler, Grey Nurse, Long-Nose and Great White sharks) and Dhufish (*Glaucusoma hebraicum*), at a trophic level of 4.2 (Table 5). The lowest trophic level (TL=1), by definition, were the primary producers, detritus and other non-living groups (detached algae and bait). The mean TL (± 1 SD) of fish (including sharks and rays) was 3.1 ± 1.2, with Pink Snapper, Breaksea Cod and King Wrasse having TLs ranging from 3.2 to 3.6. The mean TL for invertebrates was 2.4 ± 0.5, with the TL for cephalopods (octopus and squids) ranging from 3.1 to 3.6 (Table 9). Adult Western Rock Lobster had a TL of 2.7 because they are generalist feeders, consuming a range of different plant and animals, with the major components being coralline algae, molluscs, crustaceans and bait (Waddington *et al*., 2008). Most of the functional groups (~70%) had a trophic lower than 3.5, suggesting that Jurien Bay is dominated by lower trophic groups. Trophic levels I and II dominated the biomass of the system, comprising 80% of the total biomass (Fig. 14).

The average transfer efficiency (TE) in the system, defined as the fraction of the total flows at each trophic level that are transferred to another trophic level, was 9.2% ± 1.9%. The highest TE was for primary producers (12.6%) and the lowest was for fish groups at TL III and IV. This shows the important role of primary producers (i.e. *Ecklonia,* seagrass and macroalgae assembles) in promoting the productivity of lower trophic levels in the system. The percentage of the total system throughput, which provides an index of ecosystem size that considers biomasses and flows per trophic level, was far greater at TL I than the higher trophic levels, with > 70% of the total system throughput in TLI being consumed by grazers and other secondary consumers (Fig. 15). In contrast, in TLs II and III, predators consumed 20% of the total system throughput and the highest proportion of total system throughput was consumed in respiration (up to 60%) (Fig. 15).

Table 5. Basic parameters of the Jurien Bay model. Bold numbers were parameters calculated by Ecopath. B = biomass (t km^{-2}); P/B = Production/biomass ratio (years^{-1}); Q/B = Consumption/biomass ratio (years^{-1}); EE= Ecotrophy Efficiency; Com Landings = Commercial landings (t km^{-2} year^{-1}); Rec Landing = Recreational landings (t km^{-2} year^{-1}). N.R. = not restricted by depth.

	Functional Group	TL	B	P/B	Q/B	EE
1	Dolphins	4.04	**0.005**	0.1	41.07	0.3
2	Sea lions	4.05	0.088	0.074	25.55	**0.03**
3	Intertidal birds (waders)	3.10	**5.07**	0.09	40	0.10
4	Surface diving birds	3.38	**0.001**	0.09	45	0.10
5	Large coastal sharks	4.25	0.013	0.3	6.4	**0.96**
6	Small coastal sharks	3.95	0.007	0.32	10.4	**0.56**
7	Rays	3.45	0.839	0.38	7.72	**0.01**
8	Dhufish	4.18	0.352	0.6	3.9	**0.51**
9	Pink snapper	3.35	0.08	0.48	3.8	**0.74**
10	Baldchin grouper	3.27	2.91	0.71	9.2	**0.11**
11	King wrasse	3.37	29.33	0.38	15	**0.96**
12	Western fox fish	3.11	1.36	0.55	12.2	**0.21**
13	Breaksea cod	3.38	1.03	0.635	13.9	**0.18**
14	Inshore reef ass. herbivore	2.00	17.08	0.52	29.05	**0.59**
15	Inshore reef ass. omnivore	2.36	0.17	1.329	27.78	**0.61**
16	Inshore reef ass. zoob. feed.	2.56	13.03	0.748	17.73	**0.82**
17	Inshore sand ass. carnivore	3.23	0.246	0.842	12.3	**0.22**
18	Inshore sand ass. omnivore	2.74	0.021	0.535	13.44	**0.93**
19	Inshore seagr. ass. omnivore	2.20	1.59	6	13.45	**0.05**
20	Inshore seagr. ass. zoob. feed.	3.14	0.166	1.265	9.32	**0.75**
21	Inshore benthopelagic carnivore	3.18	0.071	0.44	5.35	**0.55**
22	Inshore pelagic zoop. feed.	3.02	0.00006	1.46	13.66	**0.95**
23	N.R. reef ass. herbivore	2.00	1.89	0.485	16.75	**0.56**
24	N.R. reef ass. omnivore	2.08	9.72	1.142	21.29	**0.51**
25	N.R. reef ass. carnivore	3.43	3.2	0.444	7.01	**0.09**
26	N.R. reef ass. zoob. feed.	2.86	4.35	1.289	8.86	**0.80**
27	N.R. reef ass. zoop. feed.	3.02	0.398	2.07	10	**0.23**
28	N.R. sand ass. omnivore	2.42	15.57	0.79	11.03	**0.87**
29	N.R. sand ass. carnivore	3.34	0.003	0.653	7.5	**0.82**
30	N.R. sand ass. zooben. feed.	2.17	0.917	0.653	7.5	**0.20**
31	N.R. seagrass ass. omnivore	2.03	2.67	0.655	14.3	**0.59**
32	N.R. seagrass ass. carnivore	3.17	0.002	0.42	6.5	**0.03**
33	N.R. benthopelagic carnivore	3.66	0.009	0.298	2.875	**0.94**
34	N.R. pelagic zoop. feed.	2.77	0.021	1.12	9.5	**0.33**
35	Sessile epibenthos	2.11	172.02	2.5	6.5	**0.09**
36	Photo. corals/sponges	2.00	1.99	13.25	16.8	**0.79**
37	Infauna	2.01	1.46	3.9	27.3	**0.69**
38	Infaunal bivalves	2.01	0.154	1.35	4.67	**0.96**
39	Sessile bivlaves	2.00	2.31	1.209	23	**0.81**
40	Deposit feed. invert.	2.06	18.69	0.6	3.83	**0.20**
41	Small mobile epifauna	2.06	16.82	7.01	27.14	**0.95**
42	Small mobile herbivores	2.16	13.51	9.6	27.14	**0.93**
43	Large mobile herb. invert	2.04	94.48	1.14	7.45	**0.23**
44	Large mobile carn. invert.	2.74	5.3	0.51	2.91	**0.01**
45	Large crabs	2.00	**48.64**	2.8	8.5	0.95
46	Cuttlefish	2.96	**16.94**	2.37	5.8	0.60
47	Squid	3.63	**1.51**	1.8	17.5	0.30
48	Octopus	3.10	**2.51**	2.37	7.9	0.80
49	Lobster - post puerulus	2.01	4.16	2.77	13.45	0.96
50	Lobster - juvenile	2.18	23.56	0.679	5.749	0.66
51	Lobster - Adolescent	2.50	10.32	1.258	4.365	0.26
52	Lobster - adult	2.68	0.716	2.15	4	0.32
53	Small gastropods	2.06	1.033	2.7	14	0.82
54	Large carn. gastropods	3.08	0.101	2.8	14	0.68
55	Large herb. gastropods	2.00	15.75	2.8	14	0.60
56	Sea turtles	2.16	**0.002**	0.05	3.5	0.10
57	Roe abalone	2.00	**0.059**	2.8	14	0.80
58	Small zooplankton	2.00	1.98	29.5	55	**0.22**
59	Large zooplankton	2.02	12.5	17.3	95	**0.04**
60	Chaetognaths	2.07	**1.86**	8.7	29	0.95
61	Carnivorous jellyfish	3.05	0.265	16.5	80	0.00
62	Microbial heterotrophs	2.00	2.5	95	215	**0.84**
63	Ecklonia	1.00	7	3	-	**0.43**
64	Sargassum	1.00	75	2	-	**0.52**
65	Low algae	1.00	240	2	-	**0.43**
66	Turfs	1.00	24	2	-	**0.87**
67	Corraline algae	1.00	96	2	-	**0.43**
68	Ephemeral seagrasses	1.00	64.77	2.145	-	**0.81**
69	Perenial seagrasses	1.00	92.44	7.3	-	**0.94**
70	Seagrass epiphytes	1.00	34.68	2	-	**0.96**
71	Microphytobenthos	1.00	0.088	706.5	-	**0.67**
72	Small phytoplankton	1.00	13.1	50.97	-	**1.00**
73	Large phytoplankton	1.00	3.9	24.2	-	**0.85**
74	Detached seagrass	1.00	4.5	-	-	0.00
75	Deatached brown algae	1.00	7.16	-	-	0.00
76	Detached algae other	1.00	6.82	-	-	0.00
77	Dead carcasses	1.00	0.024	-	-	0.00
78	Bait	1.00	2	-	-	0.00
79	Watercolumn detritus	1.00	5.2	-	-	0.00
80	Sediment detritus	1.00	17.94	-	-	0.25

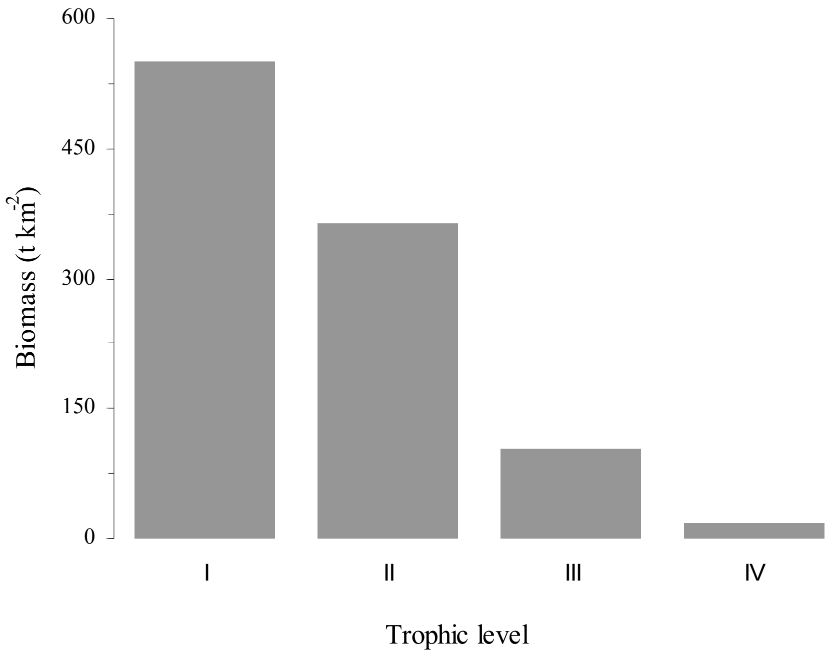


Figure 14. Distribution of the total biomass per trophic level predicted by the mass-balanced model in Jurien Bay Marine Park.

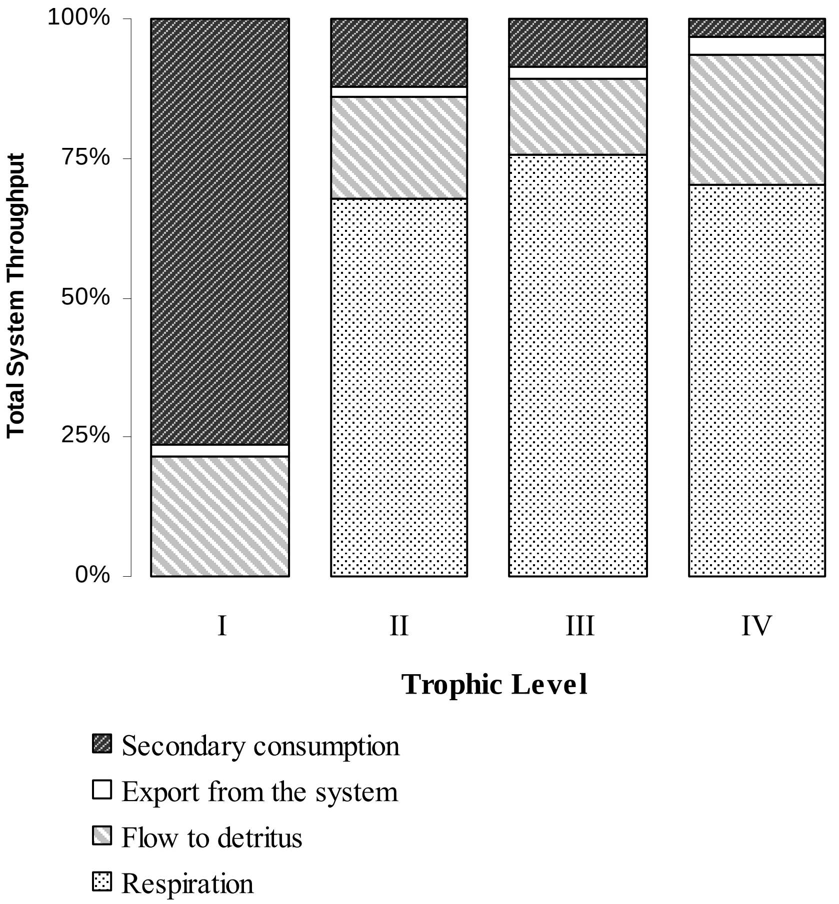


Figure 15. Main flows of the total system throughput (index of the ecosystem size) in percentage per trophic level in the Jurien Bay Marine Park.

Mixed trophic impacts

Results from the mixed trophic impact analysis (MTI) showed that a large number of functional groups (> 60%) were impacted by the changes in the biomass (of 10%) of groups at the bottom of the food web (i.e. *Ecklonia*, seagrasses, macroalgae, phytoplankton and benthic invertebrates) (Fig. 16). An increase in the biomass of *Ecklonia* resulted in an increase in biomass and trophic flows of many invertebrates groups such as post-puerulus rock lobster, juvenile rock lobster, crabs, and infauna and increases in biomasses of some commercial and recreational finfish species (Fig. 16). The overall relative change in MTI (biomass and energy flow) of rock lobster (post-puerulus, juvenile and adult) was 22%, or more than twice the magnitude of relative change in *Ecklonia* production.

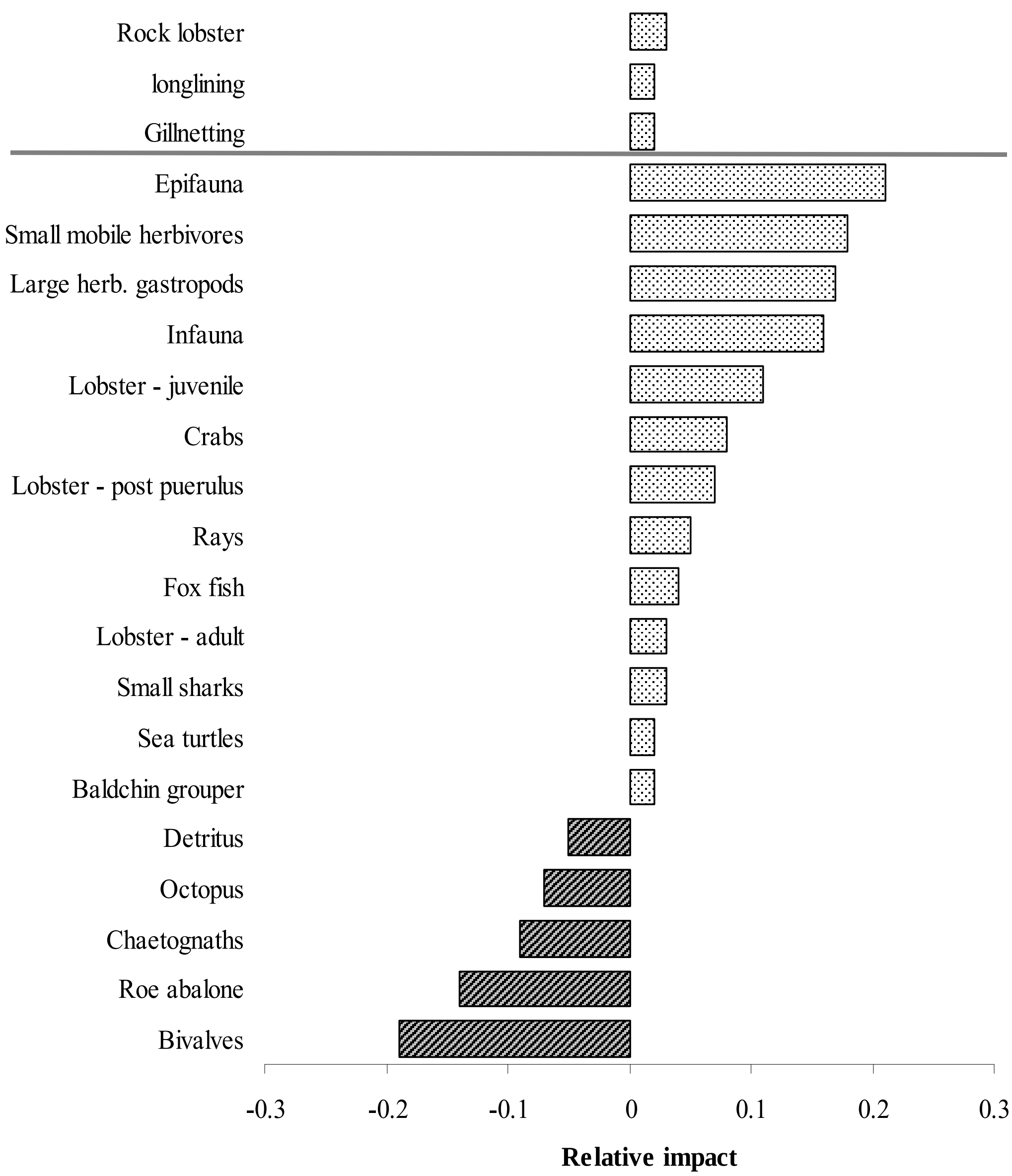


Figure 16. Mixed Trophic Impact analysis of increased *Ecklonia* biomass. Analysis of the Jurien Bay model, representing the direct and indirect impacts that a 10% increase in the biomass of *Ecklonia* (on the horizontal axis) would have on those on the vertical axis. The shaded grey bars represent positive impacts on the biomasses and energy flows, whereas the black bars are negative impacts on both. The impacts are relative, but are comparable between groups. Fisheries are shown above the horizontal line.

The MTI was also used to explore the trophic role of Western Rock Lobster (adults) in Jurien Bay. A small increase in the MTI of adult lobsters resulted in a theoretical increase in the lobster catch of about 18% and in a minor decline in the biomass and trophic flows (1-20%) of its prey (e.g. coralline algae, small gastropods, epifauna, crabs and small grazers (Fig. 16); this negative impact is probably because the increment in competition imposed by lobsters. In contrast, a simulated increase of adult lobster produced small positive direct trophic impacts on its predators (small sharks, rays, octopus, sea lions), increasing biomass and trophic flows of these groups by up to 15%. The biomass of other potential finfish prey of these predators (i.e. the carnivorous reef associated fishes - blennies, wrasses and leather-jackets) also growth (up to 20%; not shown in Fig. 17) as result of an enlargement of 10% in the biomass of macrophytes (suitable habitat; Fig. 17) due to higher predation rates of adult lobsters on benthic grazing invertebrates (i.e. sea urchins). Biomass and trophic flows to juvenile lobster decreased when the adult population was increased (Fig. 17), suggesting density-dependent competition may take place. Note that the imposition of the biomass increase is evaluated after a short time so that any affects of increased spawning biomass would not be seen at the juvenile stages. The relative negative impact on adult lobster predicted by MTI routine is probably because of an increase in competition for limited resources (i.e. food or suitable habitat) including greater time search of food (reduced energy flow), and increasing the vulnerability to predation (including mortality imposed by fishing). The results from the mixed trophic interactions should be seen as a diagnostic representation of changes in biomass and energy flows of a steady-state of Jurien Bay and changes in abundance cannot be predicted under this analysis.

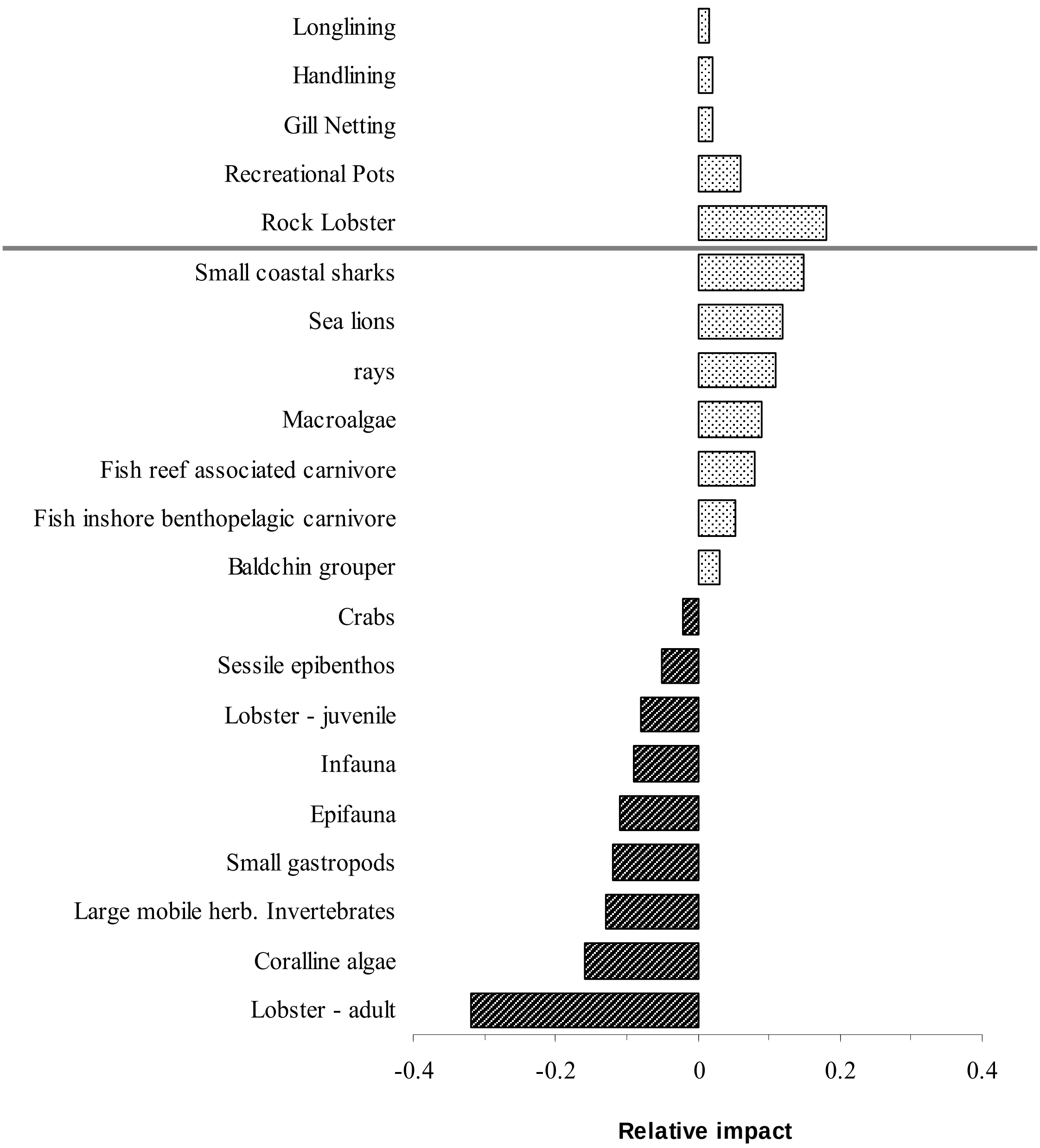


Figure 17. Mixed Trophic Impact analysis of increased adult lobster *(Palinurus cygnus)* biomass. Mixed trophic impacts of the principal groups of the Jurien Bay model, representing the direct and indirect impacts that a 10% increase in the biomass of rock lobster on the horizontal axis would have on those on the vertical axis. The shaded grey bars represent positive impacts on biomasses and energy flows, whereas the black bars are negative impacts on both. The impacts are relative, but are comparable between groups. Fisheries are shown above the horizontal line.

Comparisons with other ecosystems

The Jurien Bay Ecopath model is one of the most detailed models constructed to date in Australia. Although the spatial extent of the Jurien Bay model (823 km^2) is smaller than all other systems examined in our study (4,500 to 1,074,984 km^2), the Jurien model has the highest number of functional groups (80 cf 16 to 50) in the models examined (Table 6). The total system throughput for the Jurien Bay ecosystem was 15,343 t· km^{-2} ·$year^{-1}$, with a small to medium proportion of this energy flowing into the detritus groups (35%) (Table 6). The primary production slightly exceeded respiration (P:R = 1.1) and the biomass of primary production was about double the total biomass of all functional groups in the model (P:B = 2.1). The total landings from commercial and recreational fishing were

0.53 t· km^{-2} ·year^{-1} (Western Rock Lobster (71%), Pink Snapper (6%), Dhufish (5%), and others (18%)), which is low compared with the south Catalan Sea, Venezuela and the Upper Gulf of Mexico (Table 6). The mean trophic level of the catch was 2.9, which is similar to all other systems, except the north east shelf of Brazil (3.4) and the north Yucatán (4.1). The gross efficiency of the catch, defined as the ratio of the biomass of catch to primary production, was the third highest recorded (0.0006, Table 6).

Temporal dynamic simulations: the impact of fishing

The results from the model revealed that fishing is an important source of consumption in the system, consuming 0.54 t km^{-2} year^{-1} (= 8% of the total biomass removed by consumption) in the region (Table 7). The fisheries removed about three times more biomass of large sharks than is removed by predators and a slightly higher biomass of adult rock lobster than other predators (Table 7). For all other fished species, predators removed at least twice the biomass that was removed by the fisheries, except for Pink Snapper and small sharks, where predators removed only about 1.6 times the biomass removed by fishing (Table 7).

Results from the Ecosim simulations showed that a reduction of 50% in the fishing mortality of the commercial Scalefish Fishery (gillnets and long-lines fishing gears) over 3 years resulted in a decline of 10% in the total catch in the marine park and an increase in the biomass of several target species e.g. Pink Snapper and Dhufish up to 200% after 20 years of simulation (Fig. 18). The biomass of other larger fished species, including Baldchin Grouper, Foxfish and Breaksea Cod, also increased by about 10% after 20 years (not shown in Fig. 18). No major changes in biomass were predicted for rock lobster after 20 years but the biomass of groups like octopus and sardines, were predicted to decline by up to 30% as result of an increase in predation rates. The biomass of Labrids (smaller than the Baldchin Grouper and Foxfish) also declined (~30%), potentially due to competition with other targeted finfish.

The simulations of a closure of all fisheries operating within the marine park (introduced over 3 years) resulted in predicted major increases in the biomass of many of the harvested species after 20 years. For example, after 20 years, the biomass of Pink Snapper, small shark and Dhufish was predicted to increase by five to eight fold, while that of rock lobster increased by almost three times (Fig. 19). In contrast to the increase in biomass of top predators and lobster, the biomasses of some of their prey (e.g. cephalopods, small and medium-sized pelagic and reef fish, Foxfish and Baldchin Grouper) were predicted to decrease by up to 30% after 20 years (Fig. 19).

Figure 18. Simulated effect of a 50% reduction in commercial scalefish fisheries over 3 years (a reduction in fishing mortality of 16.6% per year). Final biomass/initial ratio (Bf/Bi) through 2005-2025. Trajectories (lines) represent the relative biomass of each group/species at the start of the run. The outputs of this scenario predict important increments of up to 200% in Pink Snapper. Recreational fisheries remained open.

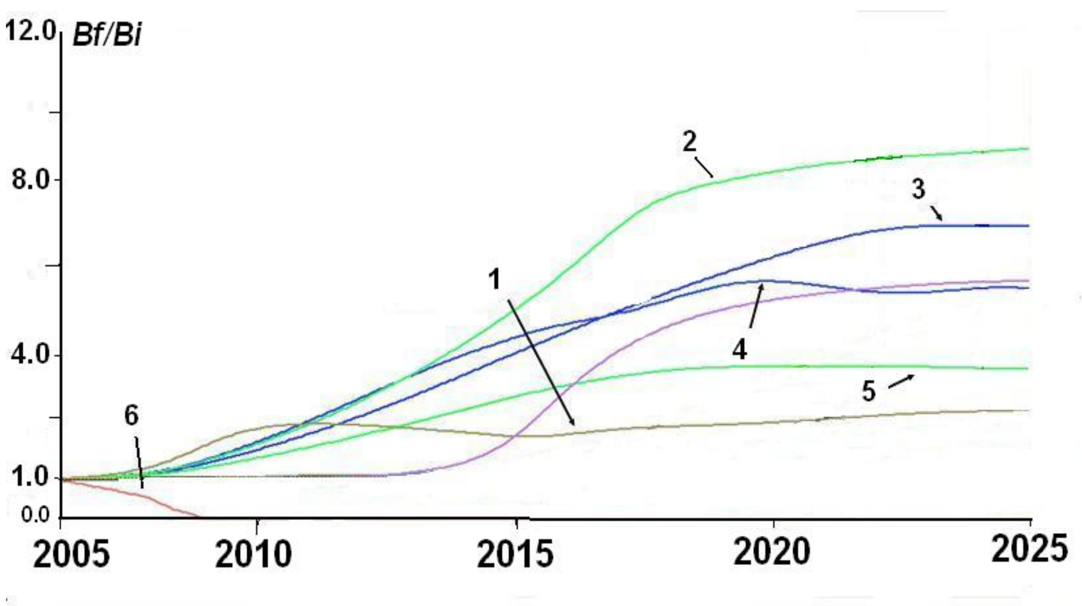


Figure 19. Simulated effect of a complete cessation of fishing. Screen-play from Ecosim indicating the impact of close of fisheries in Jurien Bay. The scenario suggests that the biomass of heavily exploited groups (i.e. Pink Snapper, Dhufish, rock lobster) will increase up to 700% after 20 years. 1-rock lobster (adult); 2-Pink Snapper; 3-large sharks; 4-Dhufish; 5-small sharks; 6-total catch.

Table 6. Main ecosystem attributes of the Jurien Bay model and other Ecopath with Ecosim models of shelf ecosystems in tropical and subtropical regions. [1]Okey and Puglise (2001); [2]Coll *et al.,* (2006); [3]Freire *et al.,* (2008); [4]Arreguín-Sánchez *et al.,* (1993); [5]Mendoza (1993).

Statistics and Flows	**This Study Jurien Bay** (30° 18' S)	**West Florida Shelf [1] USA** (25° 78' N)	**Shelf of south Catalan Sea [2]** (38° 45' N)	**Shelf Northeast Brazil [3]** (10° 00' S)	**North shelf of Yucatan [4] Mexico** (20° 00' N)	**Other shelves (Venezuela [5])** (8.° 00' N)	**Median**	Units
Total system throughput	15343	14518	1657	23042	2049	7621	11070	t km^{-2} year $^{-1}$
Sum of all production	4318	5420	658	10364	692	3699	4009	t km^{-2} year $^{-1}$
Calculated total net primary production	2598	4336	386	8375	454	3290	2944	t km^{-2} year $^{-1}$
Phytoplankton biomass	17.1	5.6	10.2	12.1	7.9	45	11.15	t km^{-2} year $^{-1}$
Zooplankton biomass	14.5	36.5	8.33	2.2	1.7	8.2	8.265	t km^{-2} year $^{-1}$
Total primary production/total respiration	1.1	1.7	1.18	6.6	0.8	1.8	1.44	dimensionless
Total primary production/total biomass	2.1	9.2	6.55	37.6	7	27	8.1	dimensionless
Total biomass/total throughput	0.08	0.03	0.04	0.01	0.03	0.02	0.03	dimensionless
Total biomass (excluding detritus)	1229	470	59	222	65	122	172	t km^{-2}
Prop. Total flux originating from detritus	0.35	-	0.48	0.62	0.43	0.32	0.43	dimensionless
Mean transfer efficiency between TL	9.6	-	12.6	11.4	17.6	6.6	11.4	%
Total catches	0.53	0.8	5.4	0.1	0.1	5.2	0.665	t km^{-2} year $^{-1}$
Mean trophic level of the catch	2.9	3	3.1	3.4	4.1	2.8	3.05	dimensionless
Gross efficiency (catch/net p.p.)	0.0006	0.00018	0.014	0.0002	0.00019	0.0016	0	dimensionless
Primary production required to sustain the fishery	36.9	-	41.9	1.3	53.6	7.9	36.9	%
Study Area	823	174300	4500	1074984	100000	30000		km^{-2}
Number of groups	80	42	40	41	21	16		groups

Table 7. Total biomass (t/km^2) removed by fishing and predation predicted by the Ecopath model.

	Total catch	Predation
	t/km^2	t/km^2
Large sharks	0.003	0.001
Small sharks	0.001	0.016
Dhufish	0.04	0.18
Pink snapper	0.07	0.112
Baldchin grouper	0.01	0.876
Western foxfish	0.02	1.467
Breaksea cod	0.01	0.973
Octopus	0.008	2.127
Lobster Adult	0.39	0.342
Roe abalone	0.003	0.006
Total	0.555	6.1

Exploring alternative management strategies for conserving food webs and fisheries: results from the dynamic Ecosim model

Following the useful discussions during the progress meeting with the steering committee held at CSIRO, Floreat laboratories, Western Australia (October 15, 2009), it was possible to develop the final simulations from the dynamic Ecosim model. This section presents the final results from the fisheries scenarios designed to explore alternative management strategies in Jurien Bay Marine Park (JBMP). The changes in biomass and total catch predicted by the simulations of the main scenarios focused in Western Rock Lobster, Dhufish, Baldchin Grouper, Western Foxfish and sharks are summarised in Appendix 6.

1. **Scenario**: Close all commercial fin-fisheries in the system over a 3 year period and simulate effects over 20-year period.

- Time: 20 years run.
- Fishing mortality in 2007 (F_{2007}) = 1.0 year -1 (relative mortality imposed by all commercial gears in the model)
- Fishing mortality in 2010 (F_{2010}) = 0.0 year -1 (relative mortality imposed by all commercial gears)
- Rationale: Ecological role of fishing.

Results of Scenario 1: Significant changes in the abundance of heavily exploited species were found in the simulations of this scenario (Fig. 20). For example, the biomass of Dhufish and sharks increased between 50 to 300% respectively to those estimated in 2007. As result of the trophic interactions, the abundance of some groups (i.e. Baldchin Grouper, western Foxfish, squid) showed modest declines in their biomasses (<30%) because the abundances of their predators increased due to the closure of commercial fishing (Fig. 20). The biomass of Western Rock Lobster rose by almost 20% after 20 years displaying an oscillating pattern (Fig. 21). As expected, the total catch in the system declined by 30%, showing the relatively small significance of commercial fin-fishing in the region compared with lobster fishing. Fig. 22 shows the changes in the biomass for all the groups in the model, where the closing of the commercial finfish fisheries could impact positively on non-target species such as turtles, diving birds and some reef fishes with increments of up to 40% in biomass after 20 years.

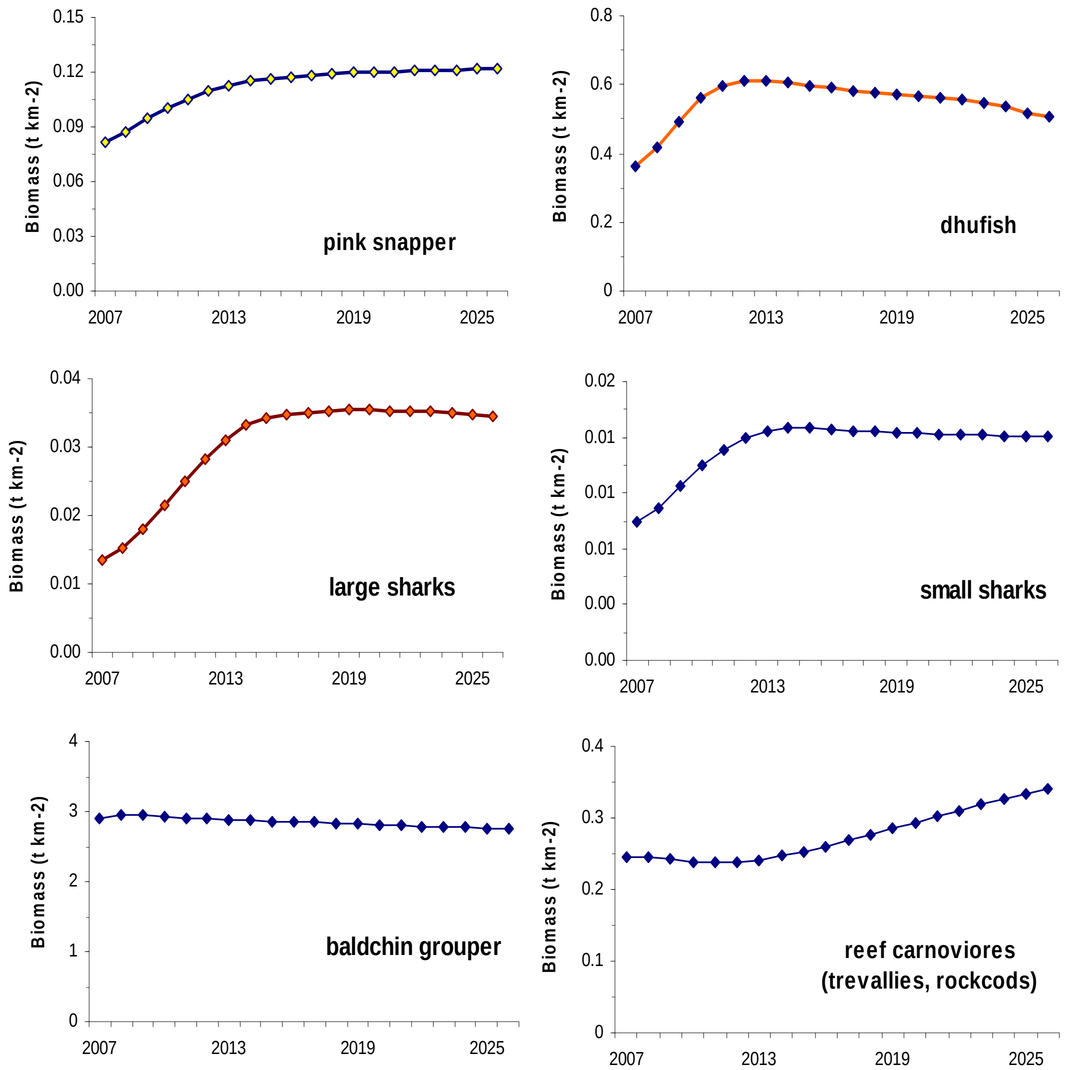


Figure 20. Projected biomasses predicting the impact of closing all commercial scale fisheries in Jurien Bay. The scenario suggests not only that the biomass of heavily exploited groups (i.e. Dhufish, sharks, Pink Snapper) could increase by up to 300%, but also abundances of non-target species like some reef fishes (trevallies and rockcods) could be positively impacted.

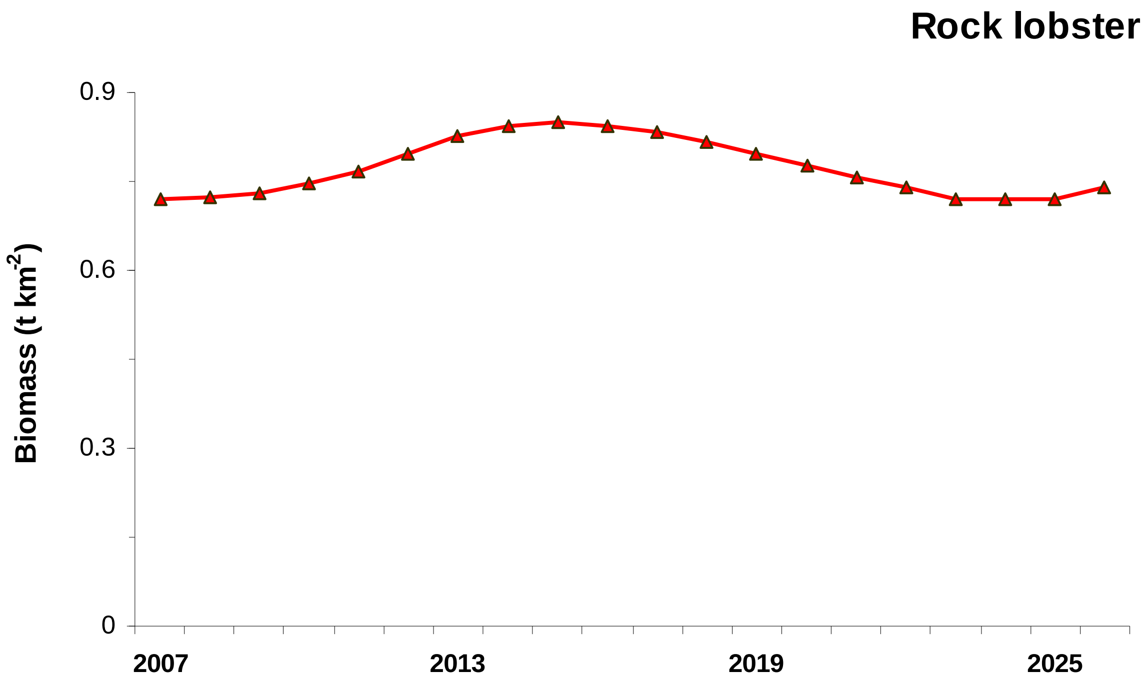


Figure 21. The biomass of Western Rock Lobster is predicted to increase by around 20% after 20 years of closing commercial fin fisheries displaying an oscillating pattern.

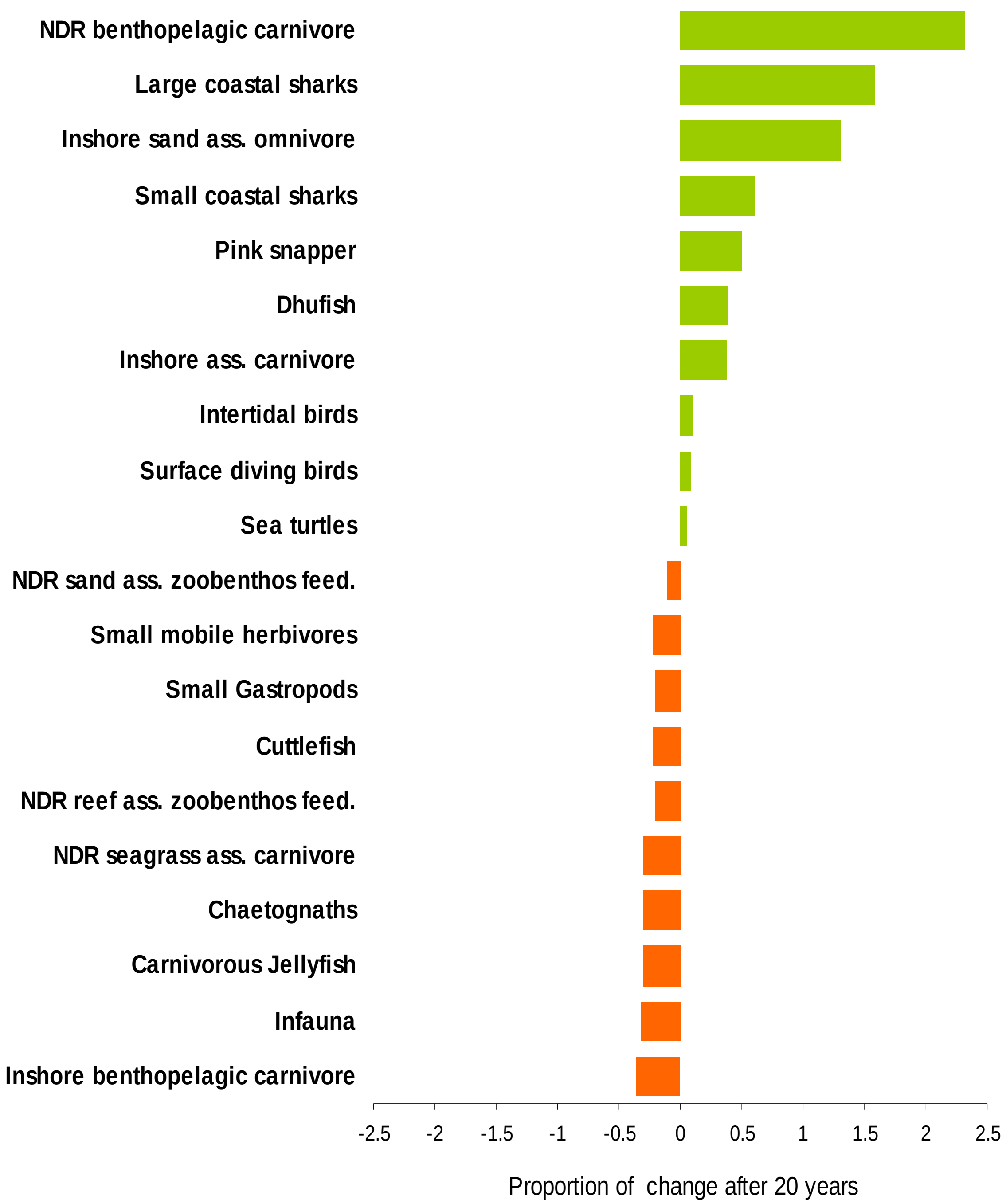


Figure 22. Percentage of change in the biomass of the functional groups in the model after 20 years of closing commercial finfish fisheries within the marine park.

2. Scenario: Fishing closures for Dhufish, Pink Snapper and Baldchin Grouper by reducing fishing mortality (F) by 50% over a 3-year period (reduction of 16.6% per year^{-1}). As it was mentioned in the introduction, these Ecosim fisheries scenarios were presented in a workshop discussion group at the Department of Fisheries, Research Laboratories on October 14th 2009. It was felt that a more realistic reduction in fishing mortality for key demersal species would be to reduce F over a 3 year period, rather than gradually reducing F over the 20 years (as suggested by people from RecFishWest).

- Time: 20 years run.
- Fishing mortality Dhufish in 2006 (F_{2007}) = 0.35 year^{-1}
- Fishing mortality Dhufish in 2029 (F_{2010}) = 0.18 year^{-1}
- Fishing mortality Pink Snapper in 2006 (F_{2007}) = 0.67 year^{-1}
- Fishing mortality Pink Snapper in 2029 (F_{2010}) = 0.33 year^{-1}
- Fishing mortality Baldchin Grouper in 2006 (F_{2007}) = 0.72 year^{-1}
- Fishing mortality Baldchin Grouper in 2029 (F_{2010}) = 0.36 year^{-1}
- Rationale: Ecological role of fishing.

Results of Scenario 2: The results suggested that reducing the fishing pressure on pink Snapper, Dhufish and Baldchin Grouper resulted in a modest decline in the total catch of ~10% (Table 8). The major changes in the biomass were displayed by Pink Snapper and Dhufish with increments of up to 200% after twenty years (Fig. 23). The biomass of adult Western Rock Lobster was predicted to increase by ~30% at the end of the run. This could be explained because the predicted increase in biomass of Pink Snapper increased the predation mortality on octopus, one of the main predators of adult rock lobsters (Fig. 24). The small decline in the biomass of Baldchin Grouper (~10%) is probably explained by the increment of 200% in the abundance of its main predator, Dhufish, which accounts for about 80% of the predation mortality on Baldchin Grouper. More information on the diet of Dhufish may be required to better assess the risk to populations of Baldchin Grouper in adopting this management strategy. Some indirect impacts were suggested by this scenario, where the predicted biomasses of some non-target groups (i.e. mullets; Fig. 25) were incremented as results of the decline of its predators by direct consumption by the magnified populations of Pink Snapper and Dhufish.

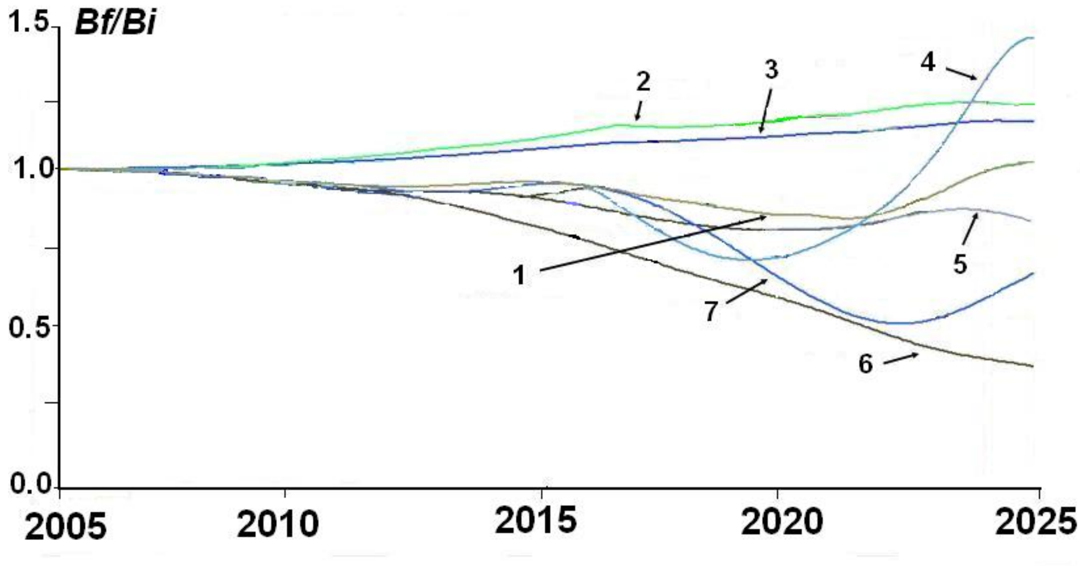


Figure 23. Projected biomasses predicted by the model showing the impact of reducing fishing mortality on Pink Snapper, Baldchin Grouper and Dhufish by 50% over twenty years. Trajectories (lines) represent the relative biomass of each group/species at the start of the run. 1-rock lobster (adult); 2-Pink Snapper; 3-large sharks; 4-squid; 5-octopus; 6-sardines; 7-labrids. Recreational fisheries remained open.

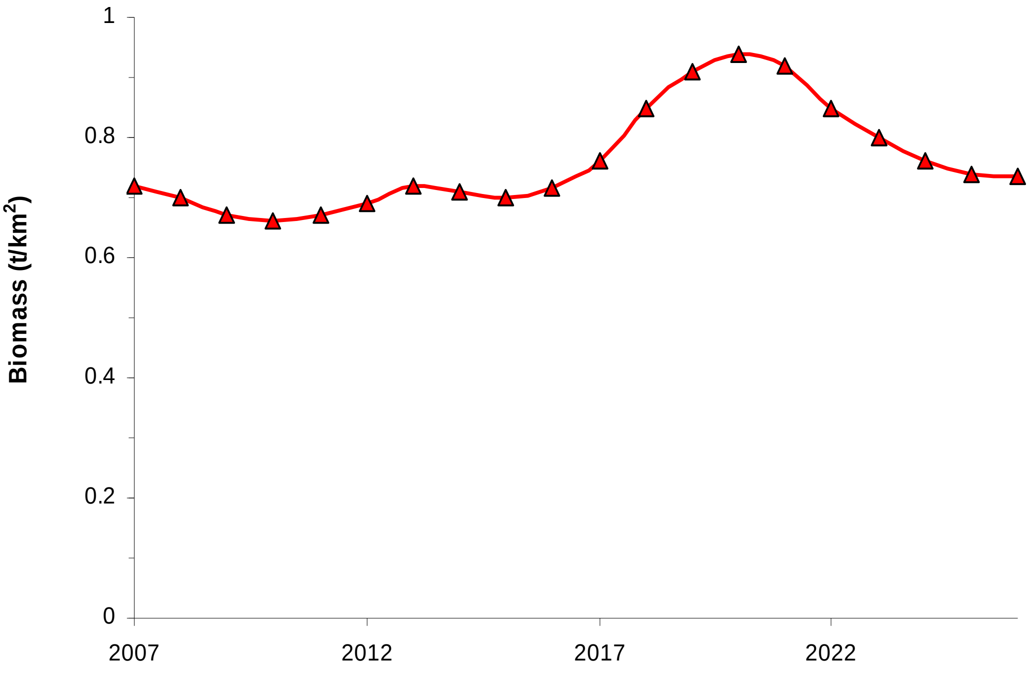


Figure 24. Projected biomasses predicted by the model showing the impact of reducing fishing mortality on Pink Snapper, Baldchin Grouper and Dhufish by 50% over twenty years. The outputs of this scenario predict important increments of up to 200% in Pink Snapper.

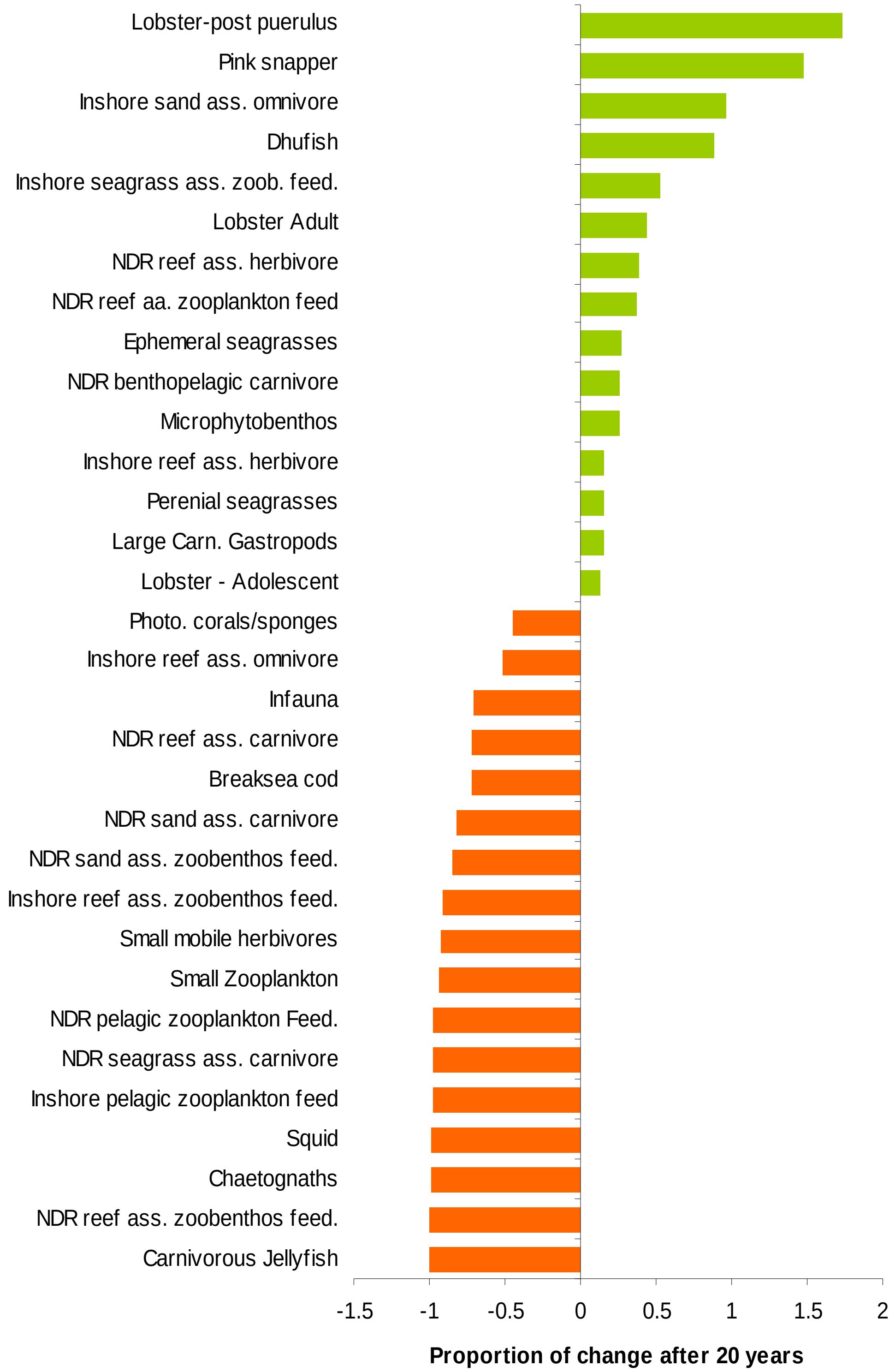


Figure 25. Percentage of change in the biomass of the functional groups in the model after 20 years of reducing the fishing mortality Pink Snapper, Baldchin Grouper and Dhufish by 50%. The outputs of this scenario suggested important increments up to 200% in the biomass of fished and non-fished groups such as Pink Snapper and post puerulus rock lobster, respectively.

3. Scenario. The effect of increasing recreational fishing by 50% over 20 years (increment of 2.5% per year^{-1}).

- Time: 20 years run.
- Fishing mortality 2006 = 1.0 year^{-1} (relative mortality of all recreational fishing in the model)
- Fishing mortality 2026 = 1.5 year^{-1} (relative mortality of all recreational fishing in the model)
- Rationale: Ecological role of fishing.

Results of Scenario 3: As result of this simulated increase in recreational fishing pressure, important reductions in the biomasses of some target species were predicted at the end of the 20 years (Fig. 26). For example, the biomass of Pink Snapper declined by 30% followed by Dhufish, Baldchin Grouper and sharks with declines of 10-20% of the biomass estimated in 2007. In the case of rock lobster (adult), its biomass also displayed a reduction of ~20% (Fig. 27; Table 8). In contrast, some potential prey (reef fishes, sardines and octopus) of the collapsed groups improved up to 30% in their biomasses. Fig. 28 shows the changes in the biomass for all the groups in the model, where negative impacts associated with the increasing recreational fishing spread across all trophic levels. No major changes (<10%) in the total catch were predicted by the model (Table 8), which implies that catch per unit effort will have declined significantly (Fig. 28).

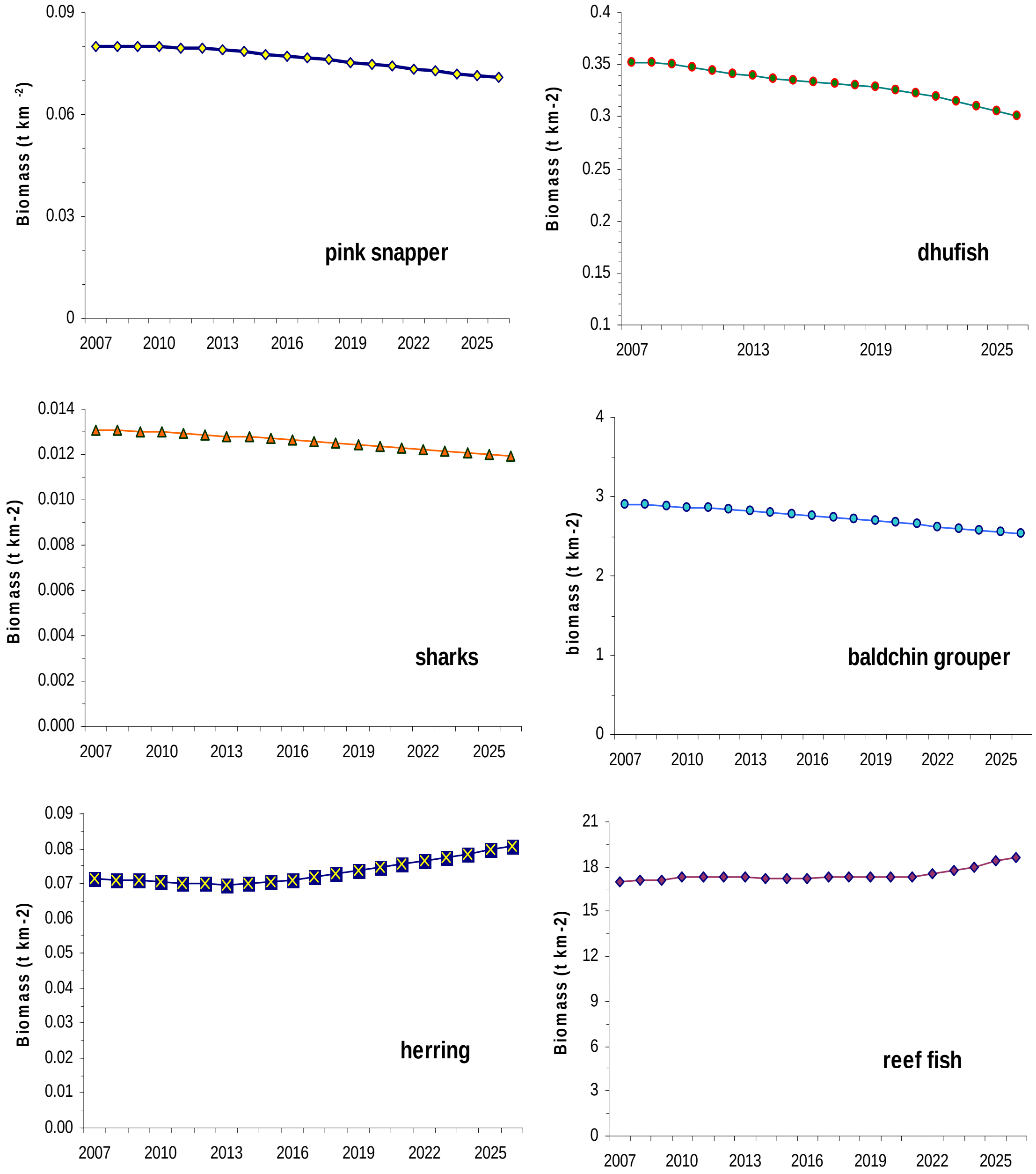


Figure 26. Projected biomasses predicted by the model when the fishing mortality imposed by recreational fisheries is increased by 50% over 20 years. The results suggest declines in the biomass of Pink Snapper (~30%), followed by Dhufish and Baldchin Grouper with declines around 20%. In contrast, some potential prey (reef fishes and herrings) of these groups improved up to 30% in their biomasses.

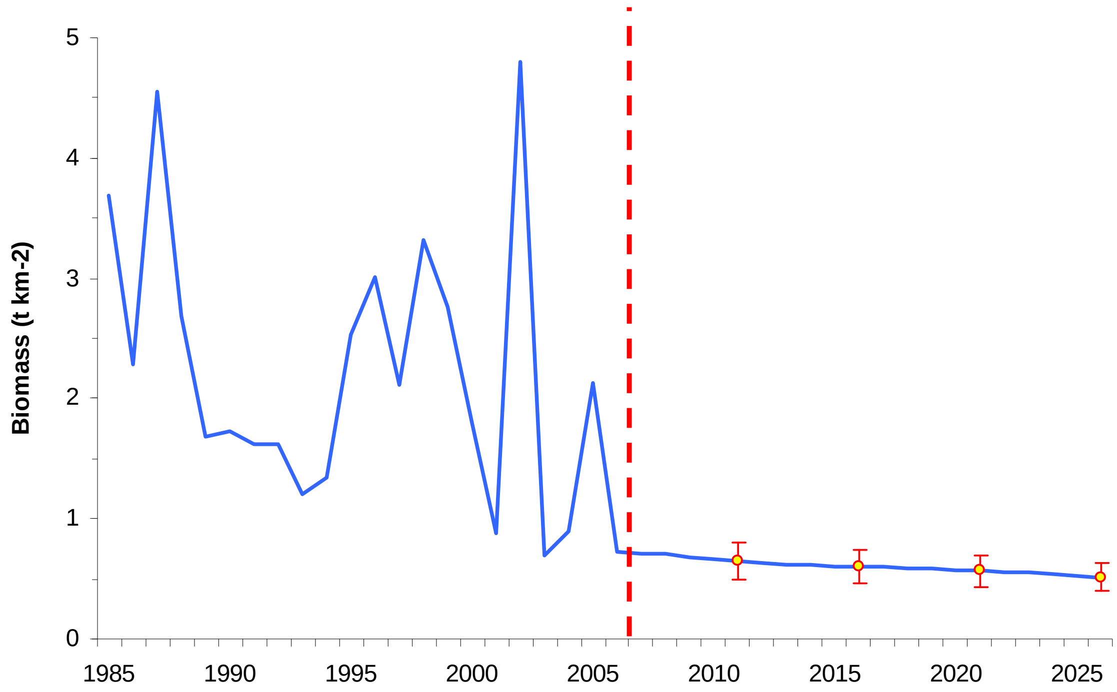


Figure 27. Projected biomass of rock lobster from 2007 to 2027 after increasing recreational fishing by 50% over 20 years (increment of 2.5% per year^{-1}). Declines around 20% at the end of the scenario were predicted by the model. Red bars represent the standard deviation of the mean biomass predicted. The dash red line is the starting point of the simulation (2007).

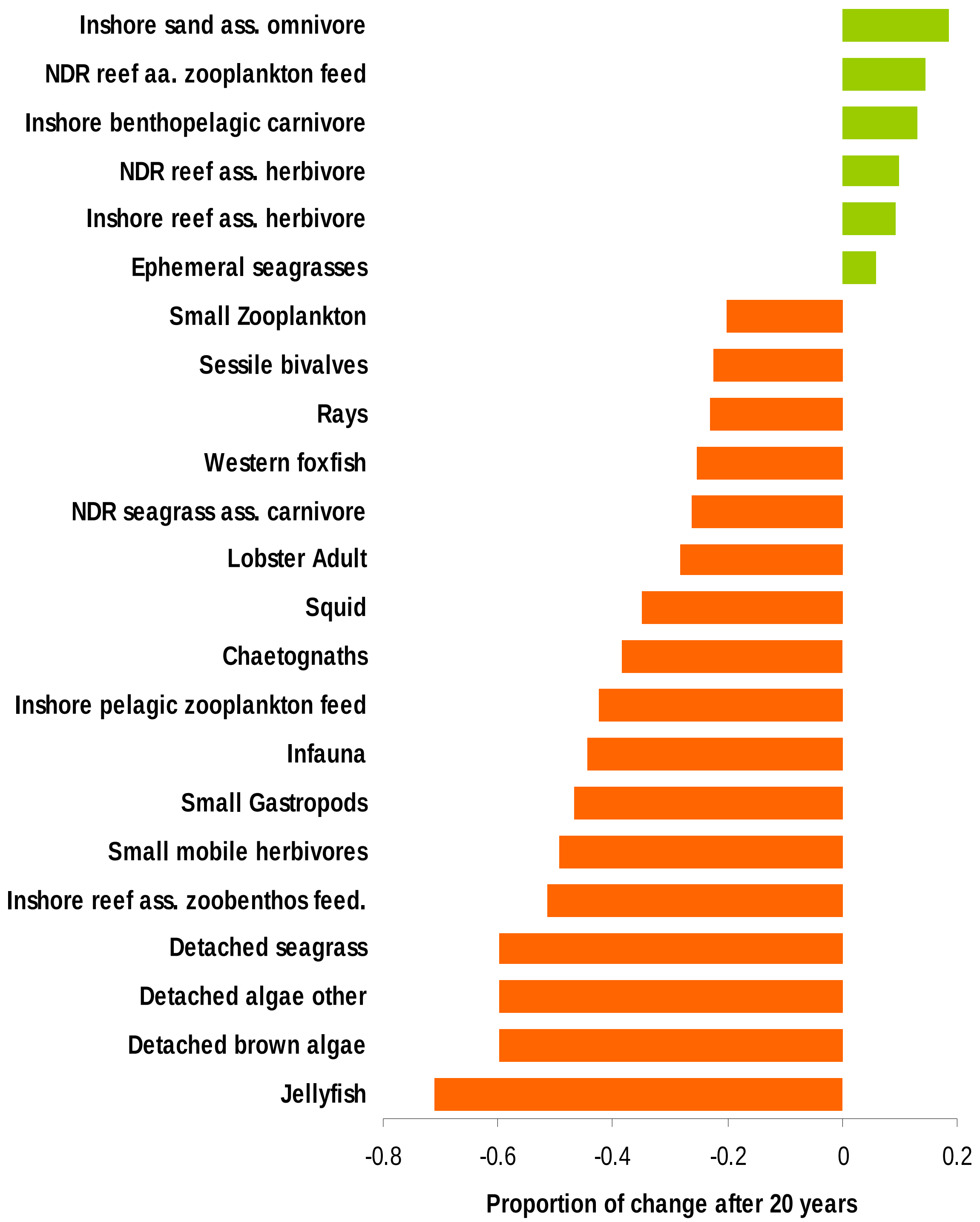


Figure 28. Percentage of change in the biomass of the functional groups in the model after increasing recreational fishing by 50% over 20 years (increment of 2.5% per year^{-1}). The outputs of this scenario suggested important reductions around 30% of important stock such as Pink Snapper and Dhufish.

One of the main goals of this project is to quantify how the changes in abundance of key fished species are likely to influence other species in Jurien Bay. For this reason, we developed a specific scenario involving adult rock lobsters.

4. Scenario: Closure of the rock lobster fishing (commercial and recreational gears) introduced over three years.

- Time: run over 20 years
- Fishing mortality 2006 = 0.62 $year^{-1}$
- Fishing mortality 2009 = 0.0 $year^{-1}$
- Rationale: Ecological role of fishing

Results of Scenario 4: The biomass of Western Rock Lobster (adult) doubled after 20 years as a result of the reduction in fishing mortality by 100% over this time (Fig. 29, Table 8). The biomass of adolescent lobsters also increased by ~40% compared with its original biomass in 2006. Some of the main predators of adult lobsters (i.e. octopus) increased in abundance as a result of increased prey availability (Fig. 29). In contrast, some species consumed by adult lobsters (i.e. sea urchins) declined. The total catch in the Marine Park declined by almost 70%, confirming the important role of rock lobster in the fisheries of Jurien Bay. Overall, a reduction in fishing mortality on the Western Rock Lobster is unlikely to produce major trophic cascades in the marine park, possibly because the prey of lobster prey are highly productive and have short life cycles (i.e. small invertebrates and algae). The Western Rock Lobster also feeds on a wide range of functional groups across many trophic levels, including primary producers, which results in numerous, relatively weak linkages throughout the system.

The results of the Ecopath model development and selected scenarios have been summarized in a manuscript that has been accepted in Marine and Freshwater Research for publication (see Appendix 5).

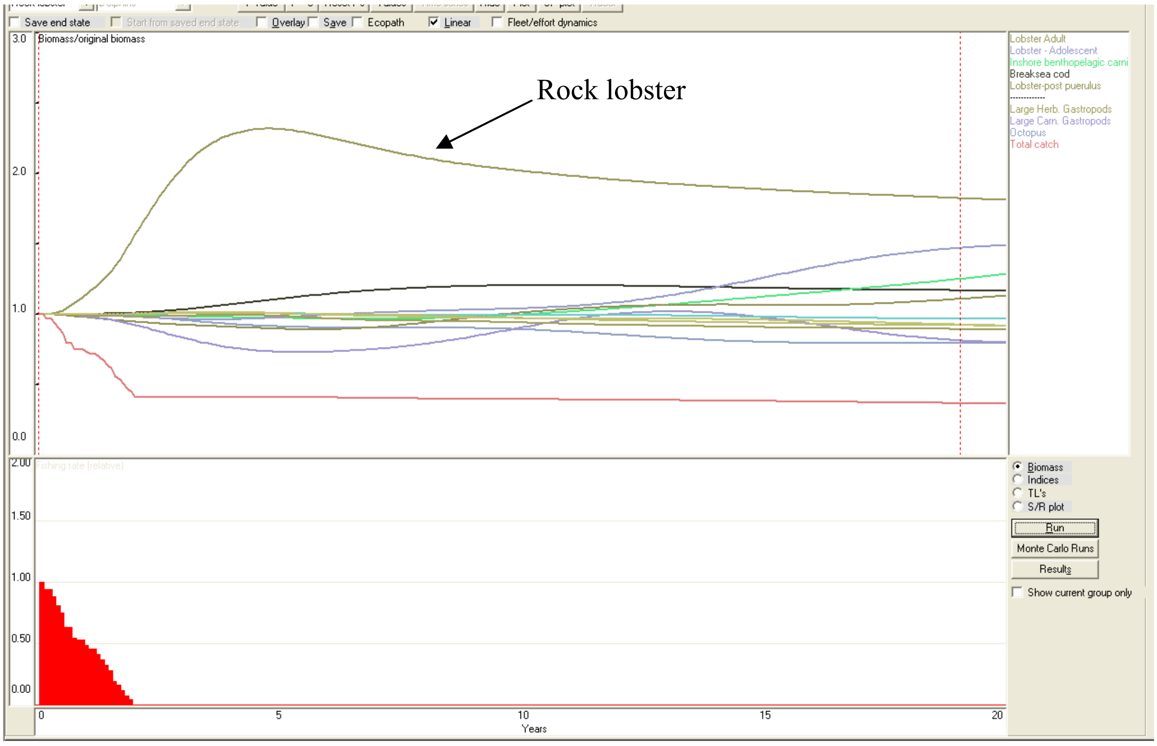


Figure 29. Projected biomasses predicted by the model when the Western Rock Lobster fishery is closed. The outputs suggested important declines in total catch of the marine park with a reduction of 70%. Trajectories (colour lines) represent the relative biomass of each group/species at the start of the scenario (2007). The red area (bottom) represents the change in the relative fishing mortality imposed by all fishing gears on rock lobster (adult).

Table 8. Summary of the results of each of the Ecosim scenarios developed for the key species considered in the Jurien Bay model. Results are presented as percentage of change in biomass and total catch after 20 years

	Change in Biomass and total Catch (%)							
	Scenario	Rock lobster	Dhufish	Pink Snapper	Baldchin Grouper	BreakSea cod	Sharks	Total Catch
1	Close all commercial fin-fisheries	-3	+ 41	+ 49	- 5	- 11	+ 158	- 8
2	Fishing closures for dhufish, pink snapper and baldchin grouper by reducing their F by 50%	+ 23	+ 88	+ 147	- 10	- 70	- 5	- 3
3	Increasing recreational fisging by 50%	- 18	- 14	- 15	- 11	- 4	- 8	+ 11
4	Closure of the rock lobster fisheries (commercial and recreational)	200	+ 25	+ 27	+ 6	- 7	+ 12	- 70

The overall results from the model revealed that fishing is an important source of consumption in the system, consuming 0.54 t km^{-2} $year^{-1}$ (= 8% of the total biomass removed by predation) in the region (Table 9). The fisheries removed about three times more biomass of large sharks than is removed by predators and a slightly higher biomass of adult rock lobster than other predators (Table 9). For all other fished species, predators removed at least twice the biomass that was removed by the fisheries, except for Pink Snapper and small sharks, where predators removed only about 1.6 times the biomass removed by fishing (Table 9).

Table 9. Total biomass (t/km^2) removed by fishing and predation predicted by the Ecopath model.

	Total catch	**Predation**
	t/km^2	t/km^2
Large sharks	0.003	0.001
Small sharks	0.001	0.016
Dhufish	0.04	0.18
Pink snapper	0.07	0.112
Baldchin grouper	0.01	0.876
Western foxfish	0.02	1.467
Breaksea cod	0.01	0.973
Octopus	0.008	2.127
Lobster Adult	0.39	0.342
Roe abalone	0.003	0.006
Total	0.555	6.1

Discussion: Ecosim modelling

The Ecopath model developed in this study is the first mass-balanced model developed for the temperate west coast of Australia to characterise the trophic structure, ecosystem attributes and impact of fishing for the region. The model integrates the data available in the region and it provides a summary of our current knowledge of the biomass, consumption, production food web and trophic flows in the Jurien Bay Marine Park ecosystem. During the process of mass-balancing the model, important gaps in the biology of some groups were identified, providing directions for further research and guidelines for future monitoring programs. For example, the unrealistic values of ecotrophic efficiency (EE > 1.0) for groups such as whiting, herring, mullet, rays, wrasses, and sharks, during the first balancing of the model indicated the need for more, higher quality data for these groups to improve the model (e.g. the importance of cannibalism in sharks needs to be calculated more carefully) and enhance its 'realism'. The trophic imbalances of these groups should be resolved in future by improving the understanding of their biology, rather than by solving the linear equations of the Ecopath model.

In comparison with some other Ecopath models of marine coastal shelves for tropical and subtropical regions (see Table 6), Jurien Bay had the highest total biomass (1,229 $t.km^{-2} \cdot year^{-1}$) among the systems. This could be explained by its unique combination of complex geomorphology (consisting of islands, subtidal and inter-tidal limestone reefs, protected inshore lagoons and deeper basins, beaches and headlands; CALM, 2005), with dense populations of temperate and tropical plants and animals, courtesy of the Leeuwin Current (Caputi *et al*., 1996; Feng *et al.,* 2003). The high biomass of the Jurien Bay system is directly related to the high abundance of benthic primary producers that represented 46% of the total biomass estimated for the system (excluding detritus). For example, biological surveys have found that brown algae (including the kelp *Eklonia*) reach biomasses of up to 300 $t \cdot km^2$ in the seagrass habitats of Jurien Bay (Wernberg *et al*., 2006). The productivity of *Ecklonia* in Western Australia (Kirkman 1989) is as high or higher than that for laminarian dominated habitats in other coastal seas, even those noted for high levels of productivity (Mann 1982, Wheeler and Dreuhl, 1986). The total system throughput of Jurien Bay (an index of the ecosystem size; Christensen and Pauly, 1993) was the second highest among the modelled ecosystems, just below the northeast of Brazil (Freire *et al.,* 2008), which suggests that the trophic interactions among benthic primary production, invertebrate and fish groups are important.

Despite the high biomass of primary producers and high system throughput in the Jurien Bay ecosystem, the total catch for Jurien Bay was one of the lowest amongst the shelf systems examined, e.g. it was up to ten times lower than that recorded in systems with intermediate levels of fishing exploitation (Mendoza, 1993; Coll *et al.,* 2006). The gross efficiency of the fisheries in the Jurien region (defined as the catch divided by the net primary production) was intermediate to those for the other systems and relatively low compared to under-exploited ecosystems (Pauly and Christensen, 1993). The low to medium value of the primary production required to sustain the fisheries of Jurien Bay (36.9%), was lower than the southern Catalan Sea or Yucatan peninsula, but within the range for the values estimated by Christensen and Pauly (1995) for global tropical shelves (16.1-48.8%). The values for both the total catch and the gross efficiency of the fisheries imply that the fisheries in Jurien Bay are having a low to medium impact on the ecosystem structure and function compared to other, more heavily exploited coastal shelves, such as south of the Catalan Sea (Coll *et al*., 2008). It should be noted, however, that comparisons of ecosystem statistics among trophic models may be seriously affected by the model structure and the definition of the systems to be modelled (Freire *et al*., 2008; Metcalf *et al*., 2008). As noted by Freire *et al.,* (2008), any comparisons among trophic models should be made with caution and need to consider the number of functional groups defined in the model.

The pedigree index of the Jurien model (0.72) was high in comparison to other similar shelf Ecopath models in Australia and around the world (Gribble, 2003 & 2005; Okey *et al.,* 2004b; Bulman *et al*., 2006). However, the parameters and structure of the model should be reviewed and new estimates included when they become available. Uncertainty around model parameters is one of the major limitations in the predictions made by Ecopath models (Metcalf *et al*., 2008). Realistic estimates of the catch by different fisheries are a vital component of trophic models as major differences can be found between reported and actual catches (Pitcher *et al*., 2002; 2005). The Jurien Bay model would benefit from more recent and comprehensive data on recreational fisheries (e.g. the number of trips and fish caught and time spent fishing) in the Marine Park to improve this component.

The Jurien Bay ecosystem is dominated by the benthic functional groups, which represent the main components of the biomass for the total system, the catch of fisheries and the energy flows in the system. This ecosystem is therefore characterized by bottom-up interactions, driven by the importance of *Ecklonia*, seagrasses and macroalgal assemblages that are major sources of habitat and food for marine invertebrates and fish in the region (Vanderklift *et al.,* 2007; England *et al*., 2008). The results from the Ecopath mixed trophic impacts routine showed that even small changes in the biomass of one species (*Ecklonia*) had far reaching impacts (both direct and indirect) on other functional groups. Benthic invertebrates, including rock lobster, responded strongly to changes in the biomass of *Ecklonia*, which could, in part, be explained by its provision of both substrata for food such as epiphytes and epifauna (Crawley *et al.,* 2006, Crawley and Hyndes, 2007) and shelter from predators (Vanderklift *et al*., 2007). Note that the low rates of recycling presented in Appendix 5 refer to the percentage of ecosystem's throughput (sum of all flows) that is recycled. This index quantifies one of the Odum's properties of system maturity (network analysis). It involves more than just biomass, it includes respiration and detritus flows, but it is computed in Ecopath more like a 'predatory cycling index' and it is expected to increase with maturity of the system (path lengths + respiration +Export). So, the Cycling Index presented in results Section 5.2 is not the same than these results were biomasses of single groups such as seagrass was increased.

The results from our study are likely to underestimate the sensitivity of the system to changes in the biomass of groups like *Ecklonia,* which in addition to contributing to trophic flows, have an important role as habitat for other flora and fauna. For example, experimental studies in the Marine Park have shown that the overall density of lobsters and the level of habitat utilisation are much greater in the vicinity of macroalgal dominated reefs than adjacent to other habitats (MacArthur *et al.,* 2008). Similar patterns have also been observed for fish immediately adjacent to reefs (Vanderklift *et al*., 2007), presumably because of increased protection from predators in these habitats, enhancing the survival of fish and crustaceans species.

The dynamic simulations of two management scenarios identified some top-down interactions flowing from reductions in fishing mortalities of fish groups at the top of the food web e.g. sharks, Dhufish and Pink Snapper. The simulated total fish closure revealed an interesting consequence of top-down interactions – the biomass of lobster was only predicted to increase modestly, presumably because the marked increase in biomass of lobster predators compensated for the decrease in fishing mortality on lobster. Even under the current levels of fishing, simulations revealed that predation is almost as great a source of mortality for lobsters as fishing (Table 7). Studies of a long-established no-take area on Western Australia’s west coast (Kingston Reefs Sanctuary Zone at Rottnest Island, established 1986) have shown increases in biomass of up to 34 times in the closed area (Babcock *et al.,* 2007). However, this was in a small area where the biomass of fish did not increase to the same degree as lobsters, probably because a greater area would be needed to allow fish to escape from fishing pressure (Kleczkowski *et al.,* 2008).

The low trophic level of the catch (2.9) in comparison with those reported in other temperate, rocky reef systems (Pauly *et al.,* 1993; 2003; Okey *et al*., 2004a, b; Pinkerton *et al*., 2006) is explained by the dominance of rock lobster in both the commercial and recreational catches in Jurien Bay. The trophic level of the catch could be used as an ecosystem attribute to evaluate future changes in the system by fishing. However, the dominance of rock lobster in the catch means that such an index would be relatively insensitive to changes in other fished species. A reduction in the mean trophic level of the catch is likely to take place under higher fishing pressure, i.e. ‘fishing down marine food webs’ – a response that has been described in other marine ecosystems where fishing is intense (Pauly *et al.,* 1998a, b).

The complexity of the Jurien Bay Marine Park ecosystem makes it difficult to evaluate interactions among different species without using quantitative modelling approach. The Ecopath model developed in this study provides an effective tool for analysing the rock lobster ecosystem in the Jurien Bay region and testing hypotheses with respect to trophic interactions of different species and fishing regimens. This model provides not only a summary of our current knowledge of the biomass, consumptions, production, food web and trophic flows in Jurien Bay Marine Park for the 2005-2007 period, but also displays its capacity for integrating important ecosystem aspects in an easily understandable way. The analyses undertaken in this study have shown the great complexity of this ecosystem: pointing out the relevance of the lower trophic groups and their potential to produce a cascade of negative effects if this production is affected. This is particularly important because understanding the process and interactions within this ecosystem, including the role of both low and high trophic level groups and the impact of fishing mortality, can promote and support plans for conservation and management.

Fishing has also been shown to indirectly affect primary producers by removing the predators of grazing benthic invertebrates. In some cases, this has lead to a massive increase in their biomass and a corresponding reduction in the biomass of primary producers e.g. the formation of urchin barrens in marine ecosystems where lobster were once abundant e.g. in the North Pacific (Estes and Palmisano 1974, Behrens and Lafferty 2004), New Zealand (Babcock *et al*., 1999); North Atlantic (Steneck *et al*., 2004) and south-eastern Australia (Pederson and Johnson 2005). The benthic ecosystem modelled at Jurien Bay appears to respond quite differently to reductions in lobster biomass, with multiple relatively weak responses in the biomass of lobster prey, rather than a few strong interactions with grazing taxa. Conversely, the model suggests that strong bottom up effects would flow from changes in the biomass of benthic primary production by macrophytes to other levels of the ecosystem.

There were many factors that might affect the performance of the model in describing the structure and trophic interactions of Jurien Bay. For example, for the functional groups without biomass data (mainly benthic invertebrates such as crabs, abalones, cuttlefish, octopus, chaetognaths), their biomasses were estimated by the model. These estimates solve the core equations of the model to achieve balance, but not necessary the more realistic abundances in the system. A second key factor lies in the diet compositions, where several species/groups in the model were estimated from studies out of Jurien Bay. These uncertainties could introduce errors in the predicted outputs of the model and its use for forecasting ecosystem dynamics and evaluating rock lobster condition under different fishing regimens should be careful. This Ecosim model provides not only a summary of our current knowledge of the biomass, consumptions, production, food web and trophic flows in Jurien Bay Marine Park for the 2005-2007 period, but also displays its capacity for integrating important ecosystem aspects in an easily understandable way. This analysis has shown the great complexity of this ecosystem: pointing out the relevance of the lower trophic groups and their potential to produce a cascade of negative effects if this production is affected. This is particularly important because understanding the process and interactions within this ecosystem, including the role of both low and high trophic level groups and the impact of fishing mortality, can promote and support plans for conservation and management.

5.4 RESULTS: Ecospace model

Modelling spatial and fishing effort restrictions in Jurien Bay

Relative Biomass Distribution

There are currently no established routines for testing, calibrating and validating Ecospace outputs against spatial reference data or time series of forcing functions to drive the simulations. However, the spatial distribution of rock lobster (probably the best known species within the park) was used as a diagnostic tool to evaluate its performance. The steering committee expressed general satisfaction with the plausibility of the model at its meeting in September 2009. The abundance gradients of rock lobster (adults) presented in Fig. 41 suggest that under the current 4% of sanctuaries established in the park, lobsters will concentrate (after 20 years of simulation) mainly in the limestone reefs located in the south of the park. This distribution changed when the area of sanctuary zones was increased to 25%, where two new high density spots, located in shallow reefs, were predicted close to the township of Jurien Bay (Fig. 30). In contrast, no high density areas were predicted to remain in the Park when the sanctuaries were removed and fishing was allowed throughout the Park (Fig. 30).

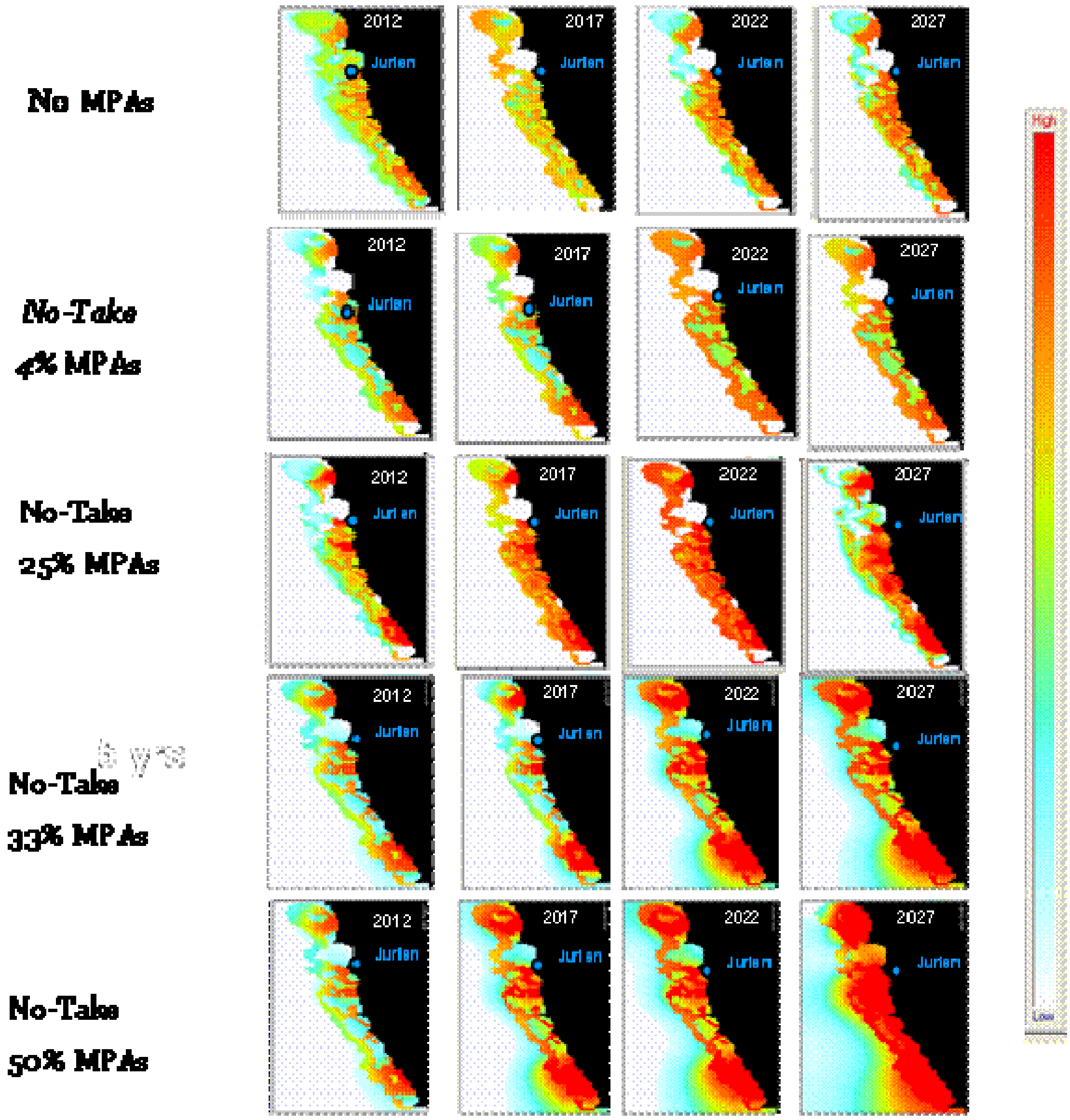


Figure 30. Western rock lobster time series of adult relative biomass distribution with 4%; 25%; 33%, 50% of no-take areas simulated (from top to bottom panels). Red colour suggests high relative abundance to the average abundance of the whole park; and white and blue patterns indicate low relative abundance. Black areas represent land. NB levels of shading are relative measures within each map, and cannot be compared between maps

Role of fishing closures

Our simulations suggest that the introduction of the current management zones with 4% of sanctuaries produced a modest benefit of ~5% in the biomass of rock lobster after 20 years (Fig. 33). However, rock lobster biomass increased by + 20% when the sanctuary area covered 25% of the park, indicating the positive effect of protection provided by this zone (Fig. 31). Similar trends were observed when the sanctuaries increased to 33% and 50% predicting proportional increases of lobster biomass by 25% and 30% from the 2006 levels, respectively after 20 years (Fig. 33). The 'no-sanctuaries' scenario was the only one that resulted in negative trend in biomass, showing a relative decline of 18% of the 2007 biomass after 20 years of simulation (Fig. 31).

For exploited fish species (e.g. Pink Snapper, Dhufish, and sharks among others) the potential benefits of increasing the sanctuary areas from 4% to 25% produced increments up to 30% in their biomass (Fig. 32). It should be noted that the scientific closures, only permit fishing from shore and thus the larger demersal species currently have an effective sanctuary area of about 22% (= 4% sanctuary zones and 18% scientific reference zones). The effect of increasing protection to 33% and 50% for the entire marine park produced positive trends in the biomass of both sedentary species (i.e. Dhufish, Pink Snapper) and pelagic species (i.e. large sharks). Marked increases in relative biomass were predicted for heavy exploited species such as Pink Snapper, where its biomass increased by up to 60% after twenty years when spatial closures covered 50% of the park (Fig. 32). In contrast, a clear decline in the biomass of the main finfish resources of the region was predicted when the closures zones (sanctuaries and scientific references zones) were removed from the model (Fig. 32). The present simulations indicate that the fishing closures in Jurien Bay Marine Park can lead to increases in the biomass of exploited resources; however an outcome beneficial to fisheries and the overall biomass is not guaranteed by the use of spatial closures for all species because of their different movement patterns. These spatial patterns and abundances predicted by the model were presented to experts of the Department of Fisheries, WA in September, 2009. Their comments and suggestions are attached as Appendix 7.

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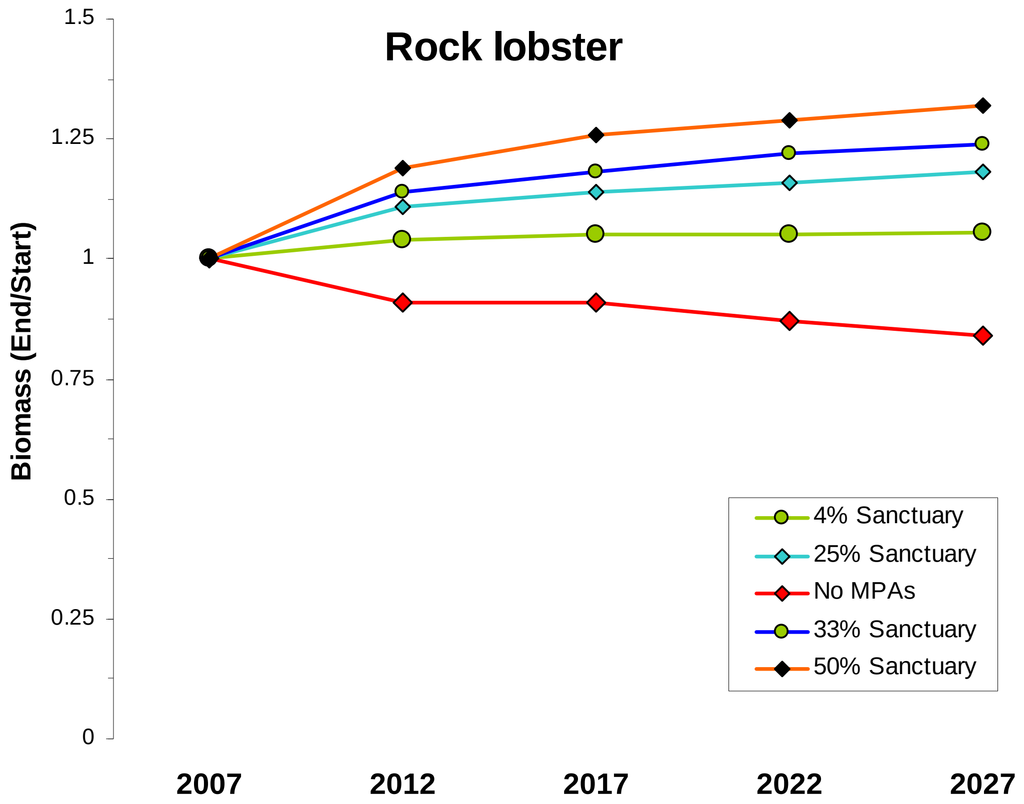

Figure 31. Simulated biomass response of Western Rock Lobster (adult) to five Marine Protected Areas simulations.

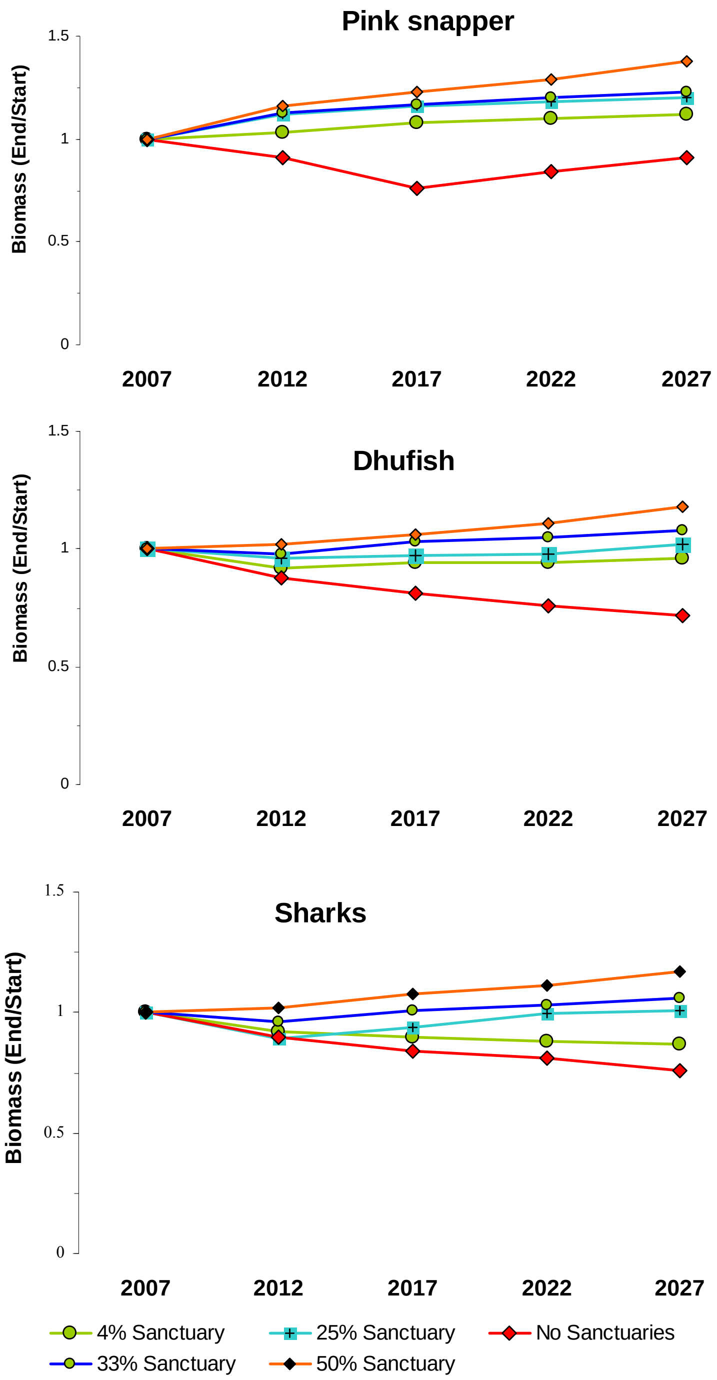

Figure 32. Simulated biomass responses of some of the target species in Jurien Bay to five Marine Protected Areas simulations.

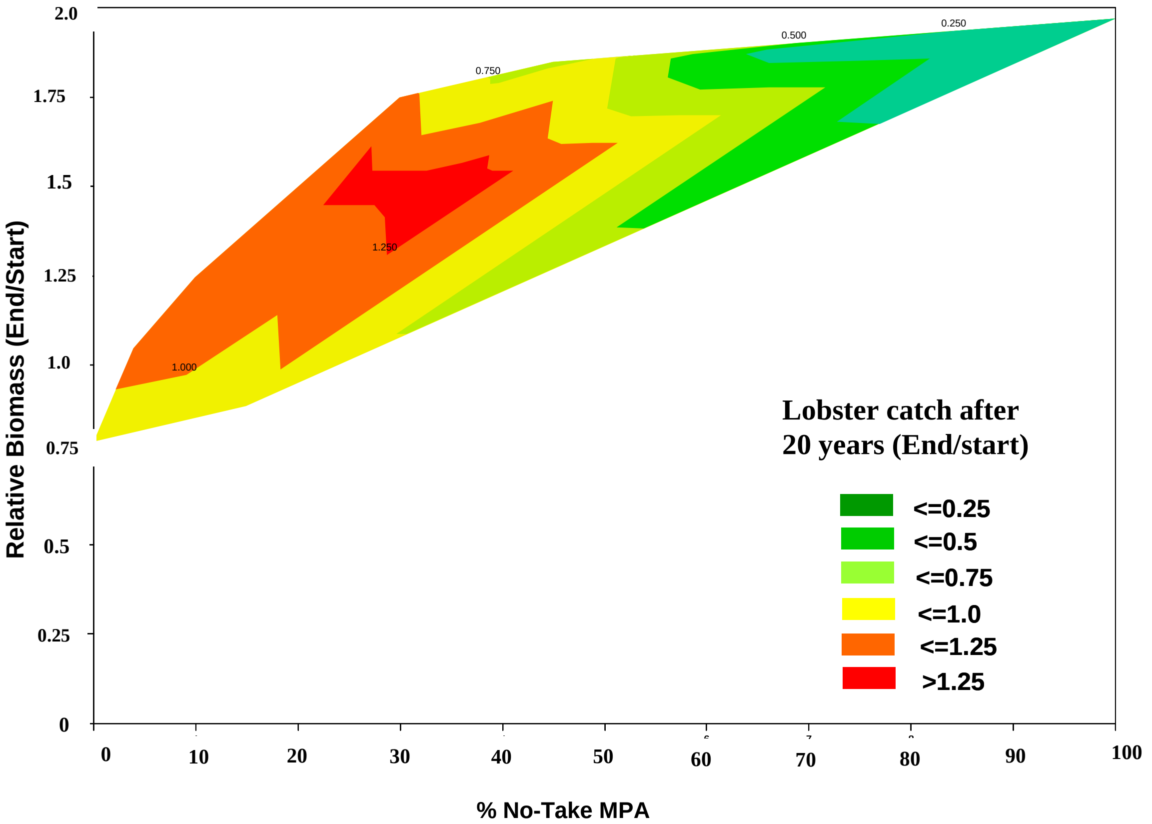

Figure 33. Predicted distribution of the catch at different proportions of no-take areas within Jurien Bay Marine Park.

The simulations indicate that the fishing closures provide positive benefits for the overall biomass of Jurien Bay and they provide support for protection provided by the current fisheries management regulations. Figure 33 shows the predicted catches of Western Rock Lobster after 20 years at different percentages of no-takes areas within the Marine Park, where the maximum relative catch was in those scenarios when the park had between 20% to 40% of no-take areas. The quantitative outputs predicted by the model must be interpreted with caution until more scenarios are developed. The results from this study assist in understanding the way in which components of this marine ecosystem interact, a key factor to predict the influence of the closed areas within the Park.

Discussion: Ecospace modelling

Our results suggest that the introduction of larger no-take areas (from 4% to 33% and 50%) in the marine park would benefit the overall biomass of some species in the Marine Park. Just five years after the closures were established in the model, there were important increases in the biomasses of sedentary targeted species such as rock lobster, Pink Snapper and Dhufish. In the case of pelagic, highly migratory species such sharks, sanctuaries had little affect on their biomass, suggesting that MPA effects vary greatly between species as has been documented by others (e.g. Mosqueira *et al.,* 2000). The MPAs created for fisheries purposes in Australia range from large closures to eliminate specific gear types (e.g. trawling) to smaller areas designed for specific habitat protection and protection of fishery nursery grounds (Ward and Hegerl, 2003, Woodley *et al.*, 2008). In this framework, fishing closures may be identified and managed as one important tool to meet the fisheries and biodiversity conservation objectives. Empirical evidence from other studies of MPAs has shown an increase in the spawning biomass and mean size of exploited populations (Gell, 2002) and population abundance (Cote *et al.*, 2001). There is increasing scientific evidence demonstrating that the abundance, biomass and length of target fish species increase inside areas closed to fishing (Babcock *et al.*, 1999; Russ *et al.*, 2005; Watson *et al.*, 2007). The effect of protection of no-take areas on targeted and non-targeted reef fish species in Western Australia has showed in some studies (e.g. Watson *et al.*, 2007; Woodley *et al.,* 2008) that the abundance inside closure areas was up to eight times greater than their abundance at fished locations, demonstrating that the removal of abundant targeted species from an ecosystem by fishing can indirectly impact non-fished species and alter the trophic structure of fish assembles. Also, reserves may produce positive outcomes in the form of spillover in the fishing areas as fish and lobsters migrate out of the reserve (Roberts *et al.*, 2001; Gell and Roberts, 2003). However, it has been observed that the establishment of no-take areas did not guarantee increases in the landings and production of some marine reserves (Grafton and Kompas, 2005). However, only a few studies on reserves have included catch data before and after the date of reserve creation (Willis, *et al.*, 2003).

In the Ecospace model, the overall fishing effort remained the same on the 20-year scenarios developed. The reduction of catch in these scenarios could be explained by a displaced effort to non-protected areas out of the marine park. The treatment of displaced effort and catch is a critical issue for the analysis of the effectiveness of MPAs because most of the fisheries around the world are managed without a spatial control quota (Watson *et al.*, 2007). The impact of displaced effort will depend on the nature of the fishery management system that is in place, the life history of the exploited species, and perhaps, the effectiveness of the MPA in providing additional recruits etc. for the fishery (Ward and Hegerl, 2003). Locally, this raises the important issue of the displacement of fishing effort outside the boundaries of the marine park, where the rock lobster fishery is managed using specific input controls, but there are no spatial constraints that control where the lobster fishermen can catch their lobster. The displaced effort of the rock lobster fishery to other locations outside the closed areas could result in additional pressure and high fishing mortality to lobster population within or nearby the marine park that could be counter productive to achieving the original objectives of the fishing closures or affect the rock lobster fishery. The shift of additional effort into the open fishing areas of Jurien Bay may reduce the production of spillover and/or puerulus lobsters that ultimately provides the basis for the long-term sustainability of the fishery.

Although the model simulates ecosystem dynamics, the quantitative outputs must be considered with caution until routines for formal validation of Ecospace are developed. The dispersal rates for most of the target species is difficult to estimate given sparse information on movement behaviour of species in the Jurien region, although it is likely to have important effects on the overall outputs. In addition, it is important to consider in the model the time lag between growth and recruitment that can affect the positive outputs of the closures. Based on the results from the model (Figs 33 and 34), the effectiveness of the fishing closures in Jurien Bay for fisheries objectives alone is likely to be critically dependent of the biology and life history characteristics of the main target species. For example, species with low dispersal and low/medium fishing mortality (e.g. groupers and wrasses) are more vulnerable to human impacts than those pelagic species with moderate/high fishing mortality (e.g. sharks). This also could occur for resident species of the marine park such as Dhufish, where accidental catch and its subsequent mortality (even if released) could have negative impacts on the populations. Despite these qualifications, the use of a complex ecosystem model allows us to explore the effects of fishing closures on ecosystem attributes and its fisheries that are beyond the scope of single-species simulations. The success of no-take areas in fisheries objectives alone is also likely to be critically dependent on the design process (Gerber *et al.*, 2002). It should be based on the specific characteristics of the target species, because their life history characteristics may have a major influence on the effectiveness of a reserve in supporting a fishery. It is clear that all the management controls (quota, fishing effort, spatial control quota, etc) need to be reviewed and assessed to ensure that wherever possible, fishing closures enhance fisheries.

The present simulations indicate that the fishing closures in Jurien Bay Marine Park can lead to increases in the biomass of exploited resources, even without reductions in overall fishing effort, but these benefits are not necessarily to the same for all species and fisheries. The reliability of the spatial patterns and abundances predicted by the model needs to be verified with local biomass sampling inside and outside the sanctuary areas. The results from this study assist us to understand the way in which components of the marine ecosystem interact, a key factor for predicting the influence of the closed areas within the Park. Given the assumptions of the model and uncertainty of many of the parameters employed (e.g. dispersion rather than migration), it may be better to improve current management controls, such as size limits and total catch within the zones of WRL fishery and increase our knowledge of the biology of key species in the park (i.e. rate movements of sedentary and pelagic species), rather than introducing larger fishing closures in the future.

The application of traditional fisheries management or spatial closures for conserving fisheries or biodiversity, and the question of which approach offers the greatest advantages for economic, ecological and social sustainability, has generated heated debate and conflict among sectors. Recently, the use of closed areas has gained greater attention for conservation and management plans due, in part, to the catastrophic collapses of some fisheries globally. In most of these cases, the fisheries were managed by simple catch or effort regulations. Both catch and effort controls often suffer from implementation uncertainty, which is the inability of management to achieve the stated target because of the difficulty of fully monitoring and controlling catch and effort (Stefansson and Rosenberg, 2005). Furthermore, in effort control-based systems the increased technology and efficiency of the fleets resulted in higher catchability of the fleets with time. Protected areas address the concerns over broader ecosystem protections in some cases (Botsford *et al.*, 20003), preventing bycatch of non-targeted species, protecting habitat from fishing gear damage and providing refuge for a broad range of species in the ecosystem. Although the buffering effect of protected areas is difficult to determine, it seems that the combination of substantial MPAs along with quota controls can have clear benefits for conservation and the sustainability of fishery yields (Stefansson and Rosenberg, 2005). Simply implementing a closed area, without also implementing measures that provide appropriate management of areas outside closed areas, is unlikely to sustain fish stocks.

Results of the final simulations from all the models (Ecopath, Ecosim and Ecospace) were presented to experts of the Department of Fisheries WA and members of the steering committee in October 14th, 2009 (Department of Fisheries, Hillarys, WA). A summary of the presentation and feedback from this meeting is provided in Appendix 7 and they were used to guide the development of the final report for the project.

5.5 RESULTS: Local Fisher’s Knowledge (LFK)

Investigate how past and future changes in abundance of key fished species are likely to influence other species.

Tracking food web changes: Information revealed by trophic levels

The trophic states of the Jurien Bay ecosystem constructed for the 1980s and 2005 cover important changes in biomasses over the past 30 years. For example, there was a reduction of around 15% in the total estimated biomass in trophic levels 3 and 4 (Fig. 34), where most of the groups that occur in this range (Pink Snapper, Foxfish, groupers, wrasses, Dhufish, sharks) are commercially exploited, emphasizing the relevance of the marine park as a help to reduce fishing mortality of these populations. The important role played by commercial and recreational fishing extractions in the composition and abundance of the marine biota in the Jurien region was confirmed by major changes in the biomass of large fish predators such as Pink Snapper, Dhufish and sharks during the last 30 years. In addition, the loss of biomass between both periods was experienced not just by high trophic levels, but also by invertebrates and other primary consumers at TL 2 with a loss of around 8% of total biomass since 1980s. Figure 35 shows the changes in the biomass in this section of the Jurien system.

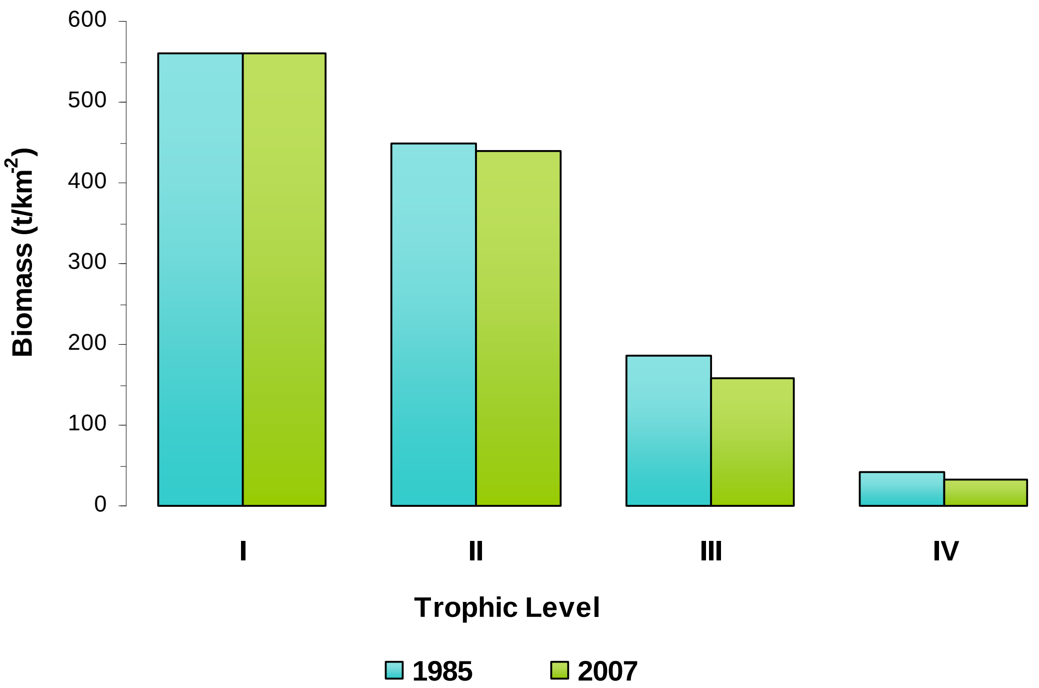

Figure 34. Total biomass by trophic level of the past and present food web models of the Jurien Bay marine park, displaying an important reduction of the biomass of organisms located above between trophic levels 2.5 from 1980 to 2005.

Trends from the LFK interviews suggested that the fishery resources in the Jurien region have declined over the past 25 years, with the relative abundance (1980-2006) of most groups showing a decreasing trend. A few groups, such as sea lions, were perceived to apparently have been increasing since the 1990s. Figures 37 and 38 show the changes in abundance since 1980s (relative to 2005) of the main fish groups (from detritivores to top predators) and marine mammals. Significant changes in the abundance of heavily exploited species were observed. For example, rock lobster declined around 60% since 1980s to the present day, based on the biomasses estimated from LFK interviews (Fig. 37). Similar trends were reported for Dhufish and Pink Snapper where the loss of biomass could reach up almost 200% in average for Pink Snapper (Fig. 35). The important role played by commercial and recreational fishing extractions in the Jurien region could be confirmed by the major changes in the biomass of large fish predators such as Dhufish and sharks during the last 20-30 years.

The results from the LFK interviews suggested that the fishery resources have declined over the past 25 years (see Fig. 37 for selected examples), with the relative abundance (1980-2006) of most groups showing a decreasing trend. A few groups, such as sea lions, have been apparently increasing since the 1990s (Fig. 36).

Agreement of LFK with DoFWA records

Unfortunately, there are no biomass surveys of the Jurien region conducted over long periods of time that can be used to compare the past LFK abundances from 1980 to 2005. However, the time series of rock lobster catch and effort from 1980 to 2005 (data provided by Department of Fisheries, WA) was used to evaluate the agreement between the LFK trends and landings of lobster recorded by DoFWA. As explained in the methods, the perceived LFK abundance was converted to an absolute index by scaling the series to the 2005 abundance. The agreement between LFK and the recorded catch and effort data was measured using the Spearman Rho nonparametric coefficient of correlation. A significant (α=0.05) concordance was found between the rock lobster abundances estimated by interviews and the catch effort (potlifts) (71%). Figure 37 shows the trajectory for rock lobster and its concordance with the number of potlifts recorded within the marine park from 1980 to 2005. For rock lobster catch, however, the correlation explained only 41% of the variation in the relationship and was statistically non-significant (α=0.05).

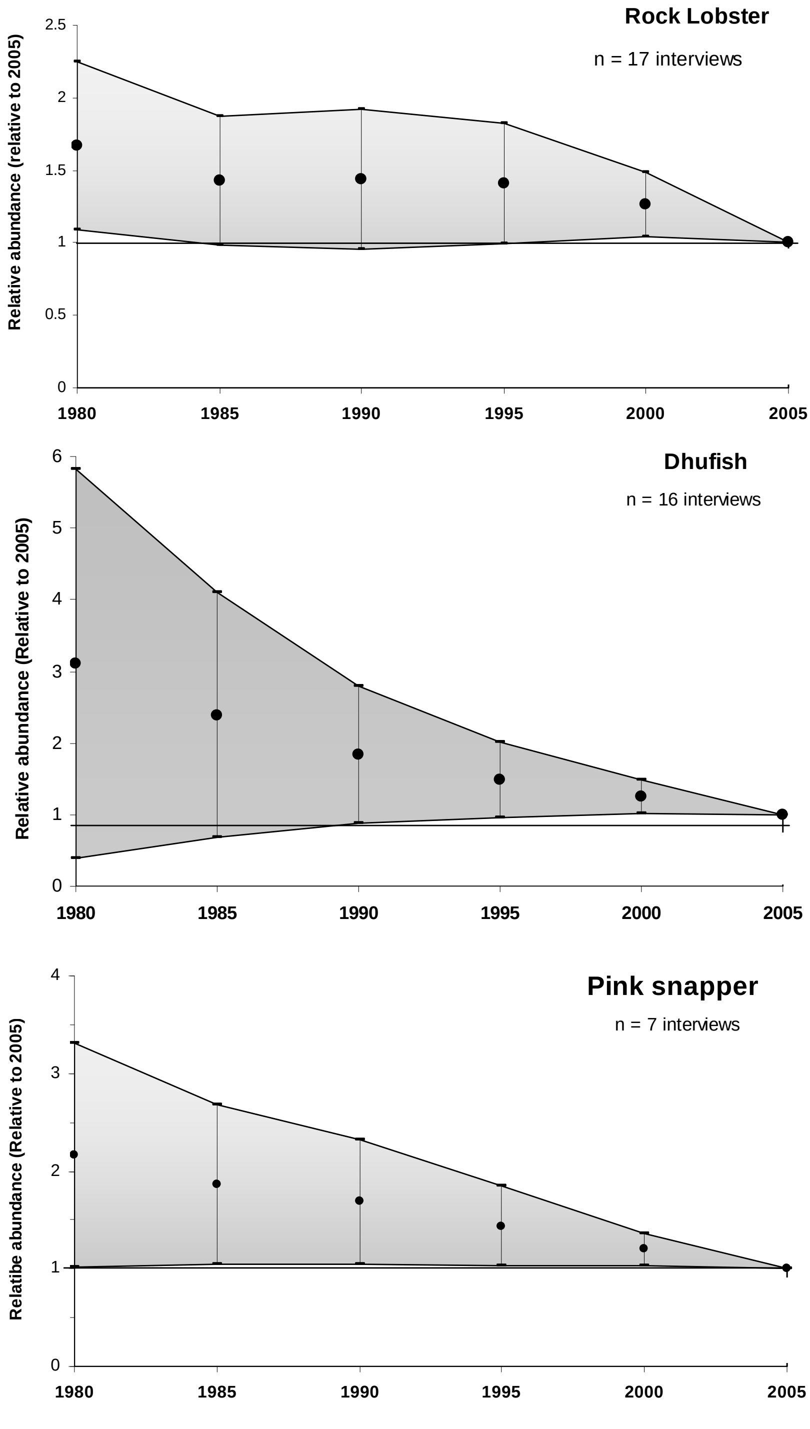

Figure 35. Past abundances (relative to 2006) for the main four species exploited in the Jurien Bay region (black dots). Bars represent the standard deviation of the mean. These abundances were estimated from interviews with local fishermen of the region.

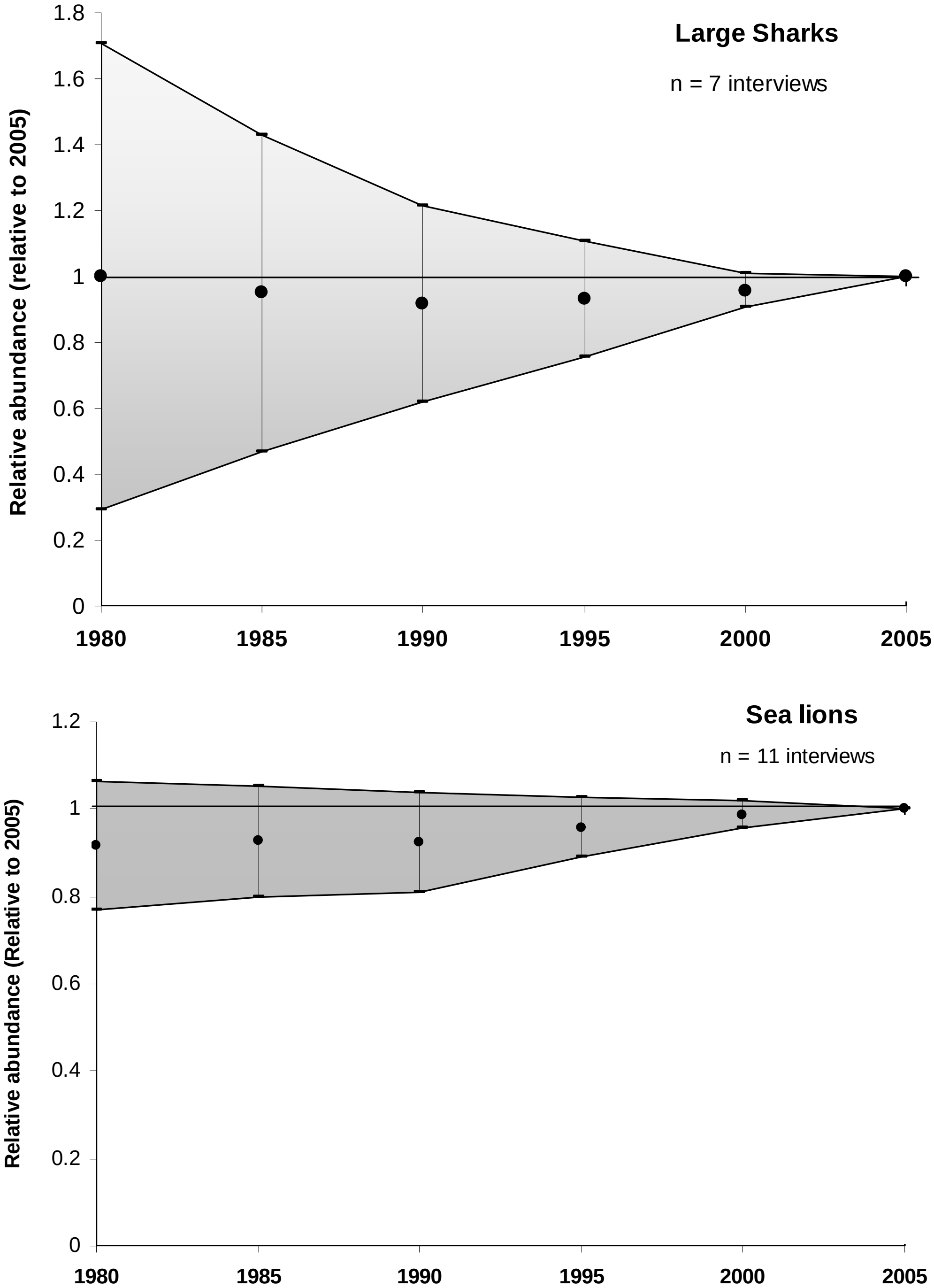

Figure 36. Past abundances (relative to 2006) for sharks (upper panel) and sea lions (bottom) in the Jurien Bay region (black dots). Bars represent the standard deviation of the mean. These abundances were estimated from interviews with local fishermen of the region.

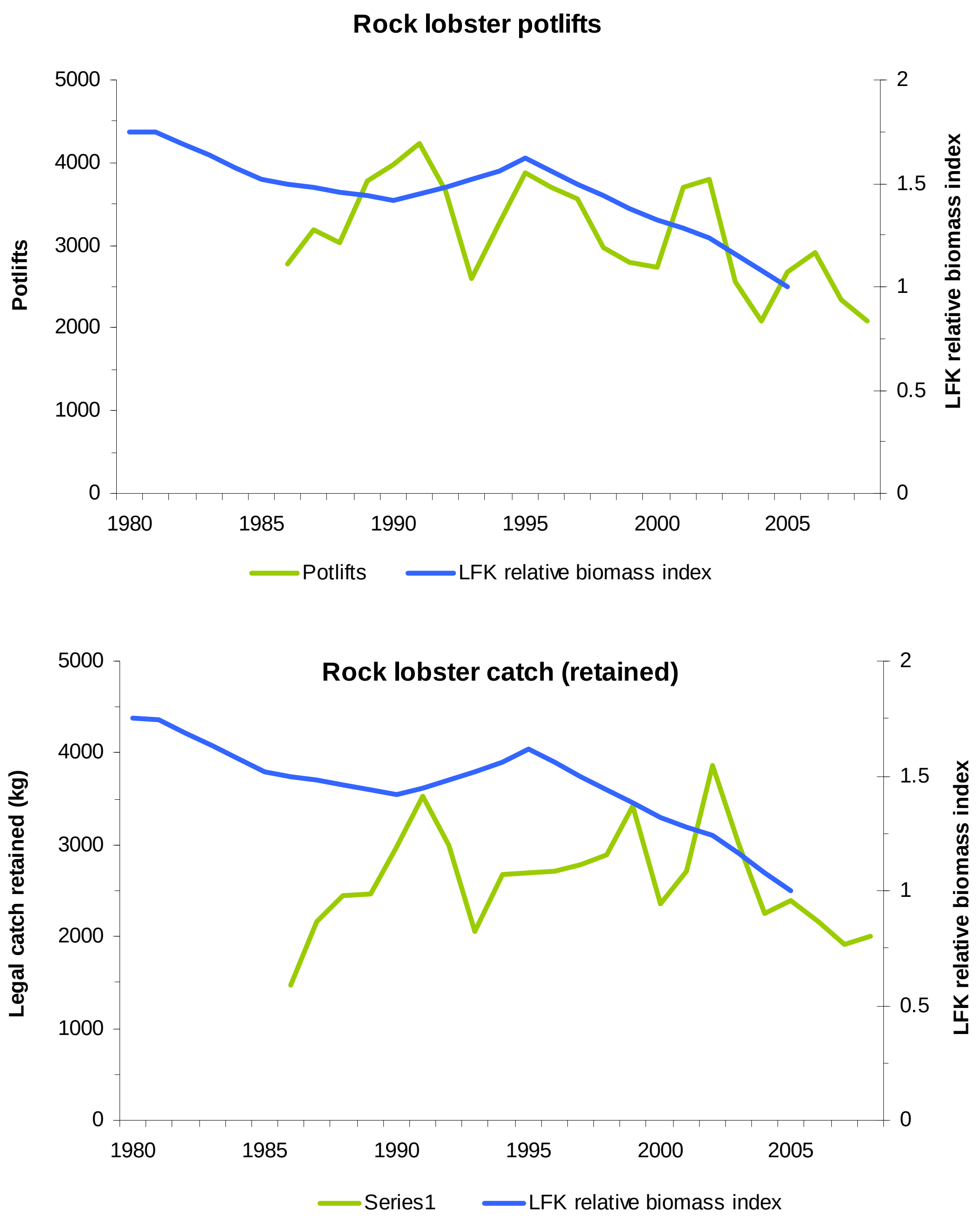

Figure 37. Concordance between relative abundances of Western Rock Lobster estimated by the LFK and catch effort (potlifts; upper panel) and landings (legal catch retained; lower panel) from 1980 to 2005. Data provided by DoFWA.

Discussion: Local Fisher's Knowledge

During the last decade, trophic level structures have been used to evaluate fishing and other human effects on marine ecosystems. For example, Pauly *et al.,* (1998) demonstrated a steady reduction of the mean trophic level of fisheries landings from 1950 to the present, suggesting that fisheries increasingly concentrate on the more abundant, fast growing fishes and invertebrates near the bottom of the aquatic food web. These findings represent examples of how trophic levels generated by Ecopath models could be used to quantify human impact on marine ecosystems. Trophic levels have been used beyond these generalizations. Thus, Pauly and Christensen (1995), who assigned trophic levels to all fish and invertebrates caught and reported in FAO global fisheries statistics (Pauly and Christensen; 1995) showed that the primary production required (also using transfer efficiencies estimated by Ecopath) to sustain the present world fisheries was much higher than previously estimated: 8% for the global ocean and between 25-35% for coastal shelves, from which 90% of the world catches originate. We employed the Local Fisher's Knowledge from the Jurien region alongside scientific biomass surveys and fishery information to construct a preliminary Ecopath model for the Jurien Bay Marine Park to explore changes in the trophic interactions and structure of this system.

In the absence of strong baseline ecological studies in the Jurien region during 1980s and 1990s, more than five hundred collective years of experience of the 20 fishers interviewed represents a valuable source of information that may be incorporated into quantitative modelling to evaluate past states of the marine park. The LFK analysis represents probably the only way to estimate past abundances for many non-commercial species (seabirds, marine mammals, fishes and invertebrates) in the area. We are aware that results from a small number of interviews can be biased (Yli-Pelkonen and Kohl, 2005), and it is noted that our LFK results from the Jurien Bay region are based on a relatively small number of interviews (n = 20); this is less than 5% of the fishers' population.

The results presented in this section should be considered preliminary. A more intensive field work with more interviews will reduce the uncertainty in the trends reported by the fishers and it will provide better estimates of the past richness of the region and its gradual changeover the past 25 years. Overall, this LFK material displays the potential value of LFK and social participation in the management of marine ecosystems. Our results suggested that fishers perceive that the fishery resources have declined over the past 25 years, with the relative abundance (of most groups) showing a decreasing trend. A few groups, such as sea lions and sharks, apparently have been increasing since the 1990s. LFK and social participation have a role to play in fisheries science. Fishers' knowledge could be incorporated into the environmental and ecosystems analysis. After all, fishers are in permanent contact with their resources and have accumulated knowledge that can be of great value in the process of understanding marine ecosystems.

We consider critical for future conservation and management plans in the marine park that young fishers and people in the Jurien region visualize and understand the previous states of their ecosystems. It seems that the richness of Jurien Bay of former times lives in the memories of old fishers, but these memories have not travelled across the new generations to today's young fishers and residents. The LFK analysis illustrates that the fishers of Jurien Bay have a rich heritage and their knowledge has much to offer in the multidisciplinary perspective needed to face the today's challenges in the management of natural resources.

5.6 RESULTS: Optimum fishing strategies

Modelling economic, social and ecological values in Jurien Bay.

The theoretical tradeoffs between extreme scenarios where fishing was reduced (high weighting on ecological values; e.g. Scenarios 14 and 15; Appendix 7) or those cases where excessive fishing effort was employed without considering the depletion of the resources (scenarios with high values on economy and number of jobs; e.g. Scenarios 4, 5, 8 – 10, Table 10) are presented in Figure 40. The results from the ten years of simulation provided the trends of the direction in the change in fishing effort ratios from 2006 to 2016.

The optimization of the economic scenarios (profit) suggested that the effort on rock lobster should be increased by around 200% and the effort in the trap and abalone fisheries should be increased by up to seven times in order to maximize profits in the system. Also, the five scenarios designed to optimize the profits suggested a reduction of up to 50% of the rest of the gears (Fig. 38). Those scenarios focused on ecological attributes suggested that gillnetting, long-lining and drop-lining should be reduced to less than 20% of the fishing effort of 2006 (Fig. 38). The scenarios designed to optimize the number of jobs (relative to each fishing sector) suggested a mean increase of 50% (±22%) in the fishing effort in the rock lobster fishery. Important theoretical increments (up to 180%) for gillnet and long-line fisheries were suggested by the model to maximize the social benefits (as number of jobs). In contrast, some fisheries, such as beach seine, traps and abalone should reduce their efforts by at least 50% of the 2006 effort (Fig. 38). In contrast, the scenarios designed to increase the Ecological values of Jurien Bay (total biomass) suggested that great reductions in the drop-lining and gill-netting fisheries within the marine park i.e. they should be virtually closed. As expected, no increases in fishing effort were indicated by the ecologically weighted scenarios, for example, rock lobster fishery increased 20% and traps and beach seine fisheries around 50% (Fig. 38).

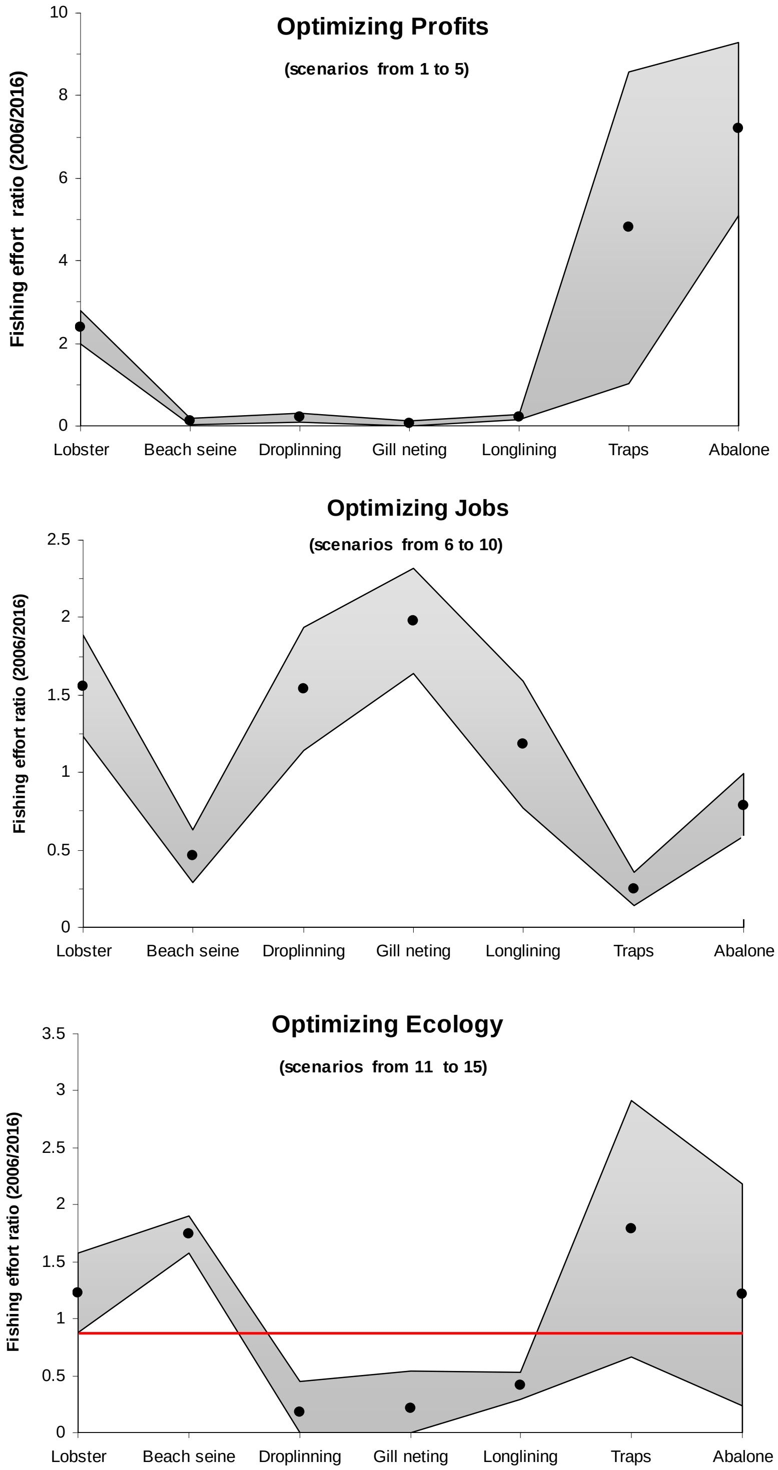

Figure 38. Mean change in the relative effort ratios (black dots) as a result of the optimization of commercial fisheries of Jurien Bay under different objectives (based on scenarios proposed in table 5; see text for details) after 10 years. Grey areas represent standard deviation and the red line is the mean fishing effort ratio (black circles) of the eight fisheries at the end of the run.

Discussion: Optimum fishing strategies

The overall results of this exploratory analysis confirm that fishing and conservation could be compatible in the marine park, but the low number of scenarios with this ‘win-win’ characteristic suggests a high risk for exploited species such as rock lobster, Pink Snapper and Dhufish. Some results from the economic scenarios (where profits are maximized) suggested that it is possible to reduce effort in the Western Rock Lobster fishery (with a reduction of catch around 10%) in order to improve the level of its profits. This could be interpreted as a shift of managing this fishery from maximum sustainable yield (MSY) to Maximum Economic Yield, MEY (as suggested by Reid, 2009), but it is important to consider that the high fixed costs used in the model need to be revised by experts. The results obtained from this analysis are based on the long term (20 years) averages, which makes it difficult to make comparisons with those trends obtained from other economic analysis (e.g. Huddleston, 2006). The original goal of this exploratory analysis was not to incorporate the results from the scenarios described above into future polices for management of the fisheries in Jurien Bay. The scenarios only represent a preliminary stage in evaluating alternative objectives and as providing an indication of which fishing effort could be modified in order to achieve conservation goals under a sustainable fisheries regime. The ‘success’ of future conservation goals and fishing plans must include a full evaluation in each of the social, economic and ecological fields with the participation of experts and targets with more solid and realistic backgrounds and to meet with the management regimes need in the Jurien Bay region. The exploratory analysis presented in this section illustrates the need to perform a more complete and detailed analysis of the cost-benefits of fishing before considering any policy goal in the region.

The current management policies in the region focus on conservation and reducing the size of fishing effort. These policies are in general agreement with the ‘win-win’ scenario criteria for long-term sustainable fishing in Jurien Bay. The results from the ‘mixed’ scenarios do not display a definite pattern, but it could be said that they represent a balance between the four criteria considered. However, the analysis showed that most of the scenarios considered were not feasible since they suggested unreasonable changes in the activities of some fleets, which were not considered to be viable. After an exhaustive search, the overall results suggest that it is necessary to examine the tradeoffs presented among the ‘win-win’ scenarios in more detail in order to obtain more realistic solutions.

5.7 RESULTS: Climate change impacts

Effects of predicted phytoplankton change on the community of Jurien Bay and its fisheries

The change of 11% of phytoplankton over 100 years produced according to the Ecopath with Ecosim model a decline of ~4% (~50 tonnes km^{-2}) in the total biomass in the marine park (Fig. 41). Biomass of functional groups of conservation interest such as turtles and sea lions also declined due probably to the decline of seagrass predicted by the Ecosim model. In addition, important increments in the biomass of reef fish (Fig. 39) could increase the competition for prey with sea lions that contributed to the decline in the model. In particular, we were interested in evaluating the trends and direction of changes in the abundance of Western Rock Lobster (*Panulirus cygnus*), the most valuable single species fishery in Australia. The model indicated that the biomass of rock lobster increased slightly by around 3% (0.02 tonnes km-2; Fig. 39). No major changes (<5%) in the community composition (captured by mean trophic level) was predicted by the change of 0.11% year^{-1} of phytoplankton as result of climate change. It worth to mention that vulnerability fitting in the Ecosim model allowed for bottom-up control and linear changes in the community composition. The Jurien model suggests that interactions between seagrass and other benthic primary producers can have large effects on community composition in the temperate waters of Jurien Bay and should be consider in the climate models for more robust and accurate predictions.

In the case of the effects of projected production on fisheries, it was predicted over 100 years that the total catch within the marine park was reduced by ~3% (12 tonnes km^{-2}; Fig. 40). These results challenged the prediction of the ocean-drive model Mk3.5 that the increased primary production will produce positive outcomes for fisheries catch. The impact of change in primary production (phytoplankton) among the fisheries of the Jurien region was diverse, some fisheries were positively impacted e.g. rock lobster (Fig. 41) and most of the recreational fisheries (Fig. 40) and others were reduced up to 5% such as gill netting, droplining and longlining (Fig. 40) as result of the decline of their main target species associated with seagrass habitats.

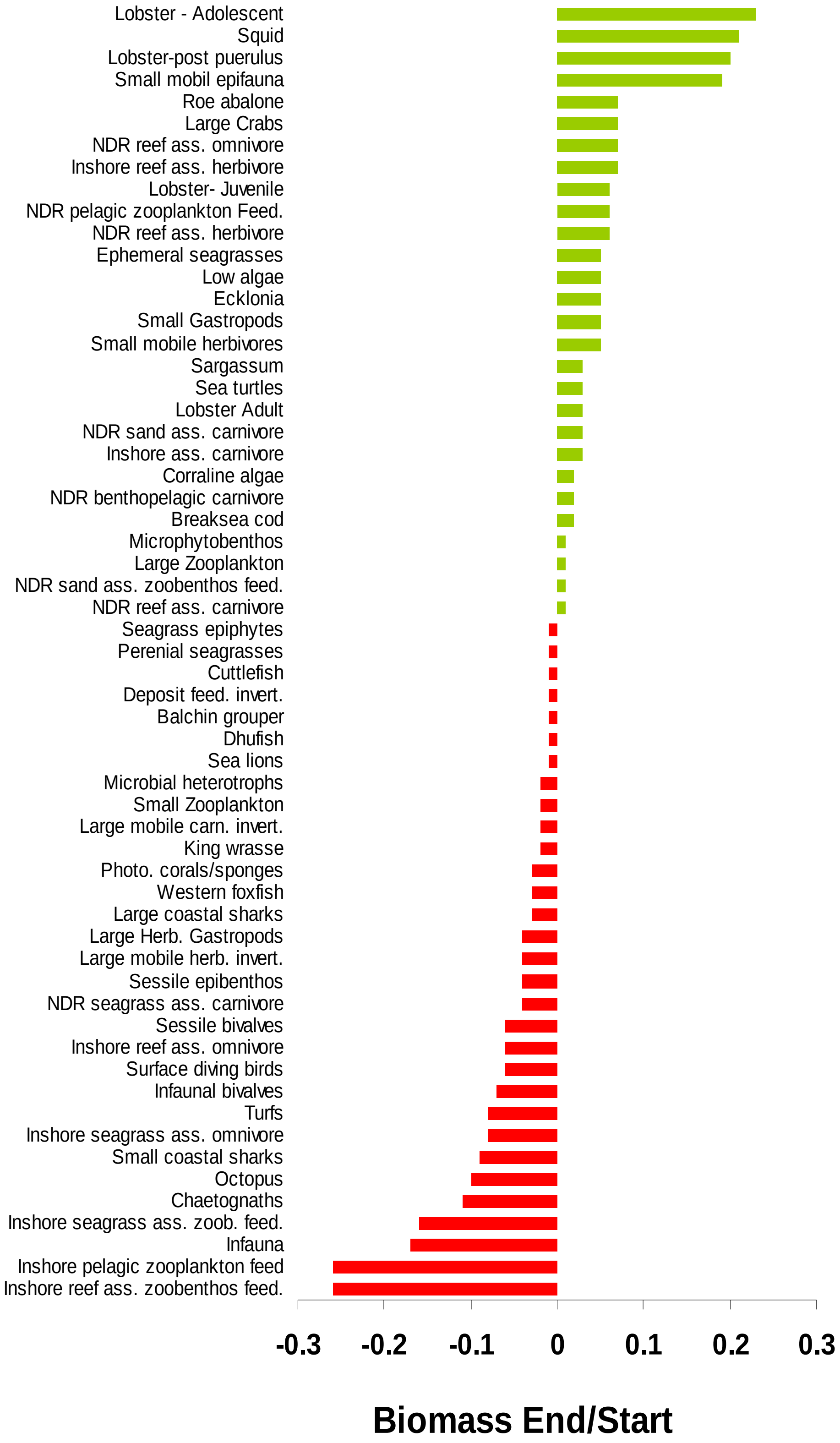

Figure 39. Simulated changes in the relative biomass of the functional groups of the Jurien Bay model after 100 years of trophic interactions under an increase of primary production of 11% (as predicted by the climate model CSIRO MK 3.5).

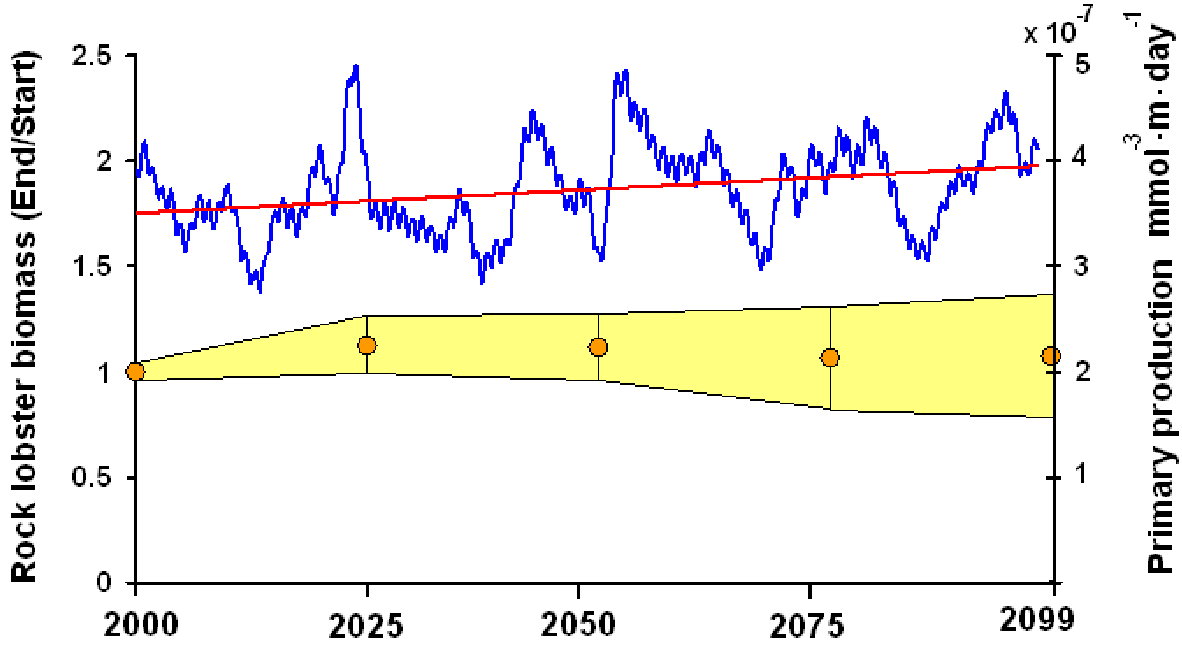

Figure 40. Simulated changes in relative biomass of rock lobster (orange circles) as result of the change in primary production (blue line) predicted by climate model CSIRO MK 3.5. Yellow area and bars represent standard deviation of the mean.

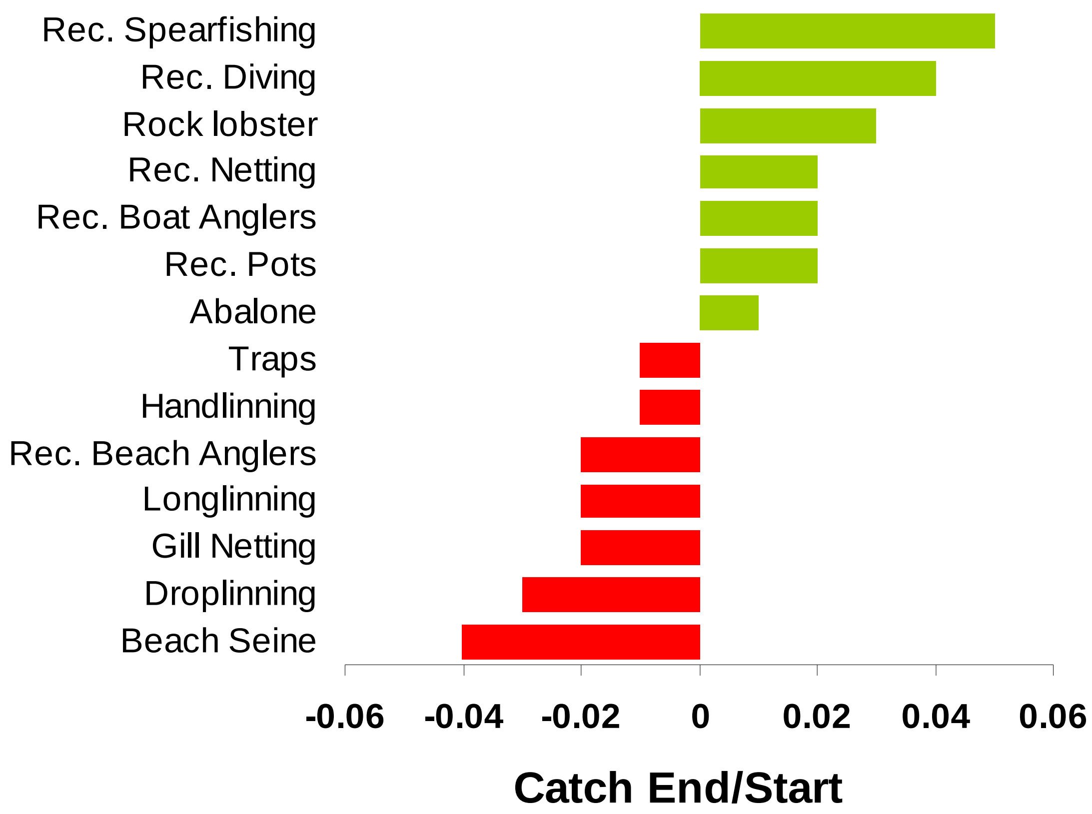

Figure 41. Simulated changes in catch of the commercial fisheries included in the Jurien Bay model after 100 years of trophic interactions under an increase of primary production of 11% (as predicted by the climate model CSIRO MK 3.5).

Discussion: Climate change impacts

Changes in primary productivity (mainly phytoplankton) of the magnitude predicted by the primary production models (i.e. Mk 3.5) could result in small changes in the biomass of marine organisms and fishery catches of temperate Western Australia (based on the Jurien Bay model). Empirical evidence suggests that fishery catch is strongly controlled by primary production (Ware and Thomson, 2005). However, our results highlight the need to develop coastal primary producer models for a more accurate prediction of the effects of climate change on marine ecosystems. The benthic primary production in the Jurien Bay region is a key factor to consider in these analyses and future models should consider alternative rates of benthic primary production associated with seagrass and macroalgae. Changes in primary production (bottom-up effects) will cause changes in the biomass of most marine organisms, but predation and competition can control the magnitude and direction of these responses. These two factors can suppress the response of some species to the predicted increase of primary production by the MK3.5 model. It is important to obtain more time-series data to parameterize predation and competition interactions in the model to improve the predicted response of food webs such as Jurien Bay ecosystem to changes in primary production. At the moment, these preliminary predictions presented in this section should be seen as a diagnostic of the model performance and they strongly indicate that more accurate predictions of the effects of climate change on benthic producers are required to improve the outputs of the Jurien Bay trophic model. These results were presented in the Climate and Resources Conference as part of the GREENHOUSE, 2009 held in Perth from March 22-26, 2009.

6. BENEFITS AND ADOPTION

The project has been invaluable as a catalyst among the marine science and management community in Western Australia. It has brought together a diverse group of experts in a successful effort to gather data and information and forge it into a broad consensus about coastal ecosystems function and trophic interactions on the central west coast.

The project has developed a deeper understanding of a range of ecological models among the Western Australian marine science and management community and of the role they can play in assessing a range of management options.

The model provides a structure that can be reviewed and modified in developing models in other regions of Western Australia, such as the metropolitan waters of Perth from Lancelin to Mandurah. The workshop process used in developing the qualitative and quantitative models has increased awareness of the Ecopath suite of programs and lead to the development of small models that have been applied to other systems in Western Australia (e.g. investigating the influence of bait on the lobster ecosystem at the University of Western Australia, and investigating the effects of dredging and shading on primary and low order secondary production at Edith Cowan University).

This project has increased the capacity for ecosystem modelling in WA, and training people in this area, through the employment of Dr Hector Lozano-Montes.

7. FURTHER DEVELOPMENT

Further development of an Atlantis Ecosystem model for the Jurien Bay region and Perth Metropolitan Area (Lancelin to Mandurah) is recommended. A large-domain Atlantis model has been developed for the South-West bioregions defined by the Department of Environment, Water, Heritage and Arts (Kangaroo Island to Kalbarri). Benefit from developing the Jurien Bay and Perth Metropolitan Area sub-components under this modelling platform will provide detailed information of the bottom up processes (including biochemistry and oceanography fields) that appear to dominate in the temperate Western Australia. This has also highlighted the need for detailed information on primary production along the coast.

Uncertainty around model parameters is one of the major limitations in the predictions made by the Ecopath model. The sensitivity analysis indicated that the Jurien model was sensitive to changes in the biomass of lower trophic levels (e.g. seagrass) and to a lesser extent, changes in top predators (e.g. sharks). Hence, obtaining more and better information of abundance for benthic producers is a critical aspect for the future.

The analysis of the optimization of the fisheries in Jurien Bay represents only a preliminary stage and they must be taken as an exploration exercise. A collection of more data on the economics of different fishing operations will be beneficial. The 'success' of future conservation goals and fishing plans in the Jurien region must include a full evaluation in each of the social, economic and ecological fields.

In the absence of strong baseline ecological studies in the Jurien region during 1980s, the Local Fishers Knowledge (LFK) analysis conducted here represents probably the only way to estimate past abundances for many non-commercial species (seabirds, marine mammals, fishes and invertebrates) in the area. It is noted that our LFK results are based on a relatively small number of interviews (n = 20). Some of the trends determined from LFK, particularly those from lobster, can be validated by comparing these trends with data held by the Department of Fisheries WA. More intensive field work with more interviews will reduce the uncertainty in the trends reported by the fishers and it will provide better estimates of the past richness of the region and its gradual change over the past 25 years.

8. PLANNED OUTCOMES

1. An assessment of the influence of fishing closures on biological communities and the implications for target fisheries in the Jurien region of Western Australia. This will allow a comparison of the effectiveness of closures with traditional fisheries management measures for fisheries and conservation.

2. The development of ecosystem understanding of fisheries in the Jurien region and the construction of an ecosystem modelling framework that can be applied to this and broader regions of temperate Western Australia.

3. Building capacity in researchers and managers for ecosystem approaches to fisheries and building ecosystem modelling expertise in researchers.

4. Identifying useful ecosystem-level performance indicators and target reference points for the Jurien region, with possible extension to the other temperate regions of Western Australia.

5. Providing a logical framework for identifying key research questions and assigning priorities for ecosystem approaches to fisheries for research and management in temperate Western Australia.

The main beneficiaries from these planned outcomes will be the commercial (lobster and finfish) and recreational fisheries and fishery researchers and managers of Western Australia.

9. CONCLUSIONS

The Ecopath model developed in this project is the first mass-balanced model developed for the temperate west coast of Australia to characterise the trophic structure, ecosystem attributes and impact of fishing in the region. The model integrates the data available in the region and it provides a summary of our current knowledge of the biomass, consumption, production food web and trophic flows in the Jurien Bay Marine Park ecosystem.

The Jurien Bay ecosystem is dominated by the benthic functional groups, which represent the main components of the biomass for the total system, the catch of fisheries and the energy flows in the system. This ecosystem is therefore characterized more by bottom-up interactions, driven by the importance of macroalgae (mainly *Ecklonia*), seagrasses and other macroalgal assemblages that are major sources of habitat and food for marine invertebrates and fish in the region. This is particularly important because understanding the process and interactions within this ecosystem can promote and support plans for conservation and management.

The results from the dynamic simulations using Ecosim showed that the fisheries in Jurien Bay have the potential to produce significant impacts on this ecosystem, either through the direct effects of fishing or through the indirect effects of fishing in altering the biomass of the higher trophic groups. The predicted biomasses removed by fishing on some groups such as Pink Snapper, Western Rock Lobster, and sharks, were up to three times higher than those removed by predation, which indicates a need for further investigation. Also, the model indicated that a reduction in fishing mortality on the Western Rock Lobster is unlikely to produce major trophic cascades in the marine park, possibly because the prey of lobster are highly productive and have short life cycles (i.e. small invertebrates and algae). The Western Rock Lobster also feeds on a wide range of functional groups across many trophic levels, including primary producers, which results in numerous, relatively weak linkages throughout the system.

The trophic level of the catch could be used as an ecosystem attribute to evaluate future changes in the system by fishing. A reduction in the mean trophic level of the catch is likely to take place under higher fishing pressure, a response that has been described in other marine ecosystems where fishing is intense.

The spatial simulations indicate that the fishing closures in Jurien Bay Marine Park can lead to increments in the abundance of exploited resources, however an outcome beneficial to fisheries catch and overall abundances is possible only in a limited subset of scenarios. It should be noted, that the reliability of the spatial patterns and abundances predicted needs to be verified with local biomass sampling inside and outside of the sanctuaries. Assumptions about movements and migrations also need to be verified, estimates improved, as well as improvements made to the model to allow these factors to be better taken into account for exploited species such as Rock Lobster, Pink Snapper, Dhufish and Baldchin Grouper. The results from this study assist us to understand the way in which components of the marine ecosystem interact, a key factor for predicting the influence of the closed areas within the Park. Given the assumptions of the model and uncertainty in many of the parameters employed (e.g. dispersion rather than migration), it would be better to improve current management controls, such as effort, size limits or total catch within the park than to put in place large increases in the area of no-take zones. At the same time the aspects of the biology of key species in the park (i.e. rate movements of sedentary and pelagic species) should be targeted for further research.

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APPENDIX 1. Intellectual Property

There is no intellectual property created as a result of this project.

APPENDIX 2. Staff

Principal Investigator	Dr. Neil Loneragan	Murdoch University
Co-Investigator	Dr. Russ Babcock	CSIRO
Co-Investigator	Dr. Hector Lozano-Montes	CSIRO
Co-Investigator	Dr. Jeffrey M. Dambacher	CSIRO
	Ms Patricio Rojo-Diaz, MSc	Murdoch University
	Ms Kelsie Jackson	Murdoch University
	Ms Toni Cannard	CSIRO

APPENDIX 3. List of Figures and Tables

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APPENDIX 4. General Methods for Qualitative Modelling

Once the structure of a system is defined with signed digraphs, it is possible to analyse the system's feedback properties, which determine the qualitative conditions for system stability and perturbation response. As an example, we consider a signed digraph of a three variable predator-prey system with omnivory involving the top predator.

Qualitative analysis can proceed via analysis of the signed digraph through graphical algorithms or through equivalent algebraic analyses of the system's community matrix. In this work we proceed with analysis of signed digraphs, and present only the basic principles required to understand our analyses, but see Levins (1975), Puccia and Levins (1985), Dambacher *et al.* (2002 and 2003a), and Dambacher and Jiliberto (2007) — additionally, computer programs for qualitative analyses can be found in the most recent revision of Supplement 1 of Dambacher *et al.,* (2002) in *Ecological Archives* E083-022-S1 at http://www.esapubs.org/archive/.

System stability — Our first task is to identify whether the model system is sign stable (Quirk and Ruppert 1965), such that its stability is assured no matter what parameter space the system occupies, or if the system's stability is conditional, in which case its stability depends on specific symbolic inequalities. The stability of a system can be judged and understood according to two criteria that depend on the relative sign and balance of the system's feedback cycles (Levins 1974 and 1975, Puccia and Levins 1985, Dambacher *et al.,* 2003a). In general, stability requires that 1) the net feedback in a system is negative, and that 2) feedback at lower levels in the system is stronger than feedback at higher levels in the system. Negative feedback ensures that a system's dynamics are self damped, and stronger feedback at lower levels ensures that a system will not overcorrect and exhibit unrestrained oscillations. For the above example model, stability depends on the relative weakness of feedback cycles involving omnivory. Here the feedback cycle $+a_{3,1}a_{1,2}a_{2,3}$ has the potential to destabilize the system through positive feedback, and the feedback cycle $-a_{2,1}a_{1,3}a_{3,2}$, even though it is negative in sign, has the potential to introduce excessive higher level feedback if it is too strong.

As system size and complexity increases, the symbolic contingencies underlying the conditions for stability in any one model quickly become too complex to reasonably interpret. To address this problem, Dambacher *et al.,* (2003a) developed a set of stability metrics that can be used to judge the potential stability of large complex models. The first of these applies to what are termed class I models. A class I model is characterized by its being prone to failing the first stability criterion through excessive positive feedback. Potential stability in class I systems is judged by the weighted feedback metric wF_n, which is a measure of the net to total number of cycles at cycles at the highest level in the system—i.e., feedback cycles that involve n number of links. Values of wF_n range between –1 and +1. A value of –1 indicates all feedback cycles are negative and thus there is no possibility for instability by the first stability criterion. A value of zero indicates an equal number of positive and negative feedback cycle. Given no information about specific conditions in the system, the probability of stability is that of a coin toss. Based on simulation results (Dambacher *et al.,* 2003a), values of $wF_n < -0.5$ have a relatively high potential for stability.

Class II models are judged by a weighted determinant $w\Delta_n$-1, which is a measure of the balance between higher and lower levels of feedback in the system measured through the penultimate (n-1) Hurwitz determinant (Dambacher *et al.,* 2003a). Weighted determinants cannot be compared to systems of different size due to the factorial increase in terms of the determinant with n. Interpretation of this metric proceeds by comparison to the n-1 weighted determinant of a "model-c" type system, which is simply a straight chain predator prey model with self-regulation at the basal variable only. We thus develop the metric $w\Delta C_{n-1}$, which is the ratio of the weighted determinant of the model in question to that of a c-type system of the same size. Values of this ratio great than 1.0 indicate that there is relatively low probability that the model will fail due to excessive higher level feedback, while values approach zero have an increasing likelihood of instability.

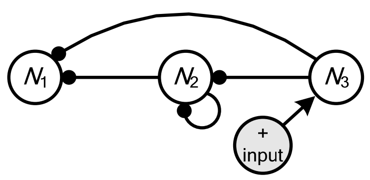
The above example system is a class I system with $wF_n = -0.67$, thus it has a high potential for stability. If the above example system was self regulated only at its basal variable $N1$, and if there was no positive direct effect between $N1$ and $N3$, then it would become a class II system. Such a model completely lacks positive feedback, yet it is dominated by higher level feedback through the cycle $a3,1a2,3a1,2$. The value of $w\Delta C_n$-1 in this model equals zero, with stability depending on $a3,1a2,3a1,2 < a1,1a2,3a3,2$.

Perturbation response.—We next seek to predict how population levels in the system change as a result of a sustained change to a rate of birth, death or migration of one of the species (Levins 1975, Puccia and Levins 1985, Dambacher *et al.,* 2002). As an example perturbation scenario we consider a positive input to $N2$, such as food supplementation that increases its rate of birth, or a shift in some environment factor that decreases its rate of death. The qualitative effect of this input to the other variables is determined by accounting for all of the feedback cycles of length n-1 that emanate from $N2$. This is accomplished by tracing all paths from the input variable to a responding variable and multiplying each path by its complementary subsystem, the resulting product is defined as a feedback cycle. The complementary subsystem is defined by the feedback of the variables not on the path from the input to the response variable. If the sign of this subsystem's feedback is positive then it will switch the sign of the path to the response variable, otherwise the sign of the path will be unchanged. The signed digraphs below illustrate the formation of feedback cycles that are used to predict perturbation response. All links that enter the input variable and all links leaving the response variable have been removed; products of the remaining links then become the feedback cycles which determine the sign of the response. For the response of $N1$ feedback cycles will be composed of the following links:

Error! Objects cannot be created from editing field codes.

Here two feedback cycles determine the sign of the response of $N1$ due to an input to $N2$. One feedback cycle, $-a1,2a3,3$, is formed by a path which goes directly from $N2$ to $N1$, and it has a complementary subsystem in the negative self-effect of $N3$. The other cycle, $-a1,3a3,2$, is composed of path with negative sign of length two. This path lacks a complementary subsystem, in which case the sign of the path remains negative. Since both feedback cycles are negative, the equilibrium abundance of $N1$ is predicted to decrease as a result of supplementation of N_2.

Next we consider the response of $N3$ when there has been a negative input to $N2$, say through an increased rate of death through culling, and note that for negative inputs the sign of the feedback cycles are switched. The sign of the response of $N3$ is determined by the following links



,

which form feedback cycles $+a_{1,2}a_{2,3}$ and $-a_{1,3}a_{2,2}$. Here the response is ambiguous, as it is determined by feedback cycles of opposing sign.

The ambiguity in the response of N_3 can be resolved through consideration of symbolic inequalities. For instance, if it is believed that $a_{3,2}a_{1,1}>a_{1,2}a_{3,1}$, then the predicted response of N_3 will be negative. Dealing with ambiguity in this manner requires a relative knowledge of interaction strengths, and an ability to make sense of contingencies presented by symbolic arguments.

In small systems ($n < 7$) the above described graphical procedures can be applied with relative ease, but as system size and complexity increases it becomes difficult to keep track of all possible paths and products of complementary subsystems. In these instances we can proceed by matrix methods described by Dambacher *et al.,* (2002), and consider analysis of the adjoint (adj) of the negative community matrix. For our above example system, the adjoint matrix is

$$\mathrm{adj}(-\mathbf{A}) = \begin{bmatrix} a_{2,2}a_{3,3}+a_{2,3}a_{3,2} & -a_{1,2}a_{3,3}-a_{1,3}a_{3,2} & a_{1,2}a_{2,3}-a_{1,3}a_{2,2} \\ a_{2,1}a_{3,3}-a_{2,3}a_{3,1} & a_{1,1}a_{3,3}+a_{3,1}a_{1,3} & -a_{1,1}a_{2,3}-a_{1,3}a_{2,1} \\ a_{2,1}a_{3,2}+a_{2,2}a_{3,1} & a_{1,1}a_{3,2}-a_{1,2}a_{3,1} & a_{1,1}a_{2,2}+a_{2,1}a_{1,2} \end{bmatrix}.$$

The results of a press perturbation to the second variable is read down the second column of this matrix, and for a negative input the sign of the matrix elements are reversed. In larger systems, complex inequalities can arise that are too difficult to interpret or comprehend symbolically. In these instances we can derive the same calculation using the signed unity of the community matrix elements, such that entries are either +1, –1, or 0. This kind of community matrix is denoted by °**A**, and its adjoint for the above system is

$$\mathrm{adj}(-{}^{\circ}\mathbf{A}) = \begin{bmatrix} 2 & -2 & 0 \\ 0 & 2 & -2 \\ 2 & 0 & 2 \end{bmatrix}.$$

Ambiguous predictions from this matrix can be interpreted through a technique of weighting the net number of feedback cycles to the absolute number in a response—i.e. the *weighted prediction* for a response prediction is equal to the net number of feedback cycles divided by the total number of cycles (Dambacher *et al.,* 2002). For instance, the predicted response of N_3 for an input to N_2 is completely ambiguous, as there is the same number of positive and negative feedback cycles. But if there were, say, a total of four feedback cycles in a perturbation response, three of which were positive and one negative, then the net number of cycles would be two and the weighted prediction of the response would be 2/4 = 0.5. The sign determinacy of responses with weighted predictions ≥0.5 has been shown to generally be >90% through simulations using random parameter space (Dambacher *et al.,* 2003b); below this threshold the sign determinacy of responses declines to zero for weighted predictions equal to zero.

Analysis of Models I-IX

Jurien Bay Model I

1 RA: reef macroalgae, 2 SgE: seagrass epiphytes, 3 Det: detritus, 4 FF: filter feeders, 5 RG: reef grazer, 6 SCR: secondary consumer (reef), 7 SgG: seagrass grazer, 8 SCSg: secondary consumer (seagrass), 9 DepF: deposit feeder, 10 Phy: phytoplankton, 11 Zoo: zooplankton, 12 Pla: planktivore.

Model Specification

"Qualitatively Specified Community Matrix (°A)"

$$A := \begin{bmatrix} -1 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & -1 & -1 & 0 & 0 & 0 & 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & -1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & -1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & -1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 \end{bmatrix}$$

Qualitative Stability Analysis

"Criterion i"

poly_coef_F0_to_Fn = [-1, -12, -74, -300, -879, -1944, -3308, -4344, -4351, -3228, -1674, -540, -81]

positive_feedback = [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]

negative_feedback = [-1, -12, -74, -300, -879, -1944, -3308, -4344, -4351, -3228, -1674, -540, -81]

absolute_feedback = [1, 12, 74, 300, 879, 1944, 3308, 4344, 4351, 3228, 1674, 540, 81]

wFn = [-1., -1., -1., -1., -1., -1., -1., -1., -1., -1., -1., -1., -1.]

"Criterion ii"

$wD_{11} = 0.75\ 10^{-8}$

$ratio\_to\_model\_C = 0.32\ 10^{9}$

"Class I Model"

Perturbation Analysis

"Change in Abundance from Positive Input"

"From Increased Birth or Immigration or from Decreased Death or Emigration"

"adjoint (-A)"

54	0	0	0	-27	27	0	0	0	0	0	0
0	54	0	0	0	0	-27	27	0	0	0	0
18	18	27	-27	-9	9	-9	9	-27	18	-9	9
18	18	27	54	-9	9	-9	9	-27	18	-9	9
27	0	0	0	27	-27	0	0	0	0	0	0
27	0	0	0	27	54	0	0	0	0	0	0
0	27	0	0	0	0	27	-27	0	0	0	0
0	27	0	0	0	0	27	54	0	0	0	0
18	18	27	-27	-9	9	-9	9	54	18	-9	9
0	0	0	0	0	0	0	0	0	54	-27	27
0	0	0	0	0	0	0	0	0	27	27	-27
0	0	0	0	0	0	0	0	0	27	27	54

"weighted predictions (W)"

1.	1.0	1.0	1.0	1.	1.	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.	1.0	1.0	1.0	1.0	1.	1.	1.0	1.0	1.0	1.0
1.	1.	1.	1.	1.	1.	1.	1.	1.	1.	1.	1.
1.	1.	1.	1.	1.	1.	1.	1.	1.	1.	1.	1.
1.	1.0	1.0	1.0	1.	1.	1.0	1.0	1.0	1.0	1.0	1.0
1.	1.0	1.0	1.0	1.	1.	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.	1.0	1.0	1.0	1.0	1.	1.	1.0	1.0	1.0	1.0
1.0	1.	1.0	1.0	1.0	1.0	1.	1.	1.0	1.0	1.0	1.0
1.	1.	1.	1.	1.	1.	1.	1.	1.	1.	1.	1.
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.	1.	1.
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.	1.	1.
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.	1.	1.

Jurien Bay Model II

1 Pred: predator, 2 InC: invertebrate consumer, 3 Sc: scraper, 4 In: invertebrates, 5 MA: macroalgae, 6 EA: epiphytic algae, 7 Cor: coral, 8 Phy: phytoplankton, 9 Zoo: zooplankton, 10 SmPe: small pelagics, 11 Cr: croppers, 12 Sg: seagrass, 13 G: grazers, 14 Det: detritus, 15 FF: filter feeders, 16 SC: 2nd consumer, 17 DF: deposit feeders, 18 HCr: herbivorous croppers, 19 SgE: seagrass epiphytes , 20 W: wracks, 21 WG: wrack grazer.

Model Specification

"Qualitatively Specified Community Matrix (°A)"

$$A := \begin{bmatrix}
-1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \\
-1 & -1 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-1 & 0 & -1 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -1 & 0 & -1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & -1 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 \\
0 & 0 & -1 & 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & -1 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & -1 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\
-1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & -1 & 0 & 0 & 0 & 0 \\
-1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 1 & 0
\end{bmatrix}$$

Qualitative Stability Analysis

"Criterion i"

poly_coef_F0_to_Fn = [-1, -18, -169, -1077, -5156, -19537, -60437, -155689, -338385, -625845, -989975, -1342173, -1558630, -1544886, -1298075, -914519, -531368, -248412, -89956, -23708, -4048, -336]

positive_feedback = [0, 0, 0, 0, 0, 0, 1, 15, 111, 533, 1847, 4873, 10081, 16611, 21936, 23176, 19400, 12616, 6160, 2128, 464, 48]

negative_feedback = [-1, -18, -169, -1077, -5156, -19537, -60438, -155704, -338496, -626378, -991822, -1347046, -1568711, -1561497, -1320011, -937695, -550768, -261028, -96116, -25836, -4512, -384]

absolute_feedback = [1, 18, 169, 1077, 5156, 19537, 60439, 155719, 338607, 626911, 993669, 1351919, 1578792, 1578108, 1341947, 960871, 570168, 273644, 102276, 27964, 4976, 432]

wFn = [-1., -1., -1., -1., -1., -1., -1.0, -1.0, -1.0, -1.0, -1.0, -0.99, -0.99, -0.98, -0.97, -0.95, -0.93, -0.91, -0.88, -0.85, -0.81, -0.78]

"Criterion ii"

$wD_{20} = 0.41\ 10^{-29}$

$ratio\_to\_model\_C = 0.32\ 10^{28}$

"Class I Model"

Perturbation Analysis

"Change in Abundance from Positive Input"

"From Increased Birth or Immigration or from Decreased Death or Emigration"

"adjoint (-A)"

72	36	36	36	72	36	144	24	24	48	72	72	24	0	0	48	0	24	24	48	0
-36	150	-18	150	-36	-18	264	-12	-12	-24	-36	-36	-12	0	0	-24	0	-12	-12	-24	0
-36	-18	150	-18	-36	150	264	-12	-12	-24	-36	-36	-12	0	0	-24	0	-12	-12	-24	0
36	-150	18	186	36	18	72	12	12	24	36	36	12	0	0	24	0	12	12	24	0
72	36	36	36	72	36	144	24	24	48	72	72	24	0	0	48	0	-312	24	48	0
36	18	-150	18	36	186	72	12	12	24	36	36	12	0	0	24	0	12	12	24	0
0	0	0	0	0	0	336	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-24	-12	-12	-12	-24	-12	-48	216	-120	96	-24	-24	-8	0	0	-16	0	-8	-8	-16	0
24	12	12	12	24	12	48	120	120	-96	24	24	8	0	0	16	0	8	8	16	0
-48	-24	-24	-24	-48	-24	-96	96	96	192	-48	-48	-16	0	0	-32	0	-16	-16	-32	0
-72	-36	-36	-36	-72	-36	192	-24	-24	-48	264	-72	-24	0	0	-48	0	-24	-24	-48	0
0	0	0	0	0	0	0	0	0	0	0	336	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	112	0	0	-112	0	112	112	-112	0
18	9	-75	9	18	93	36	6	6	12	18	186	62	168	0	124	-168	-106	62	124	-168
-6	-3	-87	-3	-6	81	-12	222	-114	108	-6	162	54	168	336	108	-168	-114	54	108	-168
0	0	0	0	0	0	0	0	0	0	0	336	112	0	0	224	0	-224	112	224	0
18	9	-75	9	18	93	36	6	6	12	18	186	62	168	0	124	168	-106	62	124	-168
-72	-36	-36	-36	264	-36	-480	-24	-24	-48	-72	-72	-24	0	0	-48	0	312	-24	-48	0
0	0	0	0	0	0	0	0	0	0	0	336	-112	0	0	112	0	-112	224	112	0
0	0	0	0	0	0	0	0	0	0	0	336	112	0	0	224	0	-224	112	224	-336
72	36	36	36	72	36	144	24	24	48	72	408	24	0	0	48	0	-312	24	384	0

"weighted predictions (W)"

1.	1.	1.	1.	1.	1.	0.50	1.	1.	1.	1.	1.	1.	1.0	1.0	1.	1.0	0.20	1.	1.	1.0
1.	0.76	1.	0.76	1.	1.	0.52	1.	1.	1.	1.	1.	1.	1.0	1.0	1.	1.0	0.20	1.	1.	1.0
1.	1.	0.76	1.	1.	0.76	0.52	1.	1.	1.	1.	1.	1.	1.0	1.0	1.	1.0	0.20	1.	1.	1.0
1.	0.76	1.	0.79	1.	1.	0.13	1.	1.	1.	1.	1.	1.	1.0	1.0	1.	1.0	0.20	1.	1.	1.0
1.	1.	1.	1.	1.	1.	0.50	1.	1.	1.	1.	1.	1.	1.0	1.0	1.	1.0	1.	1.	1.	1.0
1.	1.	0.76	1.	1.	0.79	0.13	1.	1.	1.	1.	1.	1.	1.0	1.0	1.	1.0	0.20	1.	1.	1.0
1.0	1.0	1.0	1.0	1.0	1.0	0.78	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.	1.	1.	1.	1.	1.	0.50	0.77	0.79	0.75	1.	1.	1.	1.0	1.0	1.	1.0	0.20	1.	1.	1.0
1.	1.	1.	1.	1.	1.	0.50	0.79	0.79	0.75	1.	1.	1.	1.0	1.0	1.	1.0	0.20	1.	1.	1.0
1.	1.	1.	1.	1.	1.	0.50	0.75	0.75	0.75	1.	1.	1.	1.0	1.0	1.	1.0	0.20	1.	1.	1.0
1.	1.	1.	1.	1.	1.	0.33	1.	1.	1.	0.73	1.	1.	1.0	1.0	1.	1.0	0.20	1.	1.	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.78	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.70	1.0	1.0	1.	1.0	1.	0.70	1.	1.0
0.27	0.27	0.61	0.27	0.27	0.66	0.078	0.27	0.27	0.27	0.27	1.	1.	0.78	1.0	1.	0.78	0.75	1.	1.	0.78
0.067	0.067	0.64	0.067	0.067	0.53	0.022	0.74	0.66	0.63	0.067	0.77	0.77	0.78	0.78	0.77	0.78	0.63	0.77	0.77	0.78
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.	1.	1.0	1.0	1.	1.0	1.	1.	1.	1.0
0.27	0.27	0.61	0.27	0.27	0.66	0.078	0.27	0.27	0.27	0.27	1.	1.	0.78	1.0	1.	0.78	0.75	1.	1.	0.78
1.	1.	1.	1.	0.73	1.	0.83	1.	1.	1.	1.	1.	1.	1.0	1.0	1.	1.0	1.	1.	1.	1.0
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.88	0.70	1.0	1.0	1.	1.0	1.	0.82	1.	1.0
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.	1.	1.0	1.0	1.	1.0	1.	1.	1.	0.78
1.	1.	1.	1.	1.	1.	0.50	1.	1.	1.	1.	1.	1.	1.0	1.0	1.	1.0	1.	1.	1.	1.0

Jurien Bay Model III

1 Pis1: piscivore 1, 2 Gas: gastropods, 3 MA: macroalgae, 4 EA: epiphytic algae, 5 Phy: phytoplankton, 6 Zoo: zooplankton, 7 SmPe: small pelagics, 8 Sg: seagrass, 9 G: grazers, 10 Det: detritus, 11 FF: filter feeders, 12 Iv: invertivores, 13 DF: deposit feeders, 14 Cr: croppers, 15 E: epiphytes , 16 W: wracks, 17 Ur: urchin, 18 R: reef, 19 Wr: wrasses, 20 Pis2: piscivore 2, 21 Pis3: piscivore 3, 22 Lb: lobster, 23 Bac: bacteria, 24 MiA: microalgae.

Model Specification

"Qualitatively Specified Community Matrix (°A)"

$$A := \begin{bmatrix}
-1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & -1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & -1 & 0 & 0 \\
0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -1 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & -1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & -1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & -1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & -1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & -1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 & 0 & -1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\
-1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & -1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1
\end{bmatrix}$$

Qualitative Stability Analysis

"Criterion i"

poly_coef_F0_to_Fn =
[-1, -24, -291, -2354, -14179, -67364, -261293, -845970, -2319922, -5441088, -10980701, -19130070, -28794501, -37394116, -41745624, -39816824, -32152738, -21699984, -12019801, -5323702, -1813319, -446004, -70510, -5380, 0]

positive_feedback = [0, 0, 1, 22, 247, 1860, 10460, 46464, 168565, 510160, 1306012, 2853288, 5347734, 8618088, 11938104, 14174944, 14348018, 12275216, 8766424, 5133872, 2402846, 864696, 224719, 37550, 3030]

negative_feedback = [-1, -24, -292, -2376, -14426, -69224, -271753, -892434, -2488487, -5951248, -12286713, -21983358, -34142235, -46012204, -53683728, -53991768, -46500756, -33975200, -20786225, -10457574, -4216165, -1310700, -295229, -42930, -3030]

absolute_feedback =
[1, 24, 293, 2398, 14673, 71084, 282213, 938898, 2657052, 6461408, 13592725, 24836646, 39489969, 54630292, 65621832, 68166712, 60848774, 46250416, 29552649, 15591446, 6619011, 2175396, 519948, 80480, 6060]

wFn = [-1., -1., -0.99, -0.98, -0.97, -0.95, -0.93, -0.90, -0.87, -0.84, -0.81, -0.77, -0.73, -0.68, -0.64, -0.58, -0.53, -0.47, -0.41, -0.34, -0.27, -0.21, -0.14, -0.067, 0.]

"Criterion ii"

$wD_{23} = 0.12\ 10^{-39}$

$ratio\_to\_model\_C = 0.56\ 10^{36}$

"Class I Model"

Perturbation Analysis

(Note: adjoint matrix with presumed stability of MiA-Bac subsystem, analysed with omission of link $a_{23,24}$)

"Change in Abundance from Positive Input"

"From Increased Birth or Immigration or from Decreased Death or Emigration"

"adjoint (-A)"

1260	340	750	340	0	0	0	-80	20	0	0	40	0	510	20	-100	-100	-750	920	-40	0	-240	0	0
460	850	530	850	0	0	0	-200	50	0	0	100	0	-70	50	-250	-250	-530	-390	-100	0	-600	0	0
630	170	1720	170	0	0	0	-40	10	0	0	20	0	-1090	10	-50	-50	970	460	-20	0	-120	0	0
170	-680	1190	2010	0	0	0	160	-40	0	0	-80	0	-1020	-40	200	200	1500	850	80	0	480	0	0
0	0	0	0	1614	-1076	538	0	0	0	0	0	0	0	0	0	0	0	0	0	-538	0	0	0
0	0	0	0	1076	1076	-538	0	0	0	0	0	0	0	0	0	0	0	0	0	538	0	0	0
0	0	0	0	538	538	1076	0	0	0	0	0	0	0	0	0	0	0	0	0	-1076	0	0	0
0	0	0	0	0	0	0	2690	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-10	40	-70	40	0	0	0	940	1110	0	0	-470	0	60	1110	-170	-170	70	-50	470	0	130	0	0
290	185	685	185	0	0	0	985	90	1345	0	180	-1345	-395	90	895	-450	660	105	-180	0	265	0	0
290	185	685	185	1614	-1076	538	985	90	1345	2690	180	-1345	-395	90	895	-450	3350	105	-180	-538	265	0	0
20	-80	140	-80	0	0	0	810	470	0	0	940	0	-120	470	340	340	-140	100	-940	0	-260	0	0
290	185	685	185	0	0	0	985	90	1345	0	180	1345	-395	90	895	-450	660	105	-180	0	265	0	0
-630	-170	970	-170	0	0	0	40	-10	0	0	-20	0	1090	-10	50	50	1720	-460	20	0	120	0	0
10	-40	70	-40	0	0	0	1750	-1110	0	0	470	0	-60	1580	170	170	-70	50	-470	0	-130	0	0
580	370	1370	370	0	0	0	1970	180	0	0	360	0	-790	180	1790	-900	1320	210	-360	0	530	0	0
50	-200	350	-200	0	0	0	680	-170	0	0	-340	0	-300	-170	850	850	-350	250	340	0	-650	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2690	0	0	0	0	0	0
-800	510	-220	510	0	0	0	-120	30	0	0	60	0	-580	30	-150	-150	220	1380	-60	0	-360	0	0
20	-80	140	-80	0	0	0	810	470	0	0	940	0	-120	470	340	340	-140	100	1750	0	-260	0	0
0	0	0	0	538	538	1076	0	0	0	0	0	0	0	0	0	0	0	0	0	1614	0	0	0
510	650	880	650	0	0	0	480	-120	0	0	-240	0	-370	-120	600	600	1810	-140	240	0	1440	0	0
290	185	685	185	0	0	0	985	90	1345	0	180	-1345	-395	90	895	-450	660	105	-180	0	265	2690	0
290	185	685	185	0	0	0	985	90	1345	0	180	-1345	-395	90	895	-450	660	105	-180	0	265	2690	2690

"weighted predictions (W)"

1.	1.	0.88	1.	1.0	1.0	1.0	0.67	1.	1.0	1.0	1.	1.0	0.60	1.	1.	1.	0.32	1.	1.	1.0	1.	1.0	1.0
0.82	1.	0.64	1.	1.0	1.0	1.0	0.67	1.	1.0	1.0	1.	1.0	0.11	1.	1.	1.	0.27	0.53	1.	1.0	1.	1.0	1.0
1.	1.	1.	1.	1.0	1.0	1.0	0.67	1.	1.0	1.0	1.	1.0	1.	1.	1.	1.	0.39	1.	1.	1.0	1.	1.0	1.0
0.20	0.67	0.78	1.	1.0	1.0	1.0	0.44	0.67	1.0	1.0	0.67	1.0	1.	0.67	0.67	0.67	0.48	1.	0.67	1.0	0.67	1.0	1.0
1.0	1.0	1.0	1.0	0.89	0.89	0.89	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.89	1.0	1.0	1.0
1.0	1.0	1.0	1.0	0.89	0.89	0.89	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.89	1.0	1.0	1.0
1.0	1.0	1.0	1.0	0.89	0.89	0.89	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.89	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.89	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
0.14	0.67	0.47	0.67	1.0	1.0	1.0	0.65	0.89	1.0	1.0	0.89	1.0	0.60	0.89	0.89	0.89	0.19	0.71	0.89	1.0	0.87	1.0	1.0
1.	1.	1.	1.	1.0	1.0	1.0	0.88	0.90	0.89	1.0	0.90	0.89	0.89	0.90	0.88	0.90	0.49	0.41	0.90	1.0	0.69	1.0	1.0
1.	1.	1.	1.	0.89	0.89	0.89	0.88	0.90	0.89	0.89	0.90	0.89	0.89	0.90	0.88	0.90	0.76	0.41	0.90	0.89	0.69	1.0	1.0
0.14	0.67	0.47	0.67	1.0	1.0	1.0	0.89	0.89	1.0	1.0	0.89	1.0	0.60	0.89	0.89	0.89	0.19	0.71	0.89	1.0	0.87	1.0	1.0
1.	1.	1.	1.	1.0	1.0	1.0	0.88	0.90	0.89	1.0	0.90	0.89	0.89	0.90	0.88	0.90	0.49	0.41	0.90	1.0	0.69	1.0	1.0
1.	1.	0.74	1.	1.0	1.0	1.0	0.67	1.	1.0	1.0	1.	1.0	1.	1.	1.	1.	0.83	1.	1.	1.0	1.	1.0	1.0
0.14	0.67	0.47	0.67	1.0	1.0	1.0	0.89	0.89	1.0	1.0	0.89	1.0	0.60	0.89	0.89	0.89	0.19	0.71	0.89	1.0	0.87	1.0	1.0
1.	1.	1.	1.	1.0	1.0	1.0	0.88	0.90	1.0	1.0	0.90	1.0	0.89	0.90	0.88	0.90	0.49	0.41	0.90	1.0	0.69	1.0	1.0
0.14	0.67	0.47	0.67	1.0	1.0	1.0	0.60	0.89	1.0	1.0	0.89	1.0	0.60	0.89	0.89	0.89	0.19	0.71	0.89	1.0	0.87	1.0	1.0
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.89	1.0	1.0	1.0	1.0	1.0	1.0
0.70	1.	0.24	1.	1.0	1.0	1.0	0.67	1.	1.0	1.0	1.	1.0	0.85	1.	1.	1.	0.092	1.	1.	1.0	1.	1.0	1.0
0.14	0.67	0.47	0.67	1.0	1.0	1.0	0.89	0.89	1.0	1.0	0.89	1.0	0.60	0.89	0.89	0.89	0.19	0.71	0.89	1.0	0.87	1.0	1.0
1.0	1.0	1.0	1.0	0.89	0.89	0.89	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.89	1.0	1.0	1.0
1.	1.	1.	1.	1.0	1.0	1.0	0.57	0.86	1.0	1.0	0.86	1.0	0.61	0.86	0.86	0.86	0.59	0.24	0.86	1.0	0.86	1.0	1.0
1.	1.	1.	1.	1.0	1.0	1.0	0.88	0.90	0.89	1.0	0.90	0.89	0.89	0.90	0.88	0.90	0.49	0.41	0.90	1.0	0.69	0.89	1.0
1.	1.	1.	1.	1.0	1.0	1.0	0.88	0.90	0.89	1.0	0.90	0.89	0.89	0.90	0.88	0.90	0.49	0.41	0.90	1.0	0.69	0.89	0.89

Jurien Bay Model IV

1 ALP: adult large predator fish, 2 JLP: juvenile large predator fish, 3 LaLP: larvae large predator fish, 4 Pl: planktivorous fish, 5 SmP: small predator fish.

Model Specification

"Qualitatively Specified Community Matrix (°A)"

$$A := \begin{bmatrix} -1 & 1 & 0 & 1 & 1 \\ -1 & -1 & 1 & 0 & -1 \\ 0 & 0 & -1 & -1 & 0 \\ -1 & 0 & 1 & -1 & 0 \\ -1 & 1 & 0 & 0 & -1 \end{bmatrix}$$

Qualitative Stability Analysis

"Criterion i"

poly_coef_F0_to_Fn = [-1, -5, -15, -25, -23, -8]

positive_feedback = [0, 0, 0, 1, 3, 4]

negative_feedback = [-1, -5, -15, -26, -26, -12]

absolute_feedback = [1, 5, 15, 27, 29, 16]

wFn = [-1., -1., -1., -0.93, -0.79, -0.50]

"Criterion ii"

$wD_4 = 0.087$

ratio_to_model_C = 9.3

"Class I Model"

Perturbation Analysis

"Change in Abundance from Positive Input"

"From Increased Birth or Immigration or from Decreased Death or Emigration"

"adjoint (-A)"

$$\begin{bmatrix} 4 & 4 & 4 & 0 & 0 \\ 1 & 5 & 3 & -2 & -4 \\ 2 & 2 & 6 & -4 & 0 \\ -2 & -2 & 2 & 4 & 0 \\ -3 & 1 & -1 & -2 & 4 \end{bmatrix}$$

"weighted predictions (W)"

$$\begin{bmatrix} 1. & 1. & 1. & 0. & 0. \\ 0.20 & 1. & 0.60 & 0.50 & 0.67 \\ 1. & 1. & 0.75 & 0.67 & 0. \\ 1. & 1. & 0.25 & 0.67 & 0. \\ 0.60 & 0.20 & 0.20 & 0.50 & 0.67 \end{bmatrix}$$

Jurien Bay Model V

1 ALP: adult large predator fish, 2 LaLP: larvae large predator fish, 3 JLP: juvenile large predator fish, 4 Pl: planktivorous fish, 5 SmP: small predator fish, 6 Ce: cephalopods, 7 Lo: lobster, 8 F: fishery, 9 LoF: lobster fishery, 10 Sh: sharks, 11 ShF: shark fishery.

Model Specification

"Qualitatively Specified Community Matrix (°A)"

$$
A := \begin{bmatrix}
-1 & 0 & 1 & 1 & 1 & 1 & 0 & -1 & 0 & -1 & 0 \\
0 & -1 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-1 & 1 & -1 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\
-1 & 1 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-1 & 0 & 1 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\
-1 & 0 & 0 & 0 & 0 & -1 & 1 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & -1 & -1 & 0 & -1 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & -1 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & -1 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1
\end{bmatrix}
$$

Qualitative Stability Analysis

"Criterion i"

$poly\_coef\_F0\_to\_Fn$ = [-1, -11, -66, -265, -767, -1652, -2678, -3251, -2888, -1786, -692, -128]

$positive\_feedback$ = [0, 0, 0, 1, 9, 40, 111, 209, 272, 238, 128, 32]

$negative\_feedback$ = [-1, -11, -66, -266, -776, -1692, -2789, -3460, -3160, -2024, -820, -160]

$absolute\_feedback$ = [1, 11, 66, 267, 785, 1732, 2900, 3669, 3432, 2262, 948, 192]

wFn = [-1., -1., -1., -0.99, -0.98, -0.95, -0.92, -0.89, -0.84, -0.79, -0.73, -0.67]

"Criterion ii"

$$wD_{10} = 0.75\ 10^{-7}$$

$$ratio\_to\_model\_C = 0.36\ 10^{7}$$

"Class I Model"

Perturbation Analysis

"Change in Abundance from Positive Input"

"From Increased Birth or Immigration or from Decreased Death or Emigration"

"adjoint (-A)"

$$
\begin{bmatrix}
32 & 32 & 32 & 0 & 0 & 16 & 16 & -32 & 0 & -16 & 16 \\
16 & 80 & 16 & -64 & 0 & 8 & 8 & -16 & 0 & -8 & 8 \\
8 & 40 & 72 & -32 & -64 & 4 & 4 & -8 & 0 & -4 & 4 \\
-16 & 48 & -16 & 64 & 0 & -8 & -8 & 16 & 0 & 8 & -8 \\
-24 & 8 & 40 & -32 & 64 & -12 & -12 & 24 & 0 & 12 & -12 \\
-16 & -16 & -16 & 0 & 0 & 56 & 56 & 16 & 0 & 8 & -8 \\
8 & 8 & 8 & 0 & 0 & -28 & 36 & -8 & -64 & -4 & 4 \\
32 & 32 & 32 & 0 & 0 & 16 & 16 & 96 & 0 & -16 & 16 \\
8 & 8 & 8 & 0 & 0 & -28 & 36 & -8 & 64 & -4 & 4 \\
16 & 16 & 16 & 0 & 0 & 8 & 8 & -16 & 0 & 56 & -56 \\
16 & 16 & 16 & 0 & 0 & 8 & 8 & -16 & 0 & 56 & 72
\end{bmatrix}
$$

"weighted predictions (W)"

$$\begin{bmatrix} 1. & 1. & 1. & 0. & 0. & 1. & 1. & 1. & 0. & 1. & 1. \\ 1. & 0.83 & 1. & 0.80 & 0. & 1. & 1. & 1. & 0. & 1. & 1. \\ 0.20 & 0.71 & 1. & 0.67 & 0.80 & 0.20 & 0.20 & 0.20 & 0. & 0.20 & 0.20 \\ 1. & 0.50 & 1. & 0.80 & 0. & 1. & 1. & 1. & 0. & 1. & 1. \\ 0.60 & 0.14 & 0.56 & 0.67 & 0.80 & 0.60 & 0.60 & 0.60 & 0. & 0.60 & 0.60 \\ 1. & 1. & 1. & 0. & 0. & 0.64 & 0.64 & 1. & 0. & 1. & 1. \\ 1. & 1. & 1. & 0. & 0. & 0.64 & 0.69 & 1. & 0.67 & 1. & 1. \\ 1. & 1. & 1. & 0. & 0. & 1. & 1. & 0.60 & 0. & 1. & 1. \\ 1. & 1. & 1. & 0. & 0. & 0.64 & 0.69 & 1. & 0.67 & 1. & 1. \\ 1. & 1. & 1. & 0. & 0. & 1. & 1. & 1. & 0. & 0.64 & 0.64 \\ 1. & 1. & 1. & 0. & 0. & 1. & 1. & 1. & 0. & 0.64 & 0.69 \end{bmatrix}$$

Jurien Bay Model VI

1 ALP: adult large predator fish, 2 LaLP: larvae large predator fish, 3 JLP: juvenile large predator fish, 4 Pl: planktivorous fish, 5 SmP: small predator fish, 6 Ce: cephalopods, 7 Lo: lobster, 8 F: fishery, 9 LoF: lobster fishery, 10 Sh: sharks, 11 ShF: shark fishery.

Model Specification

"Qualitatively Specified Community Matrix (°A)"

$$A := \begin{bmatrix} -1 & 0 & 1 & 1 & 1 & 1 & 0 & -1 & 0 & -1 & 0 \\ 0 & -1 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 1 & -1 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 1 & 0 & -1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ -1 & 0 & 1 & 0 & -1 & 0 & 1 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & 0 & -1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -1 & -1 & -1 & -1 & 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & -1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & -1 \end{bmatrix}$$

Qualitative Stability Analysis

"Criterion i"

poly_coef_F0_to_Fn = [-1, -11, -68, -283, -847, -1873, -3087, -3767, -3323, -2016, -758, -135]

positive_feedback = [0, 0, 0, 1, 15, 88, 285, 581, 777, 672, 346, 81]

negative_feedback = [-1, -11, -68, -284, -862, -1961, -3372, -4348, -4100, -2688, -1104, -216]

absolute_feedback = [1, 11, 68, 285, 877, 2049, 3657, 4929, 4877, 3360, 1450, 297]

wFn = [-1., -1., -1., -0.99, -0.97, -0.91, -0.84, -0.76, -0.68, -0.60, -0.52, -0.45]

"Criterion ii"

$$wD_{10} = 0.40\ 10^{-7}$$

$$ratio\_to\_model\_C = 0.19\ 10^{7}$$

"Class I Model"

Perturbation Analysis

"Change in Abundance from Positive Input"

"From Increased Birth or Immigration or from Decreased Death or Emigration"

"adjoint (-A)"

38	26	30	-4	-8	22	16	-38	6	-19	19
10	85	15	-65	5	20	-10	-10	30	-5	5
-4	47	75	-28	-56	19	-23	4	42	2	-2
-10	50	-15	65	-5	-20	10	10	-30	5	-5
-24	12	45	-33	69	-21	-3	24	-18	12	-12
-2	-44	-30	-14	-28	77	56	2	21	1	-1
18	-9	0	-9	-18	-18	36	-18	-54	-9	9
38	26	30	-4	-8	22	16	97	6	-19	19
18	-9	0	-9	-18	-18	36	-18	81	-9	9
19	13	15	-2	-4	11	8	-19	3	58	-58
19	13	15	-2	-4	11	8	-19	3	58	77

"weighted predictions (W)"

0.90	0.45	0.60	0.077	0.17	0.52	0.50	0.90	0.10	0.90	0.90
0.38	0.53	0.43	0.64	0.15	0.56	0.29	0.38	0.48	0.38	0.38
0.067	0.42	0.63	0.34	0.47	0.30	0.42	0.067	0.43	0.067	0.067
0.38	0.37	0.43	0.64	0.15	0.56	0.29	0.38	0.48	0.38	0.38
0.46	0.13	0.48	0.48	0.71	0.38	0.055	0.46	0.20	0.46	0.46
0.037	0.44	0.45	0.17	0.41	0.55	0.54	0.037	0.14	0.037	0.037
0.82	0.18	0.	0.21	0.53	0.31	0.69	0.82	0.49	0.82	0.82
0.90	0.45	0.60	0.077	0.17	0.52	0.50	0.38	0.10	0.90	0.90
0.82	0.18	0.	0.21	0.53	0.31	0.69	0.82	0.43	0.82	0.82
0.90	0.45	0.60	0.077	0.17	0.52	0.50	0.90	0.10	0.42	0.42
0.90	0.45	0.60	0.077	0.17	0.52	0.50	0.90	0.10	0.42	0.48

Jurien Bay Model VII

1 Lo: lobster, 2 RIn: reef invertebrates, 3 FIn: fish invertevore, 4 Ce: cephalopod, 5 LFP: large fish predator, 6 SL: sea lions, 7 F: fishery.

Model Specification

"Qualitatively Specified Community Matrix (°A)"

$$A := \begin{bmatrix} -1 & 1 & -1 & -1 & 0 & -1 & -1 \\ -1 & -1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & -1 & 0 & -1 & -1 & 0 \\ 1 & 0 & 0 & -1 & -1 & -1 & 1 \\ 0 & 0 & 1 & 1 & -1 & 0 & 0 \\ 1 & 0 & 1 & 1 & 0 & -1 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & -1 \end{bmatrix}$$

Qualitative Stability Analysis

"Criterion i"

$poly\_coef\_F0\_to\_Fn = [-1, -7, -30, -81, -140, -150, -89, -22]$

$positive\_feedback = [0, 0, 0, 2, 14, 36, 43, 19]$

$negative\_feedback = [-1, -7, -30, -83, -154, -186, -132, -41]$

$absolute\_feedback = [1, 7, 30, 85, 168, 222, 175, 60]$

$wFn = [-1., -1., -1., -0.95, -0.83, -0.68, -0.51, -0.37]$

"Criterion ii"

$wD_6 = 0.0020$

$ratio\_to\_model\_C = 110.$

"Class I Model"

Perturbation Analysis

"Change in Abundance from Positive Input"

"From Increased Birth or Immigration or from Decreased Death or Emigration"

"adjoint (-A)"

$$\begin{bmatrix} 5 & 5 & -2 & -2 & 4 & -1 & -7 \\ -5 & 17 & 2 & 2 & -4 & 1 & 7 \\ -2 & -2 & 14 & -8 & -6 & -4 & -6 \\ 3 & 3 & -10 & 12 & -2 & -5 & 9 \\ 1 & 1 & 4 & 4 & 14 & -9 & 3 \\ 6 & 6 & 2 & 2 & -4 & 12 & -4 \\ 5 & 5 & -2 & -2 & 4 & -1 & 15 \end{bmatrix}$$

"weighted predictions (W)"

$$\begin{bmatrix} 0.56 & 0.56 & 0.25 & 0.25 & 0.50 & 0.11 & 0.41 \\ 0.56 & 0.33 & 0.25 & 0.25 & 0.50 & 0.11 & 0.41 \\ 0.20 & 0.20 & 0.88 & 0.80 & 0.33 & 0.25 & 0.38 \\ 0.27 & 0.27 & 0.83 & 0.86 & 0.11 & 0.29 & 0.47 \\ 0.091 & 0.091 & 0.20 & 0.25 & 0.58 & 0.60 & 0.14 \\ 0.50 & 0.50 & 0.12 & 0.14 & 0.29 & 0.67 & 0.20 \\ 0.56 & 0.56 & 0.25 & 0.25 & 0.50 & 0.11 & 0.35 \end{bmatrix}$$

Jurien Bay Model VIII

1 ALo: adult lobster, 2 SALo: subadult lobster, 3 JLo: juvenile lobster, 4 PPLo: post puerulus lobster, 5 PLo: puerulus lobster, 6 LLo: larval lobster, 7 R3: resource for 3, 8 FIn: fish invertivore, 9 LFP: large fish predator, 10 Ce: cephalopod, 11 SL: sea lions, 12 R: reef, 13 R2: resource for 2, 14 F: fishery.

Model Specification

"Qualitatively Specified Community Matrix (°A)"

A :=

-1	1	0	0	0	0	0	0	0	0	0	0	1	-1
0	-1	1	0	0	0	1	0	0	-1	-1	0	0	-1
0	0	-1	1	0	0	0	-1	0	-1	0	0	0	0
0	0	-1	-1	1	0	0	-1	0	0	0	1	0	0
0	0	0	0	-1	1	0	0	0	0	0	0	0	0
0	0	0	0	0	-1	0	0	0	0	0	0	0	0
0	0	-1	0	0	0	-1	0	0	0	0	0	0	0
0	0	1	1	0	0	0	-1	-1	0	-1	0	0	0
0	0	0	0	0	0	0	1	-1	1	0	0	0	0
0	1	1	0	0	0	0	0	-1	-1	-1	0	0	1
0	1	0	0	0	0	0	1	0	1	-1	0	0	0
0	0	0	0	0	0	0	0	0	0	0	-1	0	0
0	-1	0	0	0	0	0	0	0	0	0	0	-1	0
1	1	0	0	0	0	0	0	0	0	0	0	0	-1

Qualitative Stability Analysis

"Criterion i"

poly_coef_F0_to_Fn = [-1, -14, -103, -511, -1861, -5173, -11181, -18905, -24917, -25290, -19340, -10754, -4095, -953, -102]

positive_feedback = [0, 0, 0, 2, 32, 230, 1006, 2997, 6384, 9883, 11056, 8705, 4568, 1431, 202]

negative_feedback = [-1, -14, -103, -513, -1893, -5403, -12187, -21902, -31301, -35173, -30396, -19459, -8663, -2384, -304]

absolute_feedback = [1, 14, 103, 515, 1925, 5633, 13193, 24899, 37685, 45056, 41452, 28164, 13231, 3815, 506]

wFn = [-1., -1., -1., -0.99, -0.97, -0.92, -0.85, -0.76, -0.66, -0.56, -0.47, -0.38, -0.31, -0.25, -0.20]

"Criterion ii"

$wD_{13} = 0.91\ 10^{-13}$

$ratio\_to\_model\_C = 0.27\ 10^{11}$

"Class I Model"

Perturbation Analysis

"Change in Abundance from Positive Input"

"From Increased Birth or Immigration or from Decreased Death or Emigration"

"adjoint (-A)"

65	-16	6	1	1	1	-16	-5	-7	12	9	1	65	-37
-28	32	-12	-2	-2	-2	32	10	14	-24	-18	-2	-28	-28
-7	8	48	25	25	25	8	-23	29	-6	21	25	-7	-7
4	10	-42	44	44	44	10	-16	-2	18	-12	44	4	4
0	0	0	0	102	102	0	0	0	0	0	0	0	0
0	0	0	0	0	102	0	0	0	0	0	0	0	0
7	-8	-48	-25	-25	-25	94	23	-29	6	-21	-25	7	7
3	-18	-6	33	33	33	-18	39	-27	-12	-9	33	3	3
11	2	12	19	19	19	2	7	71	24	-33	19	11	11
8	20	18	-14	-14	-14	20	-32	-4	36	-24	-14	8	8
-17	34	0	17	17	17	34	17	-17	0	51	17	-17	-17
0	0	0	0	0	0	0	0	0	0	0	102	0	0
28	-32	12	2	2	2	-32	-10	-14	24	18	2	130	28
37	16	-6	-1	-1	-1	16	5	7	-12	-9	-1	37	37

"weighted predictions (W)"

0.31	0.13	0.048	0.0071	0.0071	0.0071	0.13	0.054	0.052	0.11	0.057	0.0071	0.31	0.13
0.35	0.38	0.14	0.021	0.021	0.021	0.38	0.16	0.16	0.32	0.17	0.021	0.35	0.35
0.21	0.13	0.41	0.19	0.19	0.19	0.13	0.29	0.32	0.11	0.25	0.19	0.21	0.21
0.11	0.16	0.26	0.18	0.18	0.18	0.16	0.16	0.017	0.31	0.12	0.18	0.11	0.11
1.0	1.0	1.0	1.0	0.20	0.20	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	0.20	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
0.21	0.13	0.41	0.19	0.19	0.19	0.21	0.29	0.32	0.11	0.25	0.19	0.21	0.21
0.10	0.38	0.056	0.26	0.26	0.26	0.38	0.47	0.27	0.26	0.11	0.26	0.10	0.10
0.21	0.023	0.082	0.11	0.11	0.11	0.023	0.053	0.25	0.26	0.23	0.11	0.21	0.21
0.18	0.27	0.16	0.12	0.12	0.12	0.27	0.42	0.033	0.49	0.20	0.12	0.18	0.18
0.27	0.33	0.	0.11	0.11	0.11	0.33	0.15	0.12	0.	0.26	0.11	0.27	0.27
1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.20	1.0	1.0
0.35	0.38	0.14	0.021	0.021	0.021	0.38	0.16	0.16	0.32	0.17	0.021	0.31	0.35
0.28	0.13	0.048	0.0071	0.0071	0.0071	0.13	0.054	0.052	0.11	0.057	0.0071	0.28	0.28

Jurien Bay Model IX

1 ALo: adult lobster, 2 SALo: subadult lobster, 3 JLo: juvenile lobster, 4 PPLo: post puerulus lobster, 5 PLo: puerulus lobster, 6 LLo: larval lobster, 7 FIn: fish invertivore, 8 LFP: large fish predator, 9 Ce: cephalopod, 10 SL: sea lions, 11 F: fishery.

Model Specification

"Qualitatively Specified Community Matrix (°A)"

$A :=$

-1	1	0	0	0	0	0	0	0	0	-1
0	-1	1	0	0	0	0	0	-1	-1	-1
0	0	-1	1	0	0	-1	0	-1	0	0
0	0	-1	-1	1	0	-1	0	0	0	0
0	0	0	0	-1	1	0	0	0	0	0
0	0	0	0	0	-1	0	0	0	0	0
0	0	1	1	0	0	-1	-1	0	-1	0
0	0	0	0	0	0	1	-1	1	0	0
0	1	1	0	0	0	0	-1	-1	-1	1
0	1	0	0	0	0	1	0	1	-1	0
1	1	0	0	0	0	0	0	0	0	-1

Qualitative Stability Analysis

"Criterion i"

poly_coef_F0_to_Fn = [-1, -11, -67, -276, -823, -1829, -3051, -3778, -3366, -2032, -740, -122]

positive_feedback = [0, 0, 0, 2, 24, 130, 419, 883, 1235, 1103, 566, 126]

negative_feedback = [-1, -11, -67, -278, -847, -1959, -3470, -4661, -4601, -3135, -1306, -248]

absolute_feedback = [1, 11, 67, 280, 871, 2089, 3889, 5544, 5836, 4238, 1872, 374]

wFn = [-1., -1., -1., -0.99, -0.94, -0.88, -0.78, -0.68, -0.58, -0.48, -0.40, -0.33]

"Criterion ii"

$wD_{10} = 0.13\ 10^{-7}$

ratio_to_model_C = 640000.

"Class I Model"

Perturbation Analysis

"adjoint (-A)"

61	0	0	0	0	0	0	0	0	0	-61
-28	32	4	6	6	6	2	22	-24	-10	-28
-7	8	62	32	32	32	-30	36	-6	28	-7
3	14	-44	56	56	56	-22	2	20	-12	3
0	0	0	0	122	122	0	0	0	0	0
0	0	0	0	0	122	0	0	0	0	0
4	-22	-18	34	34	34	52	-38	-14	-16	4
10	6	16	24	24	24	8	88	26	-40	10
6	28	34	-10	-10	-10	-44	4	40	-24	6
-18	38	20	30	30	30	10	-12	2	72	-18
33	32	4	6	6	6	2	22	-24	-10	33

"weighted predictions (W)"

0.33	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.33
0.39	0.38	0.067	0.091	0.091	0.091	0.043	0.31	0.40	0.12	0.39
0.21	0.15	0.63	0.29	0.29	0.29	0.45	0.47	0.13	0.41	0.21
0.086	0.26	0.35	0.33	0.33	0.33	0.28	0.022	0.42	0.16	0.086
1.0	1.0	1.0	1.0	0.33	0.33	1.0	1.0	1.0	1.0	1.0
1.0	1.0	1.0	1.0	1.0	0.33	1.0	1.0	1.0	1.0	1.0
0.14	0.52	0.23	0.38	0.38	0.38	0.81	0.49	0.37	0.25	0.14
0.20	0.081	0.16	0.21	0.21	0.21	0.087	0.42	0.35	0.38	0.20
0.14	0.44	0.46	0.14	0.14	0.14	0.85	0.045	0.67	0.27	0.14
0.31	0.42	0.24	0.32	0.32	0.32	0.14	0.12	0.027	0.53	0.31
0.29	0.38	0.067	0.091	0.091	0.091	0.043	0.31	0.40	0.12	0.29

APPENDIX 5. Ecopath Model

METHODS

Definition of the Study Area

The Jurien Bay Marine Park is located on the central west coast of Western Australia about 200 km north of Perth (Fig. 1) and covers an area of 8,237.5 km^2. The marine park was gazetted on the 26^{th} of August 2003 as a Class *A* Marine Park. The western boundary of the marine park is defined as the seaward limit of Western Australian coastal waters, which is defined as 3 nm from Territorial Baseline. The landward point of the southern boundary (30^o 50’ 20”) is contiguous with the southern boundary of the Wanagarren Nature Reserve and its northern boundary is defined by Dynamite Bay at Green Head (30^o 4’ 9”).

The coastline of this region generally has a north-south alignment with a near shore seabed of high complexity. Inside the 20 m depth contour, a series of elongate limestone reefs run parallel to the shore, which form part of the largest continuous temperate limestone reef in Australia (running from Dongara to Trigg). Associated with this reef are numerous emergent rocks and islands. This diverse topography provides shelter and nursery areas for marine life, including finfish, crustaceans and important primary producers. The offshore areas of the marine park are under the influence of the Leeuwin current, resulting in relatively warm low nutrient waters in the region with the potential for tropical species to be transported to the area. Near shore water movements and mixing patterns are primarily wind-driven, but are also influenced by tidal movements, wave pumping, seabed topography and the steering effect of the islands and reefs. Although these process cause strong surface currents in some parts of the lagoon, the deeper lagoon areas are poorly flushed, particularly during autumn.

The Jurien Bay Marine Park has a series of sanctuary, special purpose and general use zones: (1) ***Sanctuary zones*** provide total protection of environmental values through the exclusion of human activities likely to impact on the ecology of the area, including fishing and aquaculture. The zones provide scientific reference areas, protect areas of special value and may provide refuges for some species. (2) ***Special purpose zones*** are managed for nature conservation and a designated use. Recreational and commercial activities that are compatible with the primary purpose of a special purpose zone are also permitted (e.g. aquaculture, shore based activities, puerulus monitoring and scientific reference activities). (3) ***General use zones*** are managed for nature conservation while allowing for most forms sustainable recreational and commercial activities, as apply generally outside the park.

There are specific restrictions on recreational and commercial activities within the certain zones within the marine park:

- Access by boats is permitted throughout the marine park.
- Fishing from the shore is permitted in all areas except sanctuary zones.
- Line fishing from a boat is permitted in all areas except sanctuary zones and special purpose (scientific reference) zones.
- Spear fishing is permitted in the general purpose zone and special purpose (aquaculture) zones.
- Rock lobster fishing is permitted in all areas except the sanctuary zones and the special purpose (puerulus monitoring) zone.
- Sanctuary zones: no fishing.
- Scientific reference zones: rock lobster and shore based fishing only.

Typically, there are five major marine habitats in the region of Jurien Bay: seagrass meadows, bare or sparsely vegetated mobile sand; shoreline and offshore intertidal reef platforms; subtidal limestone reefs and reef pavement (Fig. 10).

Commercial fishing for Western Rock Lobster (*Panulirus cygnus*) has the highest economic value of any single species commercial fishery in Australia and it is the main fishing target in the Jurien Bay region. In addition, recreational fishing is an important activity within the park, targeting Western Rock Lobster, Western Australian Dhufish (*Glaucosoma hebraicum*), Pink Snapper (*Pagrus auratus*), Baldchin Groper (*Choerodon rubescens*) and abalone (*Haliotis* spp.).

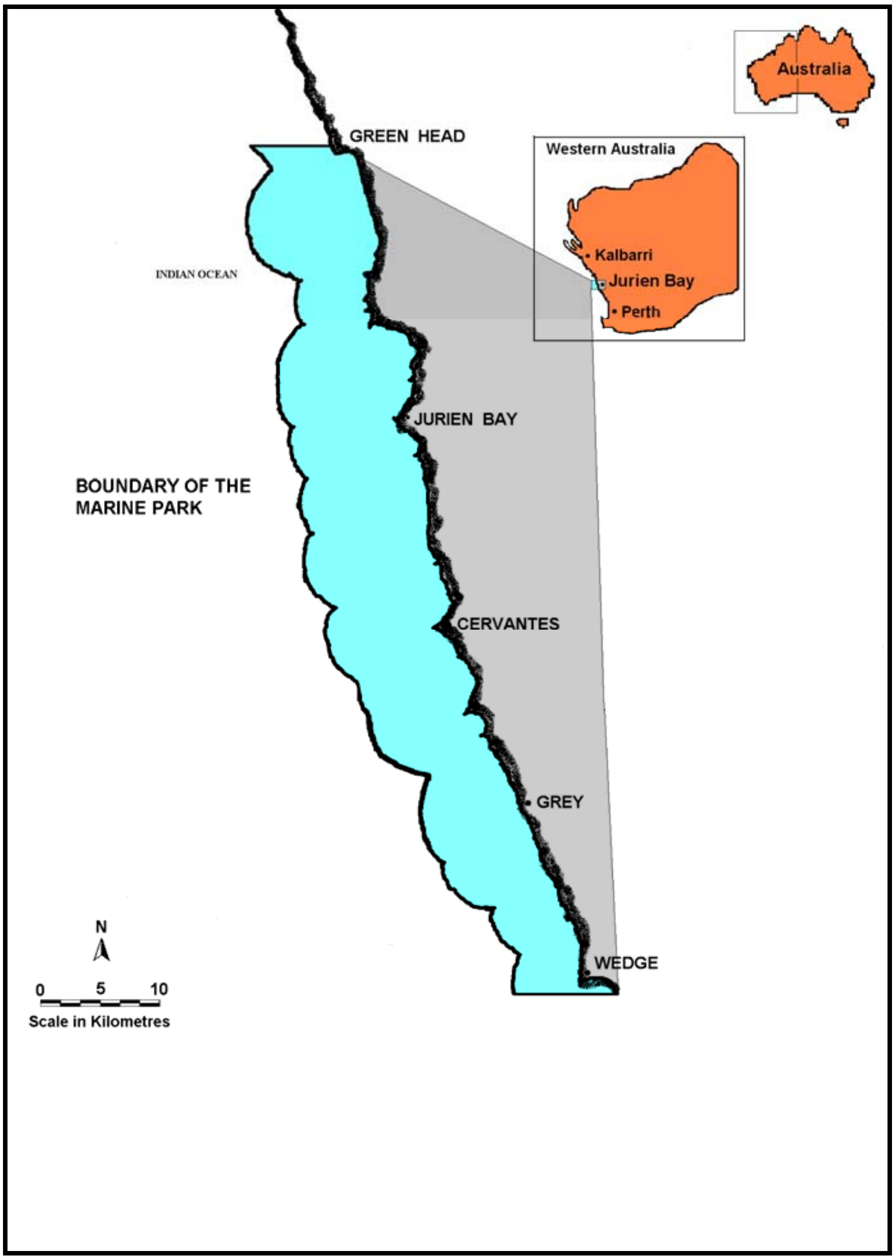


Figure 1. Jurien Bay Marine Park is located in the central coast of Western Australia. The marine park was gazetted in 2003 as a Class A marine park to promote conservation on marine biodiversity and the management of human uses. It covers an area of 823.75 km^2. The centre of the main Western Rock Lobster fishery is located in the west coast of Australia between Kalbarri and Cape Leeuwin.

Structure of the Ecopath model

According to the methodology proposed by Christensen and Walters (2004), the general approach of EwE is summarized below:

Ecopath uses a series of simultaneous linear equations, one for each functional group to quantify the energetic flows among trophic groups according to the law of conservation of mass or energy (Equation 1). The net production of a functional group equals the total mass removed by its predators and fisheries plus its net migration and its energy or mass that flows to detritus. The master equation is described as:

Production – Predation - Other mortality - Exports = 0
Or;

Production = mortality(Fishing + Predation + Other) + Biomass accumulation + Net Migration

$$B_i \cdot (P/B)_i = Y_i + \sum_{j=1}^{n} B_j \cdot (Q/B)_j \cdot DC_{ji} + E_i + BA_i + B_i(P/B)_i \cdot (1 - EE_i) \ldots \text{Equation 1}$$

Where, B_i and B_j are biomasses of prey (*i*) and predator (*j*), respectively;

P/B_i is the production/biomass ratio;
Y_i is the total fishery catch rate of group (*i*);
Q/B_j is the consumption/biomass ratio;
DC_{ij} is the fraction of prey (*i*) in the average diet of predator (*j*);
E_i is the net migration rate (emigration – immigration); and
BA_i is the biomass accumulation rate for group (*i*).
EE_i is the ecotrophic efficiency; the fraction of group mortality explained in the model.

The second assumption is that consumption within a group equals the sum of production, respiration and unassimilated food, as in equation 2.

Conservation of energy between groups:

$$B \cdot (Q/B) = B \cdot (P/B) + (1 - GS) \cdot Q - (1 - TM) \cdot P + B \cdot (Q/B) \cdot GS \ldots \text{Equation 2}$$

Where GS is the proportion of food unassimilated; and TM is the trophic mode expressing the degree of heterotrophy; 0 and 1 represent autotrophs and heterotrophs, respectively. Intermediate values represent facultative consumers.

Ecopath uses a set of algorithms (Mackay, 1981) to simultaneously solve *n* linear equations of the form in equation 1, where *n* is the number of functional groups. Under the assumption of mass-balance, Ecopath can estimate missing parameters. This allows modellers to select their inputs. Ecopath uses the constraint of mass-balance to infer qualities of uncertain ecosystem components based on our knowledge of well-understood groups. It places piecemeal information on a framework that allows us to analyse the compatibility of data, and it offers heuristic value by providing scientists a forum to summarize what is known about the ecosystem and to identify gaps in knowledge.

The input data for any particular functional group are: P/B, Q/B, B, EE and DC; however, Ecopath requires DC as an input while any one of the other parameters can be estimated by mass balance if the other three are known. Normally EE is estimated, but in cases when biomass is unknown, it is possible to obtain an estimate by making an assumption about EE (0.95, for example). However, in the case of particular groups in the Jurien Bay model (rock lobster), ontogenetic changes were represented by splitting this species into post puerulus, juveniles, adolescents and adult groups.

Functional group designation

Because of the enormous amount of differentiation in life-history, morphology and feeding guilds that appears within limestone reef fish families, delineating functional groups by fish family is impractical and may be unwise. The group structure in any particular EwE model is largely subjective and should be tailored to satisfy specific requirements of the investigation. Therefore, most of the functional groups developed for the preliminary Jurien Bay Marine Park ecosystem model are based on the functional role that the fishes play in the ecosystem, with additional groups configured to allow the representation of important commercial, social and ecological interests. The JBMP model contains 80 functional groups, including fishery discards and non-living groups such as detached seagrass, detached brown algae, detached algae (others), dead carcasses, water column sediments and organic detritus. The model also represents marine mammals, sea birds, commercial and non commercial invertebrates and plants. Table 1 presents the functional groups contained in the JBMP model.

Fish species

There are 261 fish species represented in the Jurien Bay Marine Park model. At the end of this appendix we present the name of each species contained in each functional group. Fish species are represented in the model by 31 groups, where 9 groups are inshore restricted (0-20 m), 3 groups offshore (20-60 m) and the others are non-depth restricted (ndr 0-60 m). Figure 11 displays the number of groups and species contained in each of the three general categories used to assemble the fish groups. Fish functional groups were designed with the aim of representing species of commercial interest (e.g., 'rock lobster', 'Pink Snapper', 'Dhufish', 'Baldchin Grouper', 'Breaksea Cod'), or to cover in aggregated groups the wide diversity of habitats presented in Jurien Bay (e.g., reef-associated herbivores) or specific functional roles (e.g., large herbivorous gastropods).

Inshore Restricted Fish groups (0-20 m)

Where a single fish species could suitably fit into several aggregate functional groups, it was usually assigned to the most taxonomically specific group. Inshore restricted fish groups were established based on the complexity of the habitat type in the marine park system. The groups contained under this category were revised during the first Jurien Bay workshop (June, 2005) to produce the functional groups. Although all these species are associated with shallow waters to some degree, the species were subdivided into herbivore, omnivore, zoobenthos feeders, sand associated omnivores, sand associated carnivores, seagrass associated zoobenthos feeders, seagrass associated omnivore, benthopelagic carnivores and zooplankton feeders.

Non-Depth restricted fish groups (0-60 m)

A total of 19 non-depth restricted groups have been included in the model. This subjective aggregation was designed with the objective of forming a series of sub-systems in the model that could help to evaluate the role of these groups within the marine park. Some species contained in this division are: 'leatherjackets', 'parrotfish', 'pullers', 'bullseyes', 'cods', 'basses', 'wrasses', 'eels', 'rays', 'morays' among others. Appendix 3 presents the scientific names of the species contained in these groups.

Offshore groups

Large coastal sharks, small coastal sharks and off-shore reef associated carnivores are the three off-shore groups included in the JBMP model. The species included in these groups are: 'Catsharks', 'Whiskery sharks', 'Black Whaler', 'Grey Nurse sharks', 'Blue sharks', 'Tiger sharks', 'School sharks', 'Seapikes' and 'Robinson's Seabream'. .

Estimation of model parameters

This section describes the general methodology used to assign fish functional groups their basic parameters required by the Ecopath model. We present here how the functional group parameterization was obtained (reporting where literature values and other special data sources were used to set the basic parameters).

The data needs of Ecopath can be summarized as follows. Four data points are required for each functional group: biomass (in $t \cdot km^{-2}$), the ratio of production over biomass (P/B; in yr^{-1}), the ratio of consumption over biomass (Q/B; in yr^{-1}), and ecotrophic efficiency (EE; unitless). Ecopath also provides an input field representing the ratio of production over consumption (P/Q; unitless), which users may alternatively use to infer either P/B or Q/B based on the other. Each functional group requires 3 out of 4 of these input parameters and the remaining parameter is estimated using the mass-balance relationship in equations 1 and 2. A biomass accumulation rate may be entered optionally; the default setting assumes a zero-rate instantaneous biomass change. These Ecopath data points are referred to collectively in this report as the basic parameters. For further details of Ecopath data needs and parameter definitions see Christensen *et al*., (2004). Most often, Q/B was set using the empirical formulae of Christensen and Pauly (1992); a few species were set using Palomares and Pauly (1998) using tail aspect ratio as modified by Christensen *et al.,* (2004). P/B was determined based on the sum of the natural mortality rate (M), estimated using the empirical formula of Pauly (1980), and some fishing mortality rate (F) which is an assumed fraction of M. As a guideline, heavily exploited species were assumed to have an F approximately equal to M, while moderately exploited species were assumed (for most of the cases) to have an F equal to M/2 or less.

Biomass: Numerous sources of information were used to estimate the basic input parameters of Ecopath. In general, the biomasses of fish were estimated mainly from local studies using Underwater Visual Census (UVC) techniques during 2005 and 2006 performed by David Fairclough and Glenn Moore (Murdoch University, Western Australia). They provided information related to abundance per unit area for more than 87 species of fish distributed in different habitats (sand, seagrass and reef) in Jurien Bay. Rory McAuley (Department of Fisheries, WA) provided biomass estimates for sharks. Biomass estimates for primary producers were provided by Matt Vanderklift and Julia Phillips (CSIRO Marine and Atmospheric Research) and Paul Lavery (Edith Cowan University), who also provided biomass estimates for small invertebrates and seagrass (ephemeral, perennial and epiphytes associated) from quadrat sampling in Jurien Bay. Other biomass values were obtained from information available in the literature. These estimations were presented during the fourth Jurien Bay workshop held in June, 2007 (CSIRO, Floreat), where the biomass values were revised and improved with new estimates. For example, the biomasses of 19 fish groups were improved by the new estimates provided by Dr David Fairclough and Glenn Moore from Murdoch University. Equally important was the contribution of Professor Paul Lavery (ECU), who provided more and better biomass estimations of small invertebrates and seagrass (ephemeral, perennial and epiphytes associated). These new abundances were obtained from direct quadrats samples in Jurien Bay.

Estimating Consumption rates (Q/B)

The Q/B ratio represents the food intake by a group over a specified time period (consumption) divided by its biomass. Q/B was calculated using the holistic method proposed by Pauly *et al.,* (1990) was employed according to the following equation:

$$Q/B = 10.67 * 0.0313^{TK} * W_{inf}^{-0.168} * 1.38^{Pf} * 1.89^{Hd} \text{........Equation 4}$$

Where, T*K* is an expression for mean annual habitat temperature (TK=1000/T°C + 273.1); P*f* is 1.0 for top predators and zooplankton feeders; and a value of zero for other feeders. W_{inf} is the maximum weight of the fish, estimated from the asymptotic length given by FishBase (Frose and Pauly, 2000; 2001). H*d* is the food type (0 for carnivores and 1 for herbivores and detritivores). Q/B was taken preferentially from the literature or as estimated in FishBase (www.fishbase.org). Estimates of Q/Bs from FishBase sources were accepted if the data were based on a study in a region with similar water temperatures to Jurien Bay Marine Park (20°C ± 2°C). For each fish species, the Q/B value was taken directly from FishBase, if available from the 'PopQB' field of the 'QB' table. Otherwise, an empirical relationship was used to estimate Q/B for each species.

Table 1. Summary of sources of information employed to estimate biomass in the Jurien Bay model.

Functional Group	Source (s)	Institution(s)
Dolphins	No data	
Sea lions	R. Campbell, 2005	DoF (WA)
Intertidal birds (waders)	No data	
Surface diving birds	No data	
Large coastal sharks	Rory McAuley unpublished data	DoF (WA)
Small coastal sharks	D. Fairclough, Potter and Babcook (2006); Rory McAuley (2007)	
Rays	D. Fairclough, Potter and Babcook (2006)	Murdoch, WAM, CSIRO
Dhufish	D. Fairclough, Potter and Babcook (2006)	Murdoch, WAM, CSIRO
Pink snapper	D. Fairclough, Potter and Babcook (2006)	Murdoch, WAM, CSIRO
Baldchin grouper	D. Fairclough, Potter and Babcook (2006)	Murdoch, WAM, CSIRO
King wrasse	D. Fairclough, Potter and Babcook (2006)	Murdoch, WAM, CSIRO
Western fox fish	D. Fairclough, Potter and Babcook (2006)	Murdoch, WAM, CSIRO
Breaksea cod	D. Fairclough, Potter and Babcook (2006)	Murdoch, WAM, CSIRO
Inshore reef ass. herbivore	D. Fairclough, Potter and Babcook (2006)	Murdoch, WAM, CSIRO
Inshore reef ass. omnivore	D. Fairclough, Potter and Babcook (2006)	Murdoch, WAM, CSIRO
Inshore reef ass. zoob. feed.	D. Fairclough, Potter and Babcook (2006)	Murdoch, WAM, CSIRO
Inshore sand ass. carnivore	D. Fairclough, Potter and Babcook (2006)	Murdoch, WAM, CSIRO
Inshore sand ass. omnivore	D. Fairclough, Potter and Babcook (2006)	Murdoch, WAM, CSIRO
Inshore seagr. ass. omnivore	D. Fairclough, Potter and Babcook (2006)	Murdoch, WAM, CSIRO
Inshore seagr. ass. zoob. feed.	D. Fairclough, Potter and Babcook (2006)	Murdoch, WAM, CSIRO
Inshore benthopelagic carnivore	D. Fairclough, Potter and Babcook (2006)	Murdoch, WAM, CSIRO
Inshore pelagic zoop. feed.	D. Fairclough, Potter and Babcook (2006)	Murdoch, WAM, CSIRO
N.R. reef ass. herbivore	D. Fairclough, Potter and Babcook (2006)	Murdoch, WAM, CSIRO
N.R. reef ass. omnivore	D. Fairclough, Potter and Babcook (2006)	Murdoch, WAM, CSIRO
N.R. reef ass. carnivore	D. Fairclough, Potter and Babcook (2006)	Murdoch, WAM, CSIRO
N.R. reef ass. zoob. feed.	D. Fairclough, Potter and Babcook (2006)	Murdoch, WAM, CSIRO
N.R. reef ass. zoop. feed.	D. Fairclough, Potter and Babcook (2006)	Murdoch, WAM, CSIRO
N.R. sand ass. omnivore	D. Fairclough, Potter and Babcook (2006)	Murdoch, WAM, CSIRO
N.R. sand ass. carnivore	D. Fairclough, Potter and Babcook (2006)	Murdoch, WAM, CSIRO
N.R. sand ass. zooben. feed.	D. Fairclough, Potter and Babcook (2006)	Murdoch, WAM, CSIRO
N.R. seagrass ass. omnivore	D. Fairclough, Potter and Babcook (2006)	Murdoch, WAM, CSIRO
N.R. seagrass ass. carnivore	D. Fairclough, Potter and Babcook (2006)	Murdoch, WAM, CSIRO
N.R. benthopelagic carnivore	D. Fairclough, Potter and Babcook (2006)	Murdoch, WAM, CSIRO
N.R. pelagic zoop. feed.	D. Fairclough, Potter and Babcook (2006)	Murdoch, WAM, CSIRO
Sessile epibenthos	Matt Vanderklift and Russ Babcock (2007)	CSIRO
Photo. corals/sponges	Jane Front (2006)	WAM
Infauna	Paul Lavery, Kathryn McMahon, Adam Garnet (2006)	ECU
Infaunal bivalves	Paul Lavery, Kathryn McMahon, Adam Garnet (2006)	ECU
Sessile bivlaves	Matt Vanderklift and Russ Babcock (unpublished data)	CSIRO
Deposit feed. invert.	Matt Vanderklift and Russ Babcock (2007)	CSIRO
Small mobile epifauna	Paul Lavery, Kathryn McMahon, Adam Garnet (2006)	ECU
Small mobile herbivores	Paul Lavery, Kathryn McMahon, Adam Garnet (2006)	ECU
Large mobile herb. invert	Vanderklift (unpublished data)	CSIRO
Large mobile carn. invert.	Jane Front (2006)	
Large crabs	No data	
Cuttlefish	No data	
Squid	No data	
Octopus	No data	
Lobster - post puerulus	Lachlan MacArthur (unpublised data)	DoF (WA).
Lobster - juvenile	Lachlan MacArthur (unpublised data)	DoF (WA).
Lobster - Adolescent	Matt Vanderklift and Russ Babcock (unpublished data)	CSIRO
Lobster - adult	DoF (WA).	DoF (WA).
Small gastropods	Matt Vanderklift and Russ Babcock (unpublished data)	CSIRO
Large carn. gastropods	Matt Vanderklift and Russ Babcock (unpublished data)	CSIRO
Large herb. gastropods	Matt Vanderklift and Russ Babcock (unpublished data)	CSIRO
Sea turtles	No data	
Roe abalone	No data	
Small zooplankton	From other model (Okey et al. 2001)	
Large zooplankton	From other model (Okey et al. 2001)	
Chaetognaths	No data	
Carnivorous jellyfish	From other model (Okey et al. 2001)	
Microbial heterotrophs	From other model (Okey et al. 2001)	
Ecklonia	Julia Phillips, (comm. Pers.)	CSIRO
Sargassum	Wernberg, Vanderklift, How, Lavery (2006	ECU, CSIRO
Low algae	Wernberg, Vanderklift, How, Lavery (2007	ECU, CSIRO
Turfs	Julia Phillips, (comm. Pers.)	CSIRO
Corraline algae	Julia Phillips, (comm. Pers.)	CSIRO
Ephemeral seagrasses	Paul Lavery, Kathryn McMahon, Adam Garnet (2006)	ECU
Perenial seagrasses	Paul Lavery, Kathryn McMahon, Adam Garnet (2006)	ECU
Seagrass epiphytes	Paul Lavery, Kathryn McMahon, Adam Garnet (2006)	ECU
Microphytobenthos	SRFME data	SRFME
Small phytoplankton	SRFME data	SRFME
Large phytoplankton	SRFME data	SRFME
Detached seagrass	Julia Phillips, (comm. Pers.)	CSIRO
Deatached brown algae	Mat Vanderklift (unpublished data)	CSIRO
Detached algae other	Mat Vanderklift (unpublished data)	CSIRO
Dead carcasses	Guesstimated	
Bait	Kriss Waddignton, comm. Pers, 2007	UWA
Watercolumn detritus	Lesley Clementson (unpublished data)	UWA
Sediment detritus	Lesley Clementson (unpublished data)	UWA

If W_∞ could not be determined, then the empirical formula of Palomares and Pauly (1998) was used instead to estimate Q/B based on caudal fin aspect ratio (Equation 5). Here, aspect ratio (A) is defined as (tail height / area)^2; it is available from the Aspect Ratio field of the FB Swimming of FishBase table. Parameters *h* and the *d* refer to the types of food consumed (i.e., for herbivores h=1, d=0; for carnivores h=0, d=0; for detritivores d=1, h=0 as defined by Palomares (1991) and reported by Palomares and Pauly (1998)). These binary values were set for each species based on diet information provided in the FB diet table or on comment fields (e.g., in the Species table).

$$Q/B = 7.964 \cdot 0.204 \log W_\infty + 1.965\ T + 0.083A + 0.532h + 0.398d \text{….Equation 5}$$

Length-length conversions

The empirical formula of Pauly (1980) for estimating M and the formula of Pauly *et al.,* (1990) for estimating Q/B both require L_∞ as measured in total length (TL). Entries for L_∞ in FishBase (in both Species and PopGrowth tables) are usually provided in TL. Where length measurement are given in other formats by the original data sources (e.g. in fork length (FL) or standard length (SL)), FishBase usually provides conversions to TL in the 'TL-infinity' field; no conversions are provided for maximum lengths found in the 'Species' table. When required, conversions were performed manually.

To convert FL to TL, the linear empirical relationships of Booth and Isted (1997) were used. This equation is recommended for fish with forked tails. It is based on fish named 'Panga' (*Pterogymnus laniarus*) and the relationship is described as:

$$FL = 0.901 \cdot TL - 0.6848 \text{………….Equation 6}$$

For fish with emarginated tails, the relationship between FL and TL has been calculated based on the Lesser Gurnard (*Chelidonichthys quekerri*) as is presented in equation 7:

$$FL = 0.9454 \cdot TL + 3.6166 \text{………..Equation 7}$$

All pelagic, benthopelagic and bathypelagic fish were assumed to have forked tails and their TL was calculated based on Christensen and Pauly (1992) as in equation 8:

$$TL = 1.1757 \cdot SL - 0.1215 \text{………..Equation 8}$$

Estimating production per unit of biomass (P/B)

In the Ecopath mass-balanced model, the ratio of production to biomass, P/B is assumed to equal total mortality, Z (Allen, 1971). Therefore, this production parameter was calculated for commercially exploited stocks as the total of fishing (F) and natural mortalities (M). In the case of un-fished species, their natural mortality (M) was used to represent the P/B rate. For target species (with an annual catch), P/B was estimated as the sum of M and fishing mortality (F). Where available, the M was taken directly from literature sources or from data tables in FishBase. Where an estimate could not be found, the regression equation of Pauly (1980) was used to determine M (Equation 9), which requires growth information: the Von Bertalanffy growth constant (K) and the asymptotic length at infinity (L_∞). These values were obtained for most species from FishBase PopGrowth table. When L_∞ was unavailable, the maximum specimen length observed L_{MAX} was substituted, assuming that $L_\infty = 0.95 \cdot L_{MAX}$

$$M = K^{0.65} \cdot L_\infty^{-0.279} \cdot T^{0.463} \text{……………Equation 9}$$

Diet composition

The diet composition matrix was assembled as percentage weight or volume of the annual fraction that each prey contributes to the overall diet of the predator (according to the methodology recommend by Christensen *et al*., 2004). Several local reports were employed to assemble this matrix of feeding interactions, but when data from the marine park was not specifically available, values were taken from the same species from the adjacent areas or other Ecopath models in Australia. The diet composition matrix was sent to the experts of the main fields of the model (fish, invertebrates, primary producers and non-living components) with the purpose to revise and do the final tuning of the matrix. Several scientists from CSIRO, Department of Fisheries, WA and Murdoch University revised and change the diet composition matrix of the model according to their judgement. Their changes and improvements were incorporated in the final version of the model.

Fisheries

Gear types

The fishing gear types included the Jurien Bay model were selected based on the discussions with experts from the area and representatives from the Department of Fisheries, WA during the third Jurien Bay workshop held in CMAR, Floreat, WA February, 2007. The gear structure proposed for the model included fourteen gear types for both commercial and recreational fisheries. A total of eight gear types represent the commercial fisheries of the region with the following gears: Rock lobsters pots, beach seine (haul netting), drop lining, gill netting (set nets), long-lining (set line), traps, haul netting, and abalone fishing. In the case of recreational fishing, the following six gears are included in the model: Beach anglers, boat anglers, netting, diving, potting and spear fishing.

Catch statistics

Commercial Catch

Most of the commercial fisheries catch data used in this preliminary model were provided by officers of the Department of Fisheries, Western Australia during the third workshop of the Jurien Bay region held in CSIRO (Floreat, WA) in February, 2007. The fisheries data included the total catch (kg), gear types and species fished within each of the relevant districts in which the Department of Fisheries manages and reports fisheries statistics in Western Australia. According to DoFWA, the region of the JBMP model is included in districts 3014 and 3015. The proportion of the area of Jurien Bay in district 3014 and 3015 was calculated and the catch of each species was assigned to its functional group in the model. The total catch per functional group was calculated for the two fishing districts and divided by the proportion of the area estimated of Jurien Bay. Doing this transformation, the catch data was converted into standard units for use in Ecopath. The total commercial catch for the Jurien Bay Marine Park region was estimated to be 0.43/km^2.

Table 2. Functional group catches (tonnes · year^{-1}) by the eight commercial gear types operating in the region of Jurien Bay Marine Park. Catch for each group represents the total of the species fished within the group. Data proportioned by the Department of Fisheries for the districts 3014 and 3015 of Western Australia.

Group Name	Rock lobster	Beach Seine	Droplinning	Gill Netting	Handlinning	Longlinning	Traps	Abalone
Large coastal sharks			0.001	0.0000654	0.001	0.000426		
Small coastal sharks			0.00119	0.000046	0.00000106			
Rays								
Dhufish		0.00124	0.08	0.0065	0.00467			
Pink snapper		0.00017	0.009	0.000531	0.011	0.000371		
Baldchin grouper		0.0000587	0.089	0.024	0.00861			
King wrasse		0.00584	0.00321	0.0051	0.0076			
Western foxfish			0.00012	0.00467	0.0016	0.00054		
Breaksea cod					0.00381	0.00894		
Inshore reef ass. herbivore		0.0000018	0.0000011		0.00000869			
Inshore reef ass. omnivore			0.000271	0.000000607	0.0000082			
Inshore reef ass. zoobenthos feed.		0.0000207	0.0000901	0.0000365	0.0000298			
Inshore ass. carnivore		0.000121						
Inshore sand ass. omnivore		0.00605	0.000000588	0.000394	0.00000649			
Inshore seagrass ass. zoob. feed.				0.000015	0.00000026			
Inshore benthopelagic carnivore		3.69E-06		0.0000137	0.00001	0.0000117		
NDR reef ass. herbivore				0.000357		0.0000153		
NDR reef ass. carnivore			0.000000209	0.00000026	0.000000502			
NDR reef ass. zoobenthos feed.		1.15E-06						
NDR sand ass. carnivore				5.58E-08				
NDR sand ass. zoobenthos feed.			0.0000807		0.0000265			
NDR benthopelagic carnivore		4.94E-06	0.00152	0.000108	0.000188			
Large Crabs							0.0159	
Octopus	0.00512						0.009	
Lobster - Adolescent	0.02							
Lobster Adult	0.428							
Roe abalone								0.00335

Recreational Catch

The recreational catches for the main finfish and invertebrate species targeted in the marine park (i.e. Pink Snapper, Dhufish, Breaksea Cod, Baldchin Grouper) were obtained from the 2006 Recreational fishing Guide published by Department of Fisheries WA. This information was combined with the 12-month survey of coastal recreational boat fishing between Augusta and Kalbarri on the Western Australia during 1996-97 reported by Sumner and Wilson (1999). The Department of Fisheries, in its section on recreational fisheries, reported that in depths less than 20 m between Northwest and Augusta (with Perth and Geraldton with the greatest fishing activities), the recreational catch was 561 tonnes by potting and 186 tonnes by diving in 2000-2001. Using this anchor value, a recreational catch in the JBMP was estimated using a 15% of the total catch for the region (based on the area of the marine park). In some cases, DoF reported that number of organisms caught per recreational fishing per season, in those cases, a mean individual weight was established as 50% of the max weight reported in FishBase. The total recreational catch within the marine park was estimated in 0.061t/km^2 that represents approximately 9% of the commercial catch in the region. Table 3 presents the recreational catch estimated for the six gear types included in the model.

Table 3. Recreational catch (tonnes · year^{-1}) of the main gear types considered in the Jurien Bay Marine Park, WA. Catch for each group represents the total of the species fished within the group. See text for sources of information employed.

Group Name	Rec. Pots	Rec. Beach Anglers	Rec. Boat Anglers	Rec. Netting	Rec. Diving	Rec. Spearfishing
Dhufish			0.00521		0.000005	0.0000057
Pink snapper			0.009	0.000047	0.000005	0.00000012
Baldchin grouper			0.00217	0.00197	0.000005	4.4E-09
King wrasse			0.000157	0.001		
Western foxfish		0.00895	0.00618	0.000571		0.0003
Breaksea cod			0.0000527			
Inshore reef ass. zoobenthos feed.		0.000014		0.0017		
Inshore ass. carnivore			0.000122			
Inshore sand ass. omnivore				0.0000118		
Inshore benthopelagic carnivore			0.00017			
NDR benthopelagic carnivore			0.00007			0.0007
Large Crabs						0.00049
Lobster Adult	0.00945				0.00347	

Data quality of the model

The 'pedigree' routine in Ecopath, serves as a sensitivity analysis for documenting the effect of inputs on estimated parameters and their quality. The pedigree index (P) measures the amount of local data used (i.e., minor uncertainty in the inputs) among the five basic categories of models: Biomass (B), Production to biomass (P/B), the ratio of consumption to biomass (Q/B), and diets and catches for each of the functional groups. The range of P is from 0 for data not rooted locally to 1.0 for data that are fully rooted in local data (Christensen *et al*., 2004). The pedigree Index for Jurien Bay model was calculated using the following expression:

$$P = \sum_{i=1}^{n} \frac{I_{ij}}{n}$$

Where I_{ij} is the pedigree index value for group I and parameter j for each of the living groups in the ecosystem; j can represent either B, P/B, Q/B and Y or diet.

The pedigree of an Ecopath input represents the coded statement categorizing the origin a given input (i.e., the type of data on which it is base), specifying the likely uncertainty associated with the input. There is a pre-defined table in Ecopath for each type of input parameters. The Ecoranger module of Ecopath can subsequently pick up the confidence intervals from the pedigree tables and use these as prior probability distributions for all input data. The key criterion used in the model was that input estimated from local data (i.e. fish abundance using underwater visual census) as a rule is better than date from elsewhere, be it guesstimate, derived from empirical relationships or derived from other Ecopath models.

Specifying the pedigree of data to generate Ecopath input is useful, for the following reasons:

- To be aware of the danger of constructing the model mainly from input taken from other Ecopath models
- To provide defaults for Ecoranger routine of Ecopath, and thus allow explicit consideration of uncertainties in the input
- To provide a basis for the computation of an overall index of the model 'quality'; a model of high quality when it is constructed mainly using precise estimates of various parameters, based on data from the system to be represented by the model.

These requirements are met for three scales, one for Biomass, one for total mortality (P/B) and consumption (Q/B), and one for diet composition.

- Biomass
- P/B and Q/B
- Diet composition
- Catches

Biomass: This scale is based on the observation that biomasses are very hard to estimate accurately, and that guesses may easily be off by orders of magnitude (Christensen *et al*., 2005). It is important to mention that even the best stratified random trawl surveys estimate biomass with a precision of 70% (Pauly *et al.*, 2004). Table 5 shows the pedigree index and confidence interval for each of the origin of the biomass estimation.

Production/biomass (P/B) and consumption biomass ratios (Q/B): The pedigree index for these parameters is based on the observation that P/B and Q/B are highly conservative parameters, which have characteristic values of different species. Here, values from empirical models will tend to be more reliable than guesstimates, and estimates from other Ecopath models.

Table 4. 'Pedigree' index used in the model to describe data origin and assigning confidence intervals based on the origin (*c.i.*) of the four major categories of input parameters of the model: biomass (B), production/biomass (P/B) and consumption ratios (Q/B); diet composition and catches.

	Parameter: Biomass	Index	Default *c.i,* (+/- %)
1	'Missing' parameter (estimated by Ecopath)	0.0	n.a.
2	From other model	0.0	80
3	Guesstimates	0.0	80
4	Approximate or indirect method	0.4	50-80
5	Sampling based, low precision	0.7	40
6	Sampling based, high precision	1.0	10
	Parameter: P/B and Q/B		
1	'Missing' parameter (estimated by Ecopath)	0.0	n.a.
2	From other model	0.1	90
3	Guesstimates	0.2	80
4	Empirical relationships	0.5	50
5	Similar group/species, similar system	0.6	40
6	Similar group/species, same system	0.7	30
7	Same group/species, similar system	0.8	20
8	Same group/species, same system	1.0	10
	Parameter: Diets		
1	General knowledge of related group/species	0.0	80
2	From other model	0.0	80
3	General knowledge of same group/species	0.2	80
4	Qualitative diet composition	0.5	50
5	Quantitative, but limited diet composition	0.7	40
6	Quantitative, detailed diet composition	1.0	30
	Parameter: Catches		
1	Guesstimates	0.0	>80
2	From other model	0.0	>80
3	FAO statistics	0.2	80
4	National statistics	0.5	50
5	Local study, low precision/incomplete	0.7	30
6	Local study, high precision/complete	1.0	10

The indicators from the pedigree index that are presented in Table 7 are used in the model in two different fashions:

- The approximate 95% confidence intervals associated with the indicators are passed on to Ecopath, for which they provide the default.
- The pedigree indicators scores (ranging from 0.0 to 1.0) are averaged over all parameters and functional groups of a model to provide an index of the model's quality.

The pedigree index (*P*) for the Jurien Bay model was calculated, based on 314 input parameters of the 72 living groups considered in the model. As the value of *P* could be relative to the number of groups in the model, it has been suggested to employ the Measure of the fit (*t**) as a more realistic way to evaluate how well rooted in local data is the model. *t** was estimated using this equation:

$$t^* = \frac{\sqrt{(n-2)}}{\sqrt{1-P^2}}$$

Where n in the number of living groups in the model (72 for Jurien Bay model)

The measure of fit (t*) describes how well rooted a given model is in local data. It addresses an often-aired concern of which degree 'models feed on models'. For example, models are based on data from other models, which in turn are based on data from other models. T* is recommended to be used as a comparison of 'quality' when models have been built with different number of functional groups.

For the Jurien Bay model, it was found a $P = 0.72$ and $t^* = 8.29$. The values P and t* indicate that the model has been constructed with a very reliable data generated from local samplings. Figure 2 shows a comparison of *P* and *t** from Jurien Bay model with those reported in other Ecopath models.

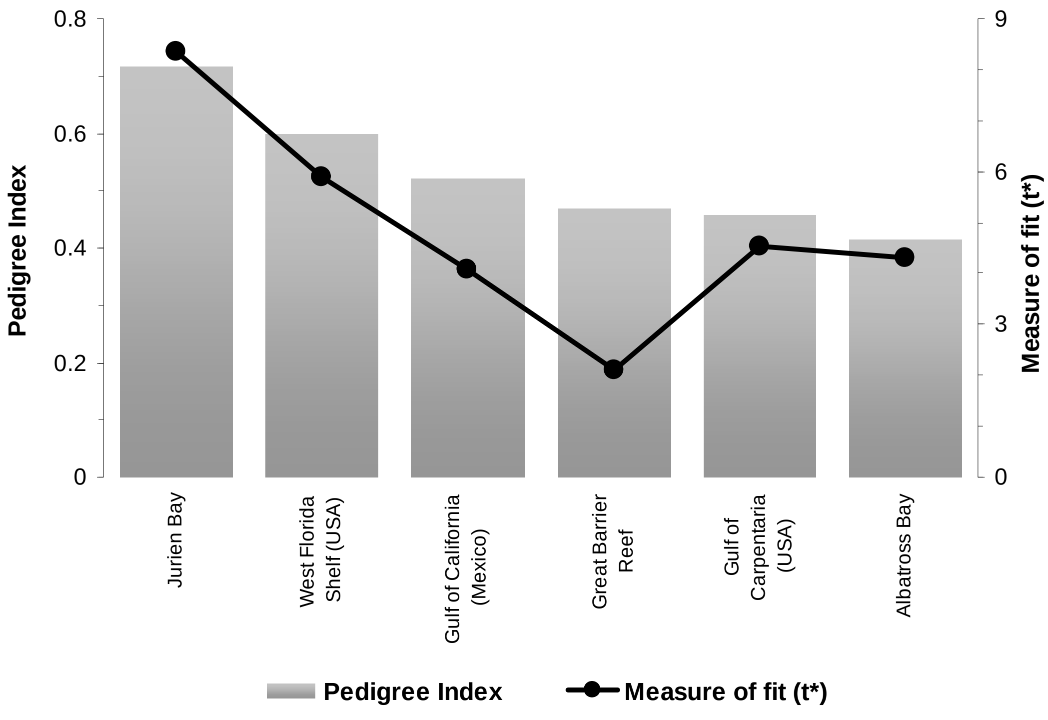


Figure 2. Comparison of the pedigree index (*P)* and its measure of fit (*t) of the Jurien Bay model with those reported in other Ecopath models. These indices indicate that the Jurien Bay model has been constructed with a very reliable data generated from local samplings.**

Mass-balance of the model

The model was balanced using a series of iterative steps. In virtually all cases, in the first attempt to balance the model, values of the ecotrophic efficiency (EE), the proportion of production that is consumed by predators, exceed 1.0 for some functional groups. During our first attempt to balance the Jurien model, 22 of the 80 groups were thermodynamically unbalanced with an average EE for living groups of only 22.19 ± 31.09 (± 1 sd). The model was balanced manually to ensure that changes to the input parameters were kept within biological reasonable limits. The first step was to minimize cannibalism within groups (i.e. large and small sharks, lobster, Dhufish and others) and liberate this energy to other groups (following Christensen *et al.,* 2000). The second step was to reduce the predation on the groups that were out of balance, but maintaining the original values of biomass for groups with local biomass estimates. The last parameter adjusted to achieve mass-balance was the consumption rate, Q/B (consumption / biomass), where changes of less than 10% were applied to those groups out of balance. It is important to mention that the process required to build the JBMP model is essentially open-ended. The parameters used in the model were revised and replaced with new estimates along the project.

Time-series fitting of the Jurien Bay Ecopath model.

Following the useful discussion from the fourth Jurien Bay workshop held at WA Fisheries' Hillarys Laboratories, Western Australia (June 25, 2008), it was recommended by scientists of the Department of Fisheries that the calibration of the model should be should be tuned using mainly the biomass of Western Rock Lobster estimated locally in Jurien Bay by depletion analysis. The biomass and catch data required to calibrate the Ecopath Jurien model were provided by the Department of Fisheries, Western Australia.

The biomasses predicted by the model were fitted using time series data of absolute abundance estimates of rock lobster (by depletion analysis). This process known as 'tuning' provides adjusted models that can track changes in biomass that are known to have occurred in the past (see details in Christensen *et al.,* 2005). In the Jurien Bay model, this required estimating the fishing mortality from 1984 to 2006 for the Western Rock Lobster. The fishing mortalities for this species were calculated in the Ecopath base year as $F_{ji0} = Y_{ji0}/B_{i0}$, where Y_{ji0} is the mean catch (1984-2006) of group i by fleet j, and B_{i0} is the mean biomass during the year (estimated by depletion techniques). The landings of rock lobster used in the tuning process (1984 to 2006) were provided by the Department of Fisheries, WA. The differential equations that express flux rates among biomass pools as a function of time varying biomass are solved by an Adams-Bashford method of integration (this method is a faster and more stable integration routine than the Range-Kutta 4th Order, see details in Christensen *et al*., 2005). The predicted biomass of Western Rock Lobster resulted of the final calibration of the Jurien Bay model is showed in Fig. 3.

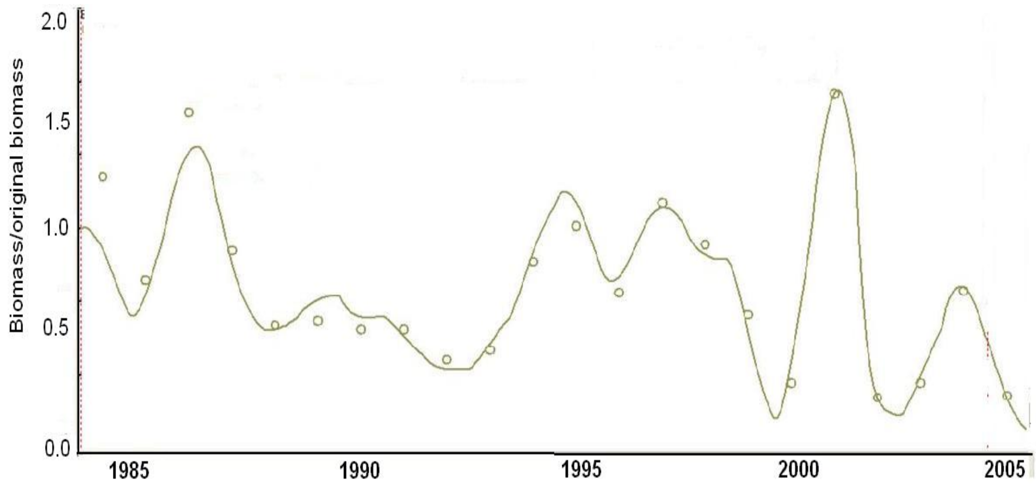


Figure 3. Calibration of the Jurien Bay Ecopath model displaying the predicted biomasses of Western Rock Lobster (line) and biomasses obtained from depletion analysis (dots) by the Department of Fisheries, WA.

Thermodynamic consistency of the model

Some of the results from the output routines of the model were used to evaluate its performance in order to check its thermodynamic consistency. For example, the ratio of biomass over production is expected to have a positive linear relation with trophic levels (Pauly *et al.,* 2003; Christensen *et al*., 2004). This is because lower trophic levels are in general characterized by high production rates (e.g. phytoplankton, zooplankton), meanwhile top predators like sharks, Dhufish, sea lions have a production rate lower. The linear trend of the ration biomass/production for the 72 living groups suggested that the model is thermodynamic stable. This result was presented to the leaders of the project in April, 2008 in order to discuss the relevance and to verify that the Jurien Bay model is not just mass-balanced and fitted, but also thermodynamic consistent.

Sensitivity analysis

A simple sensitivity routine included in Ecopath 5.2 (Christensen *et al*., 1996) was used to evaluate how the model behaves in response to changes in the input parameters. Basically, the routine varies from the biomass of all groups -50% to +50% and then it checks what effect each of these steps has for each of the input parameters on all the 'missing' basic parameters for each group in the model. In the case of the Jurien Bay model, only changes in biomass were considered in the analysis. The results obtained and overall, the sensitivity analysis suggests that the model is relatively insensitivity to parameters values for most living groups and changes in biomass of sharks and other top predators exert the greatest influence in the system (Fig. 4). Only living groups were considered in the analysis because Ecopath is not the best tool to evaluate geochemical interactions in the system (Christensen et al., 2004). For this reason, it would be desirable in the near future to combine Ecopath with Atlantis modelling in order to improve our understanding of the bio-geochemistry at Jurien. Overall, the greatest influence in the model was produced by detritus. Note that this sensitivity analysis was performed after running the model through a series of Monte Carlo runs in Ecoranger to estimate the uncertainty of the input parameters. Overall, the sensitivity analysis can be seen as a guide with which areas were the model needs to be improved with more and better data and information collected in the future.

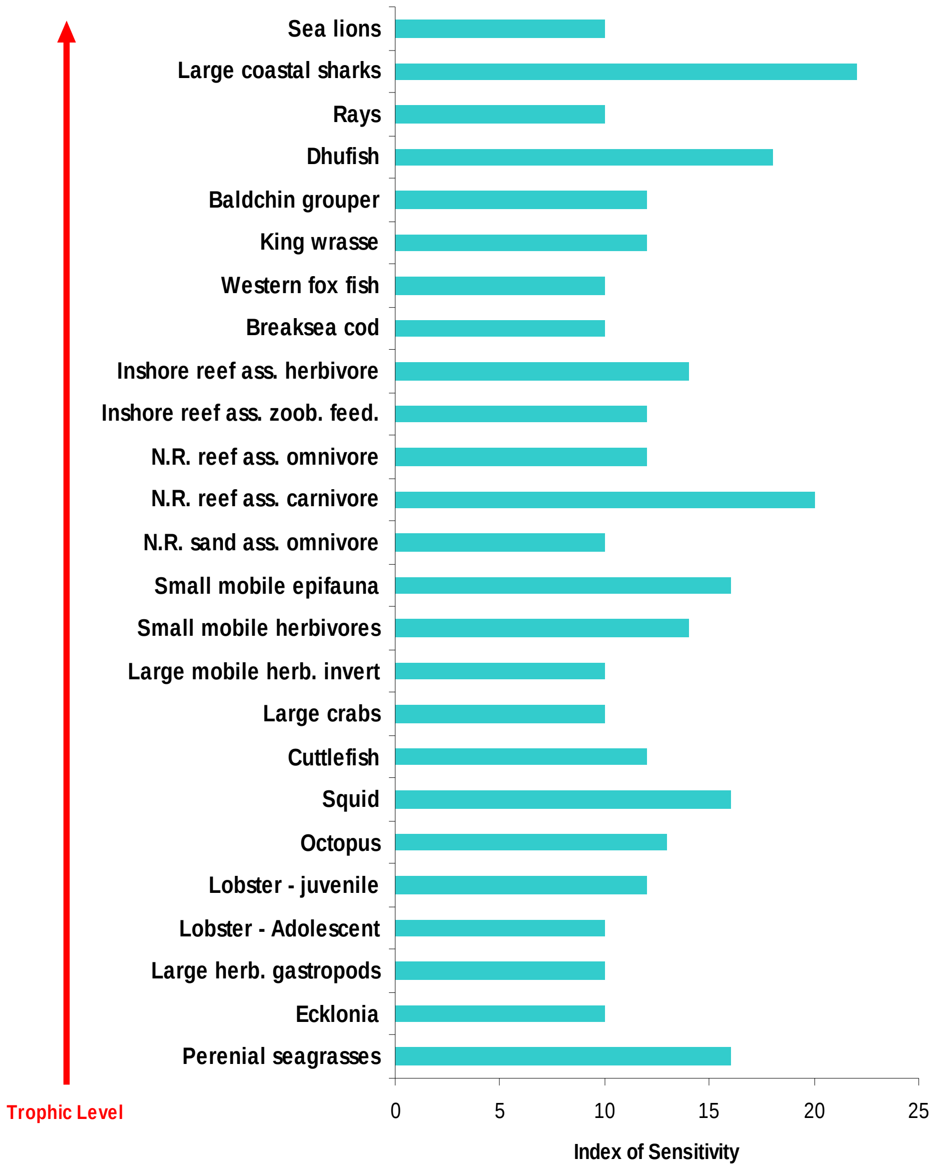


Figure 4. Results from the sensitivity analysis of the Jurien Bay Ecopath model. Overall, the model is relatively insensitive to parameter values for most of the living groups and changes in biomass of <3 TL (mainly benthic producers such as seagrass) exerted the greatest influence in the system. Only living groups are displayed (see text for details).

Performance of the model

Some of the results from the output routines of the model were used to evaluate its performance in order to check its thermodynamic consistency. The first indicator of performance was the ratio of respiration to assimilation (R/A). In Ecopath the respiration is used only to balance the flows. Thus, it is not possible to enter respiration data. It is expressed in t/km^2/year. This dimensionless ratio cannot exceed 1.0, because respiration cannot exceed assimilation. In general, the R/A is expected to be close to 1.0 for top predators, while it will tend to be lower (but, positive) for organisms at lower trophic levels. Figure 5 shows the distribution of R/A among the trophic levels predicted by the model. The positive slope found between these two variables indicates that the model is consistent thermodynamically.

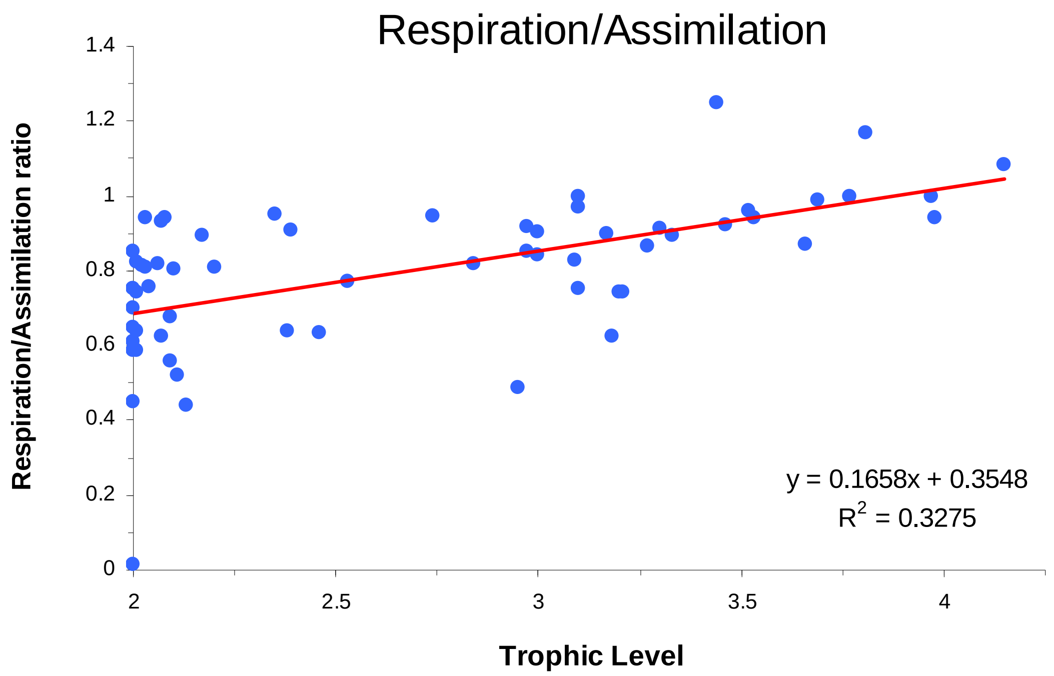


Figure 5. Relationship between the respiration to assimilation ratio and the trophic levels predicted by the Jurien Bay model. The positive slope found indicates that the model is consistent thermodynamically (see text for details).

The second indicator of performance of the model was the gross food conversion efficiency (GE) that represents the ratio between production and consumption (P/Q). Because consumption is expected to be between three to ten times higher than production, in most cases, P/Q ratios will range 0.1 to 0.3 (except for fast growing organisms and corals). Most of the P/Q values of the 72 living groups of the model were within the range of 0.05 to 0.3 (except for phototropic corals), indicating that the model is consistent with this thermodynamic restriction. It was expected that phototrophic corals would have a P/Q value higher than 0.3 due to the low consumption of the group. Figure 6 shows the distribution of P/Q values predicted by the model.

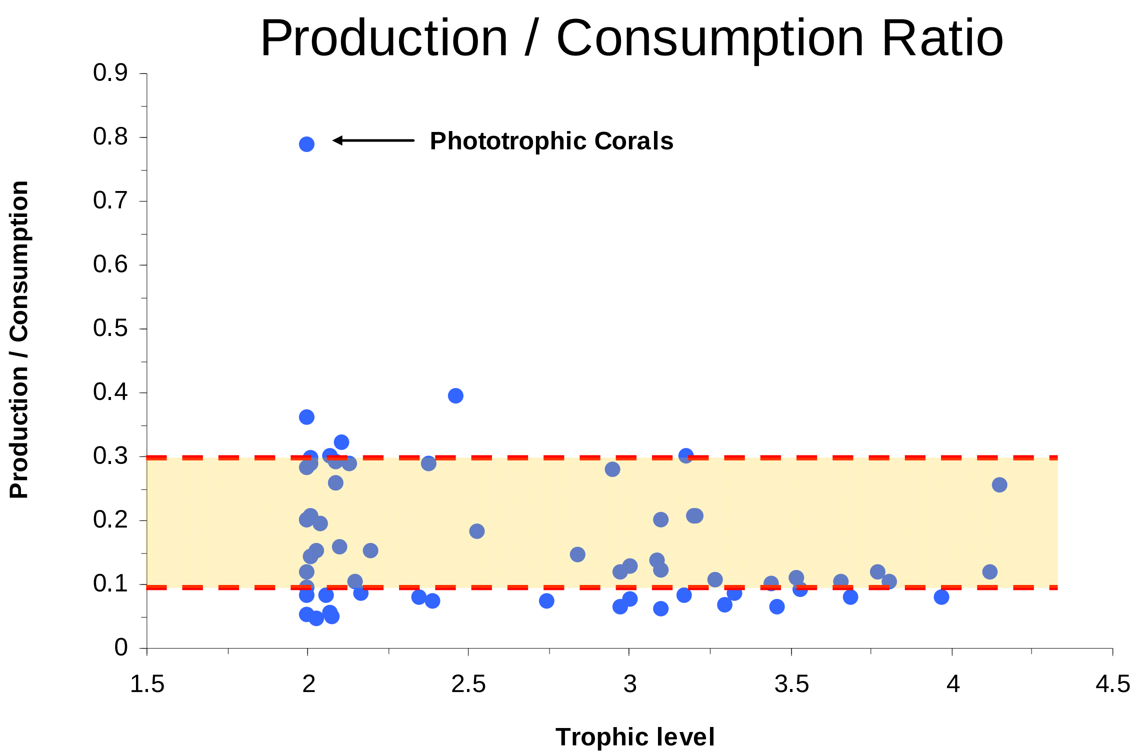


Figure 6. Distribution of the ratios of production to consumption (P/Q) values predicted by the model. This distribution was used to evaluate the performance of the model because it is expected that consumptions must be between 3 to 10 times higher than production (except for phototrophic corals), indicating that the model is thermodynamically consistent.

DIET COMPOSITION MATRIX.

Diet composition matrix built for the 2006 Jurien Bay model. This matrix is under evaluation for the experts of each of the major components of this food web.

	Prey \ Predator	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	Dolphins					0.00078										
2	Sea lions					0.00078										
3	Intertidal birds (waders)															
4	Surface diving birds					0.00078										
5	Large coastal sharks					0.00078										
6	Small coastal sharks					0.04										
7	Rays															
8	Dhufish					0.00078										
9	Pink snapper		0.00198			0.117			1.3E-05							
10	Baldchin grouper					0.15			0.0746							
11	King wrasse	0.107	0.0475			0.0555	0.0206	0.0943	0.16				0.261	0.0225		
12	Western fox fish	0.00079	0.00987			0.00078			0.0746							
13	Breaksea cod					0.0506			0.0746							
14	Inshore reef ass. herbivore	0.009	0.00495			0.00815	0.0108	0.0516	0.0175			0.00495		0.00107		
15	Inshore reef ass. omnivore					0.00086	0.001	0.00097	0.00084		0.00092		0.00098			
16	Inshore reef ass. zoob. feed.				0.0851	0.00086	0.00687	0.00793	0.00754			0.00495	0.0069	0.00858		0.00077
17	Inshore sand ass. carnivore					7.8E-05			9.2E-05							
18	Inshore sand ass. omnivore					0.0408										
19	Inshore seagr. ass. omnivore				0.0851											
20	Inshore seagr. ass. zoob. feed.			0.0476			0.00099		0.00084							
21	Inshore benthopelagic carn.					0.00078	0.001									
22	Inshore pelagic zoop. feed.	7.8E-06			0.0851											
23	N.R. reef ass. herbivore															
24	N.R. reef ass. omnivore	0.005	0.00495			0.00653	0.00687			0.00689	0.00825	0.0109	0.00985	0.00751		
25	N.R. reef ass. carnivore					0.00896	0.157		0.0859							
26	N.R. reef ass. zoob. feed.												0.117			0.0923
27	N.R. reef ass. zoop. feed.								0.00503							
28	N.R. sand ass. omnivore	0.109	0.109			0.00408		0.294					0.395			
29	N.R. sand ass. carnivore					0.00078										
30	N.R. sand ass. zooben. feed.								0.0835							
31	N.R. seagrass ass. omnivore								0.00918							
32	N.R. seagrass ass. carnivore								1.5E-05							
33	N.R. benthopelagic carnivore						1.1E-06									0.0615
34	N.R. pelagic zoop. feed.															
35	Sessile epibenthos															0.00077
36	Photo. corals/sponges															0.0115
37	Infauna							0.00495	0.00835							
38	Infaunal bivalves							0.00495	0.00835							
39	Sessile bivlaves		0.0119					0.00991								
40	Deposit feed. invert.			0.00952												9.2E-06
41	Small mobile epifauna											0.19				
42	Small mobile herbivores							0.0516		0.00086	0.011	0.152		0.0569		
43	Large mobile herb. invert									0.00086	0.00092		0.0995			
44	Large mobile carn. invert.							9.9E-06					0.0995			
45	Large crabs						0.0422	0.0139		0.025	0.0229					
46	Cuttlefish	0.093				0.201	0.157		0.197					0.366		
47	Squid	0.00014	0.269			0.00012	0.001		0.0471	0.0435				0.00013		
48	Octopus		0.0267					0.102	0.0302	0.0435	0.0741					
49	Lobster - post puerulus									0.0435				4.1E-05		0.0769
50	Lobster - juvenile						0.00011							0.192		
51	Lobster - Adolescent		0.00989				0.00024		0.0099							
52	Lobster - adult		0.0109				0.00024	9.7E-06	8.4E-05		9.2E-05					
53	Small gastropods							0.00099								0.00385
54	Large carn. gastropods							0.00893		0.00047						
55	Large herb. gastropods		0.134			0.0391	0.384	0.00893		0.827	0.872					0.0423
56	Sea turtles					0.00815	0.0049									
57	Roe abalone		0.0267													
58	Small zooplankton															
59	Large zooplankton															
60	Chaetognaths															
61	Carnivorous jellyfish															
62	Microbial heterotrophs															
63	Ecklonia														0.021	0.00076
64	Sargassum														0.081	0.00923
65	Low algae														0.211	0.0646
66	Turfs														0.01	0.00923
67	Corraline algae															
68	Ephemeral seagrasses													0.00107		
69	Perenial seagrasses													0.0225	0.406	0.0608
70	Seagrass epiphytes										0.00051					0.0838
71	Microphytobenthos															
72	Small phytoplankton															
73	Large phytoplankton															
74	Detached seagrass															
75	Deatached brown algae															
76	Detached algae other															
77	Dead carcasses					0.0195	0.0196	0.0516	0.00835	0.00861	0.00916	0.0099	0.00985			
78	Bait															
79	Watercolumn detritus															
80	Sediment detritus														0.19	0.441
	Import	0.676	0.333	0.943	0.745	0.242	0.185	0.293	0.0961			0.627		0.322	0.081	0.0408
	Sum	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Diet composition matrix. Continuation

Prey \ Predator	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Dolphins															
Sea lions															
Intertidal birds (waders)		0.00825													
Surface diving birds															
Large coastal sharks															
Small coastal sharks															
Rays															
Dhufish															
Pink snapper															
Baldchin grouper															
King wrasse		0.0198				0.043				0.147				0.031	
Western fox fish															
Breaksea cod															
Inshore reef ass. herbivore						0.001				0.109					
Inshore reef ass. omnivore						0.005									
Inshore reef ass. zoob. feed.										0.00833					
Inshore sand ass. carnivore															
Inshore sand ass. omnivore		0.00082													
Inshore seagr. ass. omnivore		0.00082			0.222										
Inshore seagr. ass. zoob. feed.		0.00082		0.00079											
Inshore benthopelagic carn.		0.00165													
Inshore pelagic zoop. feed.															
N.R. reef ass. herbivore		0.0991													
N.R. reef ass. omnivore															
N.R. reef ass. carnivore															
N.R. reef ass. zoob. feed.															
N.R. reef ass. zoop. feed.										0.00833					
N.R. sand ass. omnivore		0.207												0.469	
N.R. sand ass. carnivore															
N.R. sand ass. zooben. feed.														0.022	
N.R. seagrass ass. omnivore				0.0373											
N.R. seagrass ass. carnivore															
N.R. benthopelagic carnivore															
N.R. pelagic zoop. feed.										0.00011					
Sessile epibenthos															
Photo. corals/sponges	0.127			0.00318					0.00013						
Infauna		0.207		0.119						0.00023	0.001	0.001	0.113	0.001	0.01
Infaunal bivalves		0.0825											0.135		
Sessile bivlaves		0.0825													
Deposit feed. invert.			0.167												
Small mobile epifauna	0.0552			0.0953	0.376	0.001	0.001		1E-05		0.0804		0.00823		0.022
Small mobile herbivores	0.0403	0.0825	0.0183	0.0405	0.263	0.005			0.012	0.0491	0.315			0.011	
Large mobile herb. invert		0.0825	0.00832			0.082			0.021	0.0908				0.227	0.117
Large mobile carn. invert.	0.0115												7.5E-07		
Large crabs	0.154									0.0009	0.195		0.101		0.001
Cuttlefish					0.0479	0.127				0.0102					
Squid						0.0001				0.00023	0.00069				
Octopus					0.0197	0.001				0.00023			0.00823	0.022	
Lobster - post puerulus	0.0825			0.00715	0.00558	0.002				0.0741					
Lobster - juvenile	0.00345								0.023	0.0009			0.00075		
Lobster - Adolescent	0.00115	0.00082				0.001			0.001		9.8E-07		0.00075	0.001	
Lobster - adult		9.1E-05				0.001					9.8E-07			0.00017	
Small gastropods	0.257	0.124												0.005	
Large carn. gastropods					0.00093						0.00098			0.011	
Large herb. gastropods					0.00093	0.731					0.00098				
Sea turtles															
Roe abalone															
Small zooplankton							0.499					0.599			
Large zooplankton							0.499					0.4			
Chaetognaths					9.3E-05										
Carnivorous jellyfish															
Microbial heterotrophs															
Ecklonia				0.00079				0.005	0.00086				0.0075		
Sargassum			0.00074	0.00079				0.014	0.0519				0.0497		
Low algae			7.4E-05	0.00079				0.402	0.299				0.0497		
Turfs								0.025	0.012						
Corraline algae				0.0524	0.0263			0.167	0.021						
Ephemeral seagrasses	0.0515		0.00832	0.105	0.0291			0.0609	0.034						
Perenial seagrasses	0.0426		0.0375	0.0564				0.0886	0.182		0.00603				
Seagrass epiphytes				0.0159				0.016	0.023				0.0015		
Microphytobenthos			0.00749						0.048				0.00823		
Small phytoplankton															
Large phytoplankton															
Detached seagrass									0.0956				0.00075		
Deatached brown algae															
Detached algae other															
Dead carcasses	0.118			0.303	0.00931				0.013		0.0984		0.00823		
Bait															
Watercolumn detritus				0.0564							0.035				
Sediment detritus	0.0552			0.105							0.02		0.101		0.79
Import			0.752					0.222	0.163	0.5	0.246		0.407	0.199	0.06
Sum	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Diet composition matrix . Continuation

Prey \ Predator	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
Dolphins															
Sea lions															
Intertidal birds (waders)		0.00923													
Surface diving birds															
Large coastal sharks															
Small coastal sharks															
Rays															
Dhufish															
Pink snapper															
Baldchin grouper															
King wrasse															
Western fox fish															
Breaksea cod															
Inshore reef ass. herbivore															
Inshore reef ass. omnivore															
Inshore reef ass. zoob. feed.															
Inshore sand ass. carnivore															
Inshore sand ass. omnivore															
Inshore seagr. ass. omnivore															
Inshore seagr. ass. zoob. feed.															
Inshore benthopelagic carn.															
Inshore pelagic zoop. feed.			0.0781												
N.R. reef ass. herbivore															
N.R. reef ass. omnivore															
N.R. reef ass. carnivore															
N.R. reef ass. zoob. feed.															
N.R. reef ass. zoop. feed.															
N.R. sand ass. omnivore															
N.R. sand ass. carnivore															
N.R. sand ass. zooben. feed.															
N.R. seagrass ass. omnivore															
N.R. seagrass ass. carnivore															
N.R. benthopelagic carnivore															
N.R. pelagic zoop. feed.															
Sessile epibenthos													0.00099	0.658	
Photo. corals/sponges	0.002														
Infauna			0.00234							1.2E-05	0.001	0.001		0.00089	
Infaunal bivalves			0.141											0.00089	0.0001
Sessile bivlaves															0.001
Deposit feed. invert.														0.00011	
Small mobile epifauna	0.00099		0.135											0.00011	
Small mobile herbivores		0.0467												1.1E-06	
Large mobile herb. invert	0.02	0.103	0.105											0.00011	
Large mobile carn. invert.														0.01	
Large crabs		0.0234	0.0117												
Cuttlefish		0.0671	0.525												
Squid	0.00094	0.00085	0.00234	0.001											
Octopus		0.00085													
Lobster - post puerulus		0.0654													
Lobster - juvenile															
Lobster - Adolescent														0.000089	
Lobster - adult															
Small gastropods															0.001
Large carn. gastropods															
Large herb. gastropods															
Sea turtles															
Roe abalone															
Small zooplankton				0.418											
Large zooplankton				0.36											
Chaetognaths		0.406													
Carnivorous jellyfish															
Microbial heterotrophs					0.112		0.01	0.01	0.001	0.098	0.086	0.09	0.031		0.00608
Ecklonia											0.001	0.001	0.00013		
Sargassum															
Low algae	0.005									0.00016	0.003	0.003	0.002		0.001
Turfs													0.00099		
Corraline algae											0.01				
Ephemeral seagrasses	0.109			0.01			0.005				0.021	0.042	0.031		0.05
Perenial seagrasses	0.465	0.139					0.019				0.087	0.137	0.08		0.121
Seagrass epiphytes	0.003														
Microphytobenthos					0.146		0.583	0.35	0.173	0.32	0.328	0.295	0.29		
Small phytoplankton						0.00005	0.006	0.005							
Large phytoplankton							9.7E-06		0.00001						
Detached seagrass															
Deatached brown algae															0.001
Detached algae other															
Dead carcasses							0.194								0.161
Bait															
Watercolumn detritus	0.095				0.061	0.7	0.077	0.05	0.01	0.005					
Sediment detritus	0.17			0.211	0.681	0.3	0.106	0.585	0.816	0.577	0.463	0.431	0.564		0.506
Import	0.129	0.138												0.33	0.151
Sum	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Diet composition matrix . Continuation

Prey \ Predator	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62
Dolphins																	
Sea lions																	
Intertidal birds (waders)																	
Surface diving birds																	
Large coastal sharks																	
Small coastal sharks																	
Rays																	
Dhufish																	
Pink snapper																	
Baldchin grouper																	
King wrasse																	
Western fox fish																	
Breaksea cod																	
Inshore reef ass. herbivore																	
Inshore reef ass. omnivore																	
Inshore reef ass. zoob. feed.	0.05																
Inshore sand ass. carnivore																	
Inshore sand ass. omnivore																	
Inshore seagr. ass. omnivore																	
Inshore seagr. ass. zoob. feed.																	
Inshore benthopelagic carn.																	
Inshore pelagic zoop. feed.																	
N.R. reef ass. herbivore																	
N.R. reef ass. omnivore																	
N.R. reef ass. carnivore																	
N.R. reef ass. zoob. feed.	0.018																
N.R. reef ass. zoop. feed.																	
N.R. sand ass. omnivore																	
N.R. sand ass. carnivore																	
N.R. sand ass. zooben. feed.																	
N.R. seagrass ass. omnivore																	
N.R. seagrass ass. carnivore																	
N.R. benthopelagic carnivore																	
N.R. pelagic zoop. feed.		0.000011															
Sessile epibenthos					0.000167	0.000775	0.0864	0.00012	0.003								
Photo. corals/sponges						0.00698											
Infauna		0.002		0.001	0.000755	0.0674	0.0438	0.000961							0.001		
Infaunal bivalves						0.0388	0.0628										
Sessile bivlaves						0.0388	0.0314		0.005								
Deposit feed. invert.																	
Small mobile epifauna				0.011	0.0671	0.0388	0.0942		0.706								
Small mobile herbivores	0.275	0.156			0.0671	0.0388	0.0864		0.212								
Large mobile herb. invert	0.012	0.002	0.581			0.000775	0.00627		0.055								
Large mobile carn. invert.																	
Large crabs	0.312		0.0528			0.216					0.04						
Cuttlefish		0.838	0.0528														
Squid																	
Octopus		0.002										0.00099					
Lobster - post puerulus							0.0376										
Lobster - juvenile			0.0264				0.00785										
Lobster - Adolescent			0.127				0.0393										
Lobster - adult			0.00106														
Small gastropods					0.0875	0.031	0.0595										
Large carn. gastropods						0.00775			0.019								
Large herb. gastropods						0.031											
Sea turtles																	
Roe abalone			0.106														
Small zooplankton														0.533			
Large zooplankton																0.272	
Chaetognaths																0.728	
Carnivorous jellyfish																	
Microbial heterotrophs								0.032							0.074		
Ecklonia								0.00016									
Sargassum								0.002		0.011	0.16	0.00026					
Low algae	0.00025			0.051	0.00755	0.0233	0.0446	0.000961		0.011		0.002					
Turfs										0.00095		0.00099					
Corraline algae				0.351	0.0176	0.0636	0.156			0.104		0.11			0.051		
Ephemeral seagrasses					0.0604	0.0333				0.03	0.16						
Perenial seagrasses				0.104	0.186	0.144	0.112	0.215		0.092	0.32	0.088					
Seagrass epiphytes					0.127	0.144											
Microphytobenthos								0.359									
Small phytoplankton													0.001	0.413			
Large phytoplankton													0.006	0.054			
Detached seagrass																	
Deatached brown algae								0.005		0.02		0.207			0.146		
Detached algae other								0.000961		0.00095		0.011			0.001		
Dead carcasses			0.000394	0.251	0.0838	0.0364		0.335	0.000011	0.076			0.716		0.727		0.7
Bait	0.124		0.0528			0.0388	0.132										
Watercolumn detritus				0.05									0.069				0.3
Sediment detritus				0.181	0.295					0.355		0.446	0.208				
Import	0.209							0.048		0.299	0.32	0.134					
Sum	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

APPENDIX 6. ECOSIM MODEL

METHODS

Ecopath mass-balance models account for trophic interactions among organisms within a defined ecosystem area, averaged over a pre-defined area and time, at multiple trophic levels (Polovina, 1984; Christensen and Pauly, 1992; Christensen *et al*., 2004). The ecosystem components are summarised into a smaller number of functional groups (i.e., species aggregated by trophic similarity) and Ecopath describes the flux of matter and energy into and out of each group. The human influence on the ecosystem, such as fishing, can be represented in the model.

Ecopath uses a series of simultaneous linear equations, one for each functional group, to quantify the energetic flows among trophic groups according to the law of conservation of mass or energy. The main Ecopath equations are presented in Appendix 5. The net production of a functional group equals the total mass removed by its predators and fisheries plus its net migration and its energy or mass that flows to detritus.

Under the assumption of mass-balance, Ecopath can estimate missing parameters, which allows modellers to select their inputs. Ecopath uses the constraint of mass-balance to infer qualities of unsure ecosystem components based on our knowledge of well-understood groups. Four categories of data are required for each functional group: biomass (in $t \cdot km^{-2}$); the ratio of production over biomass (P/B; in yr^{-1}); the ratio of consumption over biomass (Q/B; in yr^{-1}); and ecotrophic efficiency (EE; unitless). Ecopath also provides an input field representing the ratio of production over consumption (P/Q; unitless), which alternatively, users may use to infer either P/B or Q/B (Christensen and Pauly, 1992; Christensen *et al*., 2000 - see Christensen *et al.,* 2004, for a detailed description of Ecopath data requirements).

Because of the enormous amount of differentiation in life-history, morphology and feeding guilds in the limestone reef fish families of the region, delineating functional groups by fish family is impractical and may be unwise. Most of the functional groups developed in our model were based on the functional role that the fishes play in the ecosystem, with additional groups defined to represent species of particular commercial, social and ecological significance. The functional groups for the Jurien model were defined during three workshops with marine scientists, modellers, fisheries and conservation managers and fishers.

As mentioned in Appendix 5, the model contains 80 functional groups, including fishery discards and non-living groups such as detached seagrass, detached brown algae, detached algae (others), dead carcasses, water column sediments and organic detritus. The model also represents marine mammals, sea birds, commercial and non-commercial invertebrates and plants. The 211 fish and elasmobranch species are represented in the model by 31 groups, where nine groups are inshore restricted (0-20 m), three groups offshore (20-60 m) and the others (19 groups) are non-depth restricted (0-60 m). Most of the species were aggregated into groups or boxes based on similarities in their functional roles (e.g. zooplankton feeders) or biology (e.g. reef-associated herbivores). A number of single species functional groups were defined for species of significance to commercial or recreational fishing fishers (e.g., lobster, Pink Snapper, Dhufish, Baldchin Grouper, Breaksea Cod). Lobster were further subdivided into three ontogenetic groups due to the importance of the species and the fact that lobsters have differing habitat, dietary requirements and experience markedly different levels of fishing mortality at different life stages. Some pre-adult and adult lobsters are likely to move offshore to the spawning grounds (out of the park) at the end of the period spent on the nursery reefs (at 4 or 5 yr of age; Phillips, 1983). This migration across the modelled area boundaries was represented in the model with adjustments to the feeding behaviour of adolescent and adult stages of rock lobster as occurring outside of the marine park by setting 20% of their diets as 'import' in the Ecopath diet composition matrix.

Fourteen gear types for both commercial and recreational fisheries were included in the model based on discussions with experts from the area and representatives from the Department of Fisheries, WA. Eight gear types were selected to represent the commercial fisheries of the region: rock lobster pots, beach seine or haul netting, drop lining, gill netting (set nets), long-lining (set line), traps, haul netting, and abalone fishing. Six recreational gears were included in the model: beach anglers, boat anglers, netting, diving, potting and spear fishing. Most of the commercial fisheries catch data sets used in the model were provided by the Department of Fisheries, Western Australia. The fisheries data included the total catch (kg), gear types and species fished and fishing effort, within each of the relevant 1° fishing blocks (i.e. 60 nm grids) of the region (blocks 3014 and 3015) as recorded in the log-books for the Department of Fisheries in Western Australia. The proportion of the area of Jurien Bay Marine Park in each grid was calculated and used to estimate the catch of each species in the Marine Park from the total catch in the Block. This estimated catch was then assigned to its functional group. Data on the recreational catch for the main finfish and invertebrate species targeted in the marine park (i.e. tailor, mulloway, Pink Snapper, Dhufish, Baldchin groper and black bream) were obtained from the 2006 Recreational Fishing Guide published by Department of Fisheries WA. This information was combined with the 12-month survey of coastal recreational boat fishing between Augusta and Kalbarri on the Western Australia during 1996-97 (Sumner and Wilson, 1999).

Ecosim: Temporal dynamic simulations

Ecosim (Walters *et al.*, 1997) adds temporal dynamics into the Ecopath models. It accounts for the biomass flux between groups using coupled differential equations derived from the first Ecopath master equation (Equation 1). The set of differential equations is solved using the Adams-Bashford integration method by default. Biomass dynamics are described as:

$$\frac{dB_i}{dt} = g_i \sum_j \text{Qji} - \sum_j \text{Qij} + I_i - (M_i + F_i + e_i)B_i \text{ ….. Equation 1}$$

Where dB_i/dt represents the biomass growth rate of group (i) during the interval dt;

g_i represents the net growth efficiency (production/consumption ratio);

Q_{ji} is the consumption of group j by group i

Q_{ij} is the consumption of group i by group j

I_i is the immigration rate;

M_i and F_i are the natural and fishing mortality rates of group (i), respectively;

e_i is the emigration rate.

The principle innovation in Ecosim considers risk-dependant growth by attributing a specific vulnerability term for each predator-prey interaction (Walters *et al.*, 2000). The vulnerability parameter is directly related to the carrying capacity of the system, and it describes the maximum allowable increase in the rate of predation mortality on a given prey (Christensen and Walters, 2004). Variable speed splitting enables Ecosim to simulate the trophic dynamics of both slow and fast growing groups (e.g., whales/plankton) or multi-stanza pools such as the four stages of rock lobster considered in our model. In Ecosim, vulnerabilities (V) are assigned to individual predator/prey relationships, indicating whether the biomass of a group is controlled primarily by predators or prey. In Ecosim, vulnerabilities range from 1 to ∞; when V takes high values ('top down'), a high proportion of the biomass is vulnerable to predation. If V is closer to 1.0 ('bottom up'), prey have the opportunity to find refuge from predators. Initially, the Vs during the fitting process were allocated from 1.0 to 10.0 and the final Vs of each group were set during the tuning of the model with time-series biomass data of rock lobster.

Mixed trophic impact

The mixed trophic impact routine of Ecopath (MTI; Ulanowicz and Puccia, 1989; Christensen *et al.,* 2000) displays the short term indirect and direct trophic impacts of a very small increase in biomass (<10%) on both biomasses and trophic flows of the other functional groups throughout the system. Equation 8 was used to estimate the trophic impacts calculated in the model, where the interaction between the impacting group *i* and the impacted group *j* is described as:

$$MTI_{ij} = DC_{ij} - FC_{j,i}, \text{ ……….Equation 2}$$

Where DC_{ij} is the diet composition term expressing how much the group *j* contributes to the diet of group *i*; and $FC_{j,i}$, is a host composition term that expresses the proportion of predation on *j* that is due to *i* as predator. Thus, the MTI is a product of diet, predation and the biomass of predator and prey populations and does not simply reflect biomass. The magnitude of these impacts therefore should be interpreted in a relative and not an absolute sense. The MTI was used as a diagnostic tool for analysis of the structure and interactions of a steady-state Jurien Bay, and not to predict changes in abundance because these may lead to changes in diet compositions, which can not be accommodated with the mixed trophic impact analysis.

The model was balanced using a series of iterative steps. In virtually all cases, in the first attempt to balance the model, values of the ecotrophic efficiency (EE), the proportion of production that is consumed by predators, exceed 1.0 for some functional groups. During our first attempt to balance the Jurien model, twenty-two of the 80 groups were thermodynamically unbalanced with an average EE for living groups of only (± 1 SD) 22.19 ± 31.09. The model was balanced manually to ensure that changes to the input parameters were kept within biological reasonable limits. The first step was to minimize cannibalism within groups (i.e. large and small sharks, lobster, Dhufish and others) and liberate this energy to other groups (following Christensen *et al.,* 2000). The second step was to reduce the predation on the groups that were out of balance, but maintaining the original values of biomass for groups with local biomass estimates. The last parameter adjusted to achieve mass-balance was the consumption rate, Q/B (consumption / biomass), where changes of less than 10% were applied to those groups out of balance.

Comparisons with other ecosystems

The main ecological attributes in the Ecopath summary statistics of the Jurien Bay model were compared with those from other Ecopath ecosystem models characterized by calcareous and limestone reefs with macroalgae assemblages. These attributes, which contain the main flows, consumptions and ecological indices of the system were total system throughput, sum of all production, proportion of total flux originated from detritus, total biomass (excluding detritus), mean transfer efficiency between trophic levels, calculated net primary production, phytoplankton and zooplankton biomasses, total catches, mean trophic level of the catch, primary production required to sustain the fisheries and gross efficiency (for details of each statistic see Christensen *et al*., 2005).

Setting up Ecosim simulation routine

The following section explains the basic parameter adjustment of the Ecosim model. Figure 6.1 shows the basic set-up table used in the Jurien Bay model.

- Duration of simulation: 20 years was the duration of the Ecosim simulations.
- Integration step (per year): the step size for the integration of biomass in the 'fast' groups. The default is 100 steps per year and it is recommended to stick to it (Christensen and Walters, 2005). This parameter is used to the highest turnover rate.
- Relaxation parameter: It expresses the biomass changes for each integration step. Range for this parameter is [0, 1]. Low values cause slow changes in biomass, high values fast change. For the fisheries scenarios, a value of 0.5 was used (Fig. 6.1)

Other Parameter adjustments (Table 6.1) were made to stabilize the dynamic simulation of the Jurien Bay ecosystem model in order to generate more stable and realistic predictions after 20 years of simulation. This is because groups that were split into juvenile and adult pools (i.e. the four stages of rock lobster included in the model) set up cyclic predator-prey oscillations (Christensen and Walters, 2005).

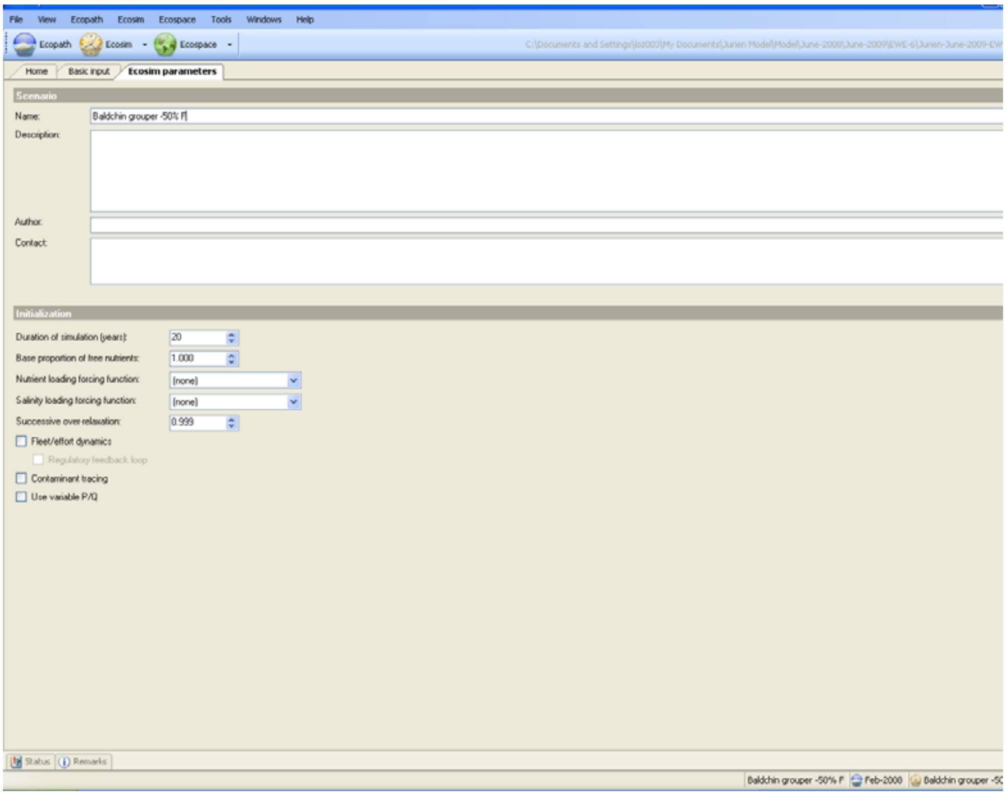


Figure 6.1 Ecosim set-up table.

Adjustments to feeding behaviour parameters allowed simulations without violent structural changes, viz.:

- For sessile organisms such as corals, their 'maximum relative feeding time' was defined as half the default amount set for other groups.
- 'Feeding time adjustment rate factors' for sessile animals and invertebrates with very little movement their feeding time factors were adjusted to 0. Adult and juvenile rock lobster had their feeding time factors set to 1.0 and 0.5, respectively. Other groups had their feeding time factors adjusted to 1.0 except for small zooplankton pelagic fish group (i.e. sardines), which was adjusted to 0.75. The 'fraction of the unexplained predation' for marine mammals, fish-eating seabirds, off-shore fish and adult rock lobster were set to 1.0. Other groups had their fractions of unexplained predation set to 1.0 (default), except for small and large sharks, which were set to 0.5.
- All other feeding behaviour parameters were accepted as suggested by the default values.

Table 6.1 displays the feeding time parameters used in the Ecosim model.

Table 6.1 Adjusted feeding behaviour parameters used for the Jurien Bay Ecosim model.

	Group name	Max rel. P/B	Max rel. feeding time	Feeding time adjust rate [0,1]	Fraction of other mortality sens. to changes in feeding time
1	Dolphins		1.000	1.000	1.000
2	Sea lions		1.000	1.000	1.000
3	Intertidal birds		1.000	1.000	1.000
4	Surface diving birds		1.000	1.000	1.000
5	Large coastal sharks		1.000	1.000	0.500
6	Small coastal sharks		1.000	1.000	0.500
7	Rays		1.500	1.000	1.000
8	Dhufish		1.000	1.000	1.000
9	Pink snapper		1.000	1.000	1.000
10	Baldchin grouper		1.000	1.000	1.000
11	King wrasse		1.000	1.000	1.000
12	Western foxfish		1.000	1.000	1.000
13	Breaksea cod		1.000	0.500	1.000
14	Inshore reef ass. herbi		1.000	1.000	1.000
15	Inshore reef ass. omni		1.000	1.000	1.000
16	Inshore reef ass. zoob		1.000	1.000	1.000
17	Inshore ass. carnivore		1.000	1.000	1.000
18	Inshore sand ass. omn		1.000	1.000	1.000
19	Inshore seagrass ass.		1.000	1.000	1.000
20	Inshore seagrass ass.		1.000	1.000	1.000
21	Inshore benthopelagic		1.000	1.000	1.000
22	Inshore pelagic zoopla		1.000	1.000	1.000
23	NDR reef ass. herbivor		1.000	1.000	1.000
24	NDR reef ass. omnivor		1.000	1.000	1.000
25	NDR reef ass. carnivor		1.000	1.000	1.000
26	NDR reef ass. zoobent		1.000	1.000	1.000
27	NDR reef aa. zooplank		1.000	1.000	1.000
28	NDR sand ass. omniv		1.000	1.000	1.000
29	NDR sand ass. carniv		1.000	1.000	1.000
30	NDR sand ass. zoobe		1.000	1.000	1.000
31	NDR seagrass ass. o		1.000	1.000	1.000
32	NDR seagrass ass. ca		1.000	1.000	1.000
33	NDR benthopelagic ca		1.000	1.000	1.000
34	NDR pelagic zooplankt		0.750	1.000	1.000

	Group name	Max rel. P/B	Max rel. feeding time	Feeding time adjust rate [0,1]	Fraction of other mortality sens. to changes in feeding time
29	NDR sand ass. carniv		1.000	1.000	1.000
30	NDR sand ass. zoobe		1.000	1.000	1.000
31	NDR seagrass ass. o		1.000	1.000	1.000
32	NDR seagrass ass. ca		1.000	1.000	1.000
33	NDR benthopelagic ca		1.000	1.000	1.000
34	NDR pelagic zooplankt		0.750	1.000	1.000
35	Sessile epibenthos		0.000	0.500	1.000
36	Photo. corals/sponges		1.000	0.500	1.000
37	Infauna		1.000	0.500	1.000
38	Infaunal bivalves		0.000	0.500	1.000
39	Sessile bivalves		0.000	0.500	1.000
40	Deposit feed. invert.		0.000	0.500	1.000
41	Small mobil epifauna		1.000	0.500	1.000
42	Small mobile herbivore		1.000	0.500	1.000
43	Large mobile herb. inv		2.000	0.500	1.000
44	Large mobile carn. inv		2.000	0.500	1.000
45	Large Crabs		2.000	0.500	1.000
46	Cuttlefish		2.000	0.500	1.000
47	Squid		2.000	0.500	1.000
48	Octopus		2.000	0.500	1.000
49	Lobster-post puerulus		2.000	0.500	1.000
50	Lobster- Juvenile		2.000	0.500	1.000
51	Lobster - Adolescent		1.000	0.500	1.000
52	Lobster Adult		0.500	0.500	1.000
53	Small Gastropods		2.000	0.500	1.000
54	Large Carn. Gastropo		2.000	0.500	1.000
55	Large Herb. Gastropo		2.000	0.500	1.000
56	Sea turtles		2.000	0.500	1.000
57	Roe abalone		2.000	0.500	1.000
58	Small Zooplankton		2.000	0.500	1.000
59	Large Zooplankton		2.000	0.500	1.000
60	Chaetognaths		2.000	0.500	1.000
61	Carnivorous Jellyfish		2.000	0.500	1.000
62	Microbial heterotrophs		2.000	0.500	1.000

APPENDIX 7. Ecospace Methods

METHODS

The Jurien Bay Ecospace model comprises the entire marine park (823 km^2). This ecosystem is represented by a grid of 6,000 cells (100 x 100 cells). The Ecospace habitat base map (Fig. 7.1) was designed based on the detailed marine biological survey carried by Burt and Anderton (1997) over 60 km of coastline off the central west coast of Western Australia, from Cervantes to Green Head. Consequently, it does not include the entire Jurien Bay Marine Park, but we assume that results for the northern sector of the park will apply in principal to the park as a whole. Using this comprehensive survey, it was possible to include the eight major habitat types within the marine park:

1. Bare sand with sparse seagrass
2. Seagrass interspersed with sand patches and some reef <10 m depth
3. Seagrass interspersed with sand patches and some reef >10 m depth
4. Seagrass meadow
5. Limestone pavement with some macroalgal cover, interspersed with patches of sand and seagrass
6. Shallow reef platform: Limestone pavement interspersed with patches of sand and seagrass
7. Subtidal reef with predominantly macroalgal cover interspersed with sand patches.
8. Deep zone >30 m

In addition to the eight habitat types considered in the model, three types of protected areas were included in the zoning map (Fig. 7.1). These zones or protected areas were defined in the Jurien Bay Marine Plan Number 49 (CALM, 2006) and are:

1. Sanctuary Zone (no commercial/recreational fishing allowed).
2. Scientific Reference Zone (Commercial lobster fishing and some recreational fisheries allowed e.g. shore-based fishing including line fishing and abalone).
3. Puerulus Monitoring Zone (only recreational line fishing allowed).
4. The remainder of the park is General Purpose Zone where all legal forms of fishing are allowed.

The area of Sanctuary Zones and Special Purpose Zones (Scientific Reference) included in the model are summarised in Table 7.1.

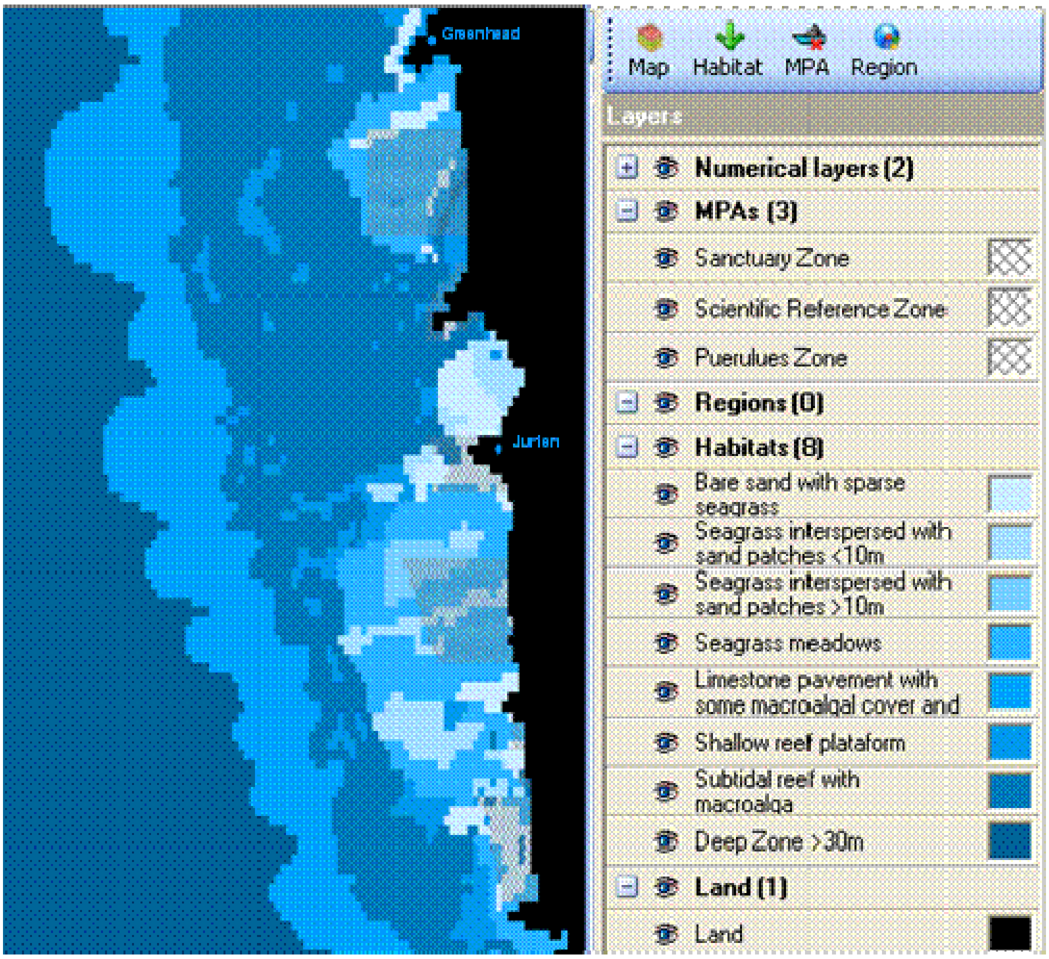


Figure 7.1 Ecospace basemap of the Jurien Bay Marine Park showing the eight major habitats and management zones (right) considered in the model.

Table 7.1 Zones in the Jurien Bay Marine Park included in the Ecospace model of Jurien Bay Marine Park.

Zone and Name	Area (ha)	% of the Marine Park
Sanctuary		
Fisherman Islands	473	0.57
North Head	204	0.24
Pumpkin hollow	99	0.12
Boullanger Island	1 334	1.61
Nambung Bay	215	0.26
Cavanagh	261	0.31
Grey	259	0.31
Target Rock	198	0.24
Wedge Island	11	0.01
Sub-total Sanctuaries	3 061	3.71
Scientific reference		
Fisherman Island	2 266	2.75
Hill River	4 190	5.08
Green Islands	7 582	9.2
Sub-total Scientific references	14 037	17.1
Puerulus monitoring	57	0.06
General use	63 742	77.3
Total area represented in the model	80 891	97.2
Zones not represented in the model: Aquaculture and Shore based-activities.	15 231	2.8

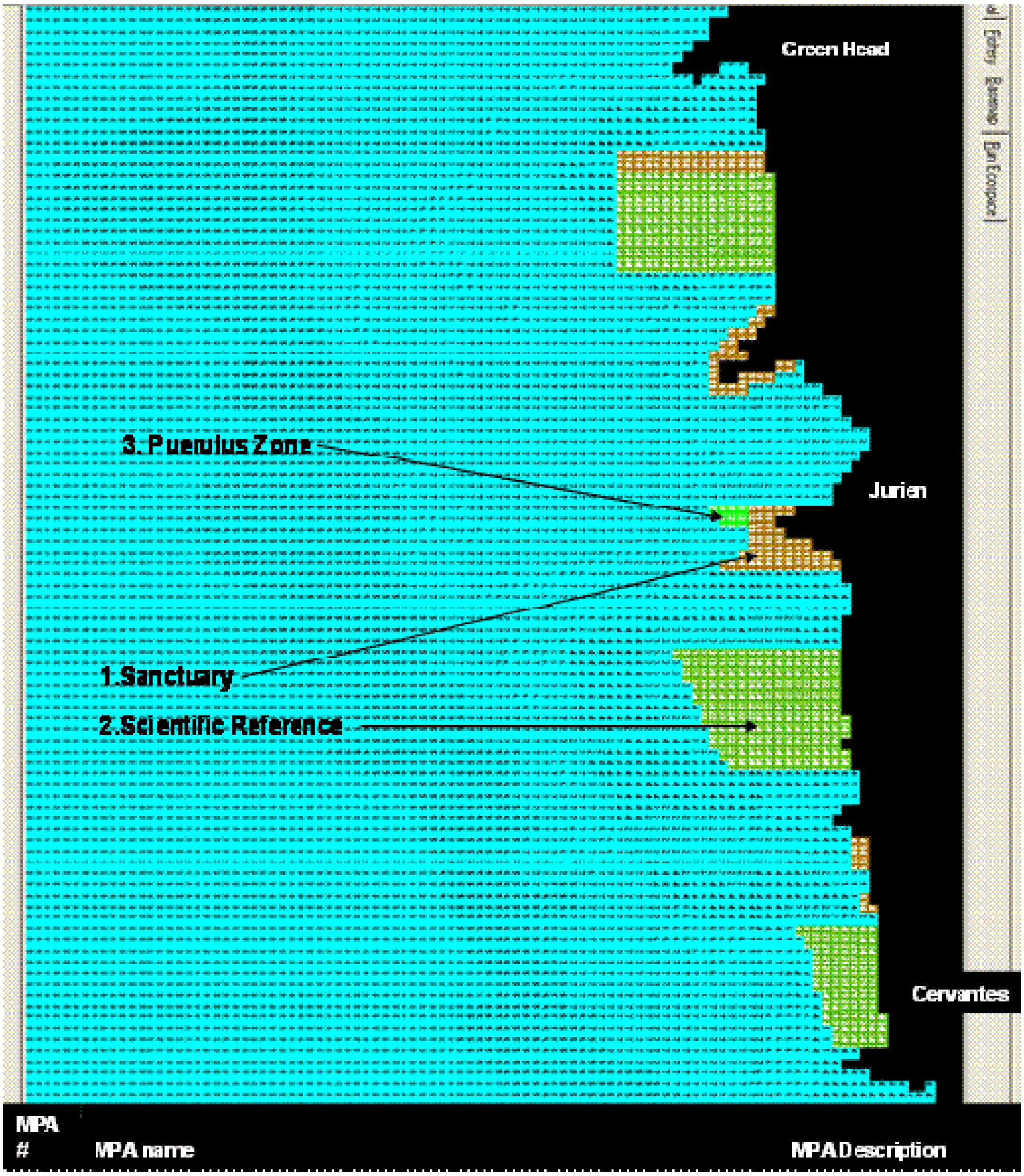


Figure 7.2 Ecospace basemap of the Jurien Bay Marine Park showing the three main management zones considered in the model: sanctuary zones (covering around 4%); scientific reference zone (covering 22%) and puerulus monitoring zone (covering less than 1% of the marine park).

Habitat assignment

Once habitats have been defined, the functional groups defined in the Ecopath model must be assigned to their 'preferred' habitat. 'preferred' here means that the group in question has a higher feeding rates in the habitat and its survival rate in also higher here (because the predation rate is higher in non-preferred habitat). The habitat assignment was based on the 1997 field survey carried out as part of the CALM's Marine Reserve Implementation Program and coordinated by the Marine conservation Branch of CALM undertaken in the waters of Jurien Bay. This comprehensive biological survey of flora and fauna was reported by Burt and Anderton (1997). The habitat assignment of the functional groups considered in the model is presented in Table 7.2. This spatial distribution was presented to researchers of Department of Fisheries, WA and other experts of the region in September, 2009 (steering committee meeting held in Department of fisheries, Hillarys, WA) in order to incorporate additional expert knowledge.

Biomass distribution predicted by the model

The first step in the spatial modeling was to assign the ‘preferred’ habitat to each of the eighty functional groups of the Ecopath model. ‘Preferred’ here means that the group in question has a higher feeding rates in the habitat and its survival rate in also higher here (because the predation rate is higher in non-preferred habitat). The habitat map was based on the 1997 field survey carried out as part of the CALM’s Marine Reserve Implementation Programme and coordinated by the Marine conservation Branch of CALM undertaken in the waters of Jurien Bay. This comprehensive biological survey of flora and fauna was reported by Burt and Anderton (1997). The preliminary habitat assignment and base dispersal rates of the functional groups considered in the model is presented in Table 7.2.

Spatial Representation of Fisheries

In the case of the fishing gears in Ecospace, the model uses multiple fishing fleets, and fishing mortality rates (F) included in the Ecopath model. In Ecospace the F’s are distributed using a simple ‘gravity model’, where the proportion of the total fishing effort allocated to each cell is assumed to be proportional to the sum over groups of the product of the biomass, as well as the catchability and profitability of fishing the target groups (Christensen *et al.*, 2005). The Ecospace model considered the 14 fishing gears included in the Ecopath model and their preliminary spatial distribution within the marine park is presented in Table 7.3.

Table 7.2 Preliminary habitat assignment, base dispersal rates, advection and migration of the functional groups in the Ecospace model. Habitats are represented as follow: Sa (Bare sand with sparse seagrass); SeR < 10 m (seagrass intersperse with sand patched and some reef < 10 m depth); SeR > 10 m (seagrass intersperse with sand patched and some reef >10 m depth); Se (seagrass); LiMa (Limerstone pavement with some macroalgal cover, interspersed with patches of sand and seagrass); Re (shallow reef platform); SubRe (Subtidal reef with predominantly macroalgal cover interspersed with sand patches); Deep Zone > 30 m (this habitat was not considered in the simulations, just included to define boundaries of the marine park). The NDR in the functional groups refers to 'Non Depth Restricted'.

Group \ Habitat #	Sa	SeR<10m	SeR>10m	Se	LiMa	Re	SubRe	Base dispersal rate (km· year^{-1})	Advected	Migrating
Dolphins	+	+	+	+	+	+	+	300		+
Sea lions	+	+	+	+	+	+	+	300		
Intertidal birds	+	+						30		
Surface diving birds	+	+	+	+	+	+	+	300		
Large coastal sharks	+	+	+	+	+	+	+	300		+
Small coastal sharks	+	+	+	+	+	+	+	300		
Rays	+	+	+	+	+	+	+	3		
Dhufish					+	+	+	3		
Pink snapper		+	+	+		+	+	30		
Balchin grouper		+	+	+		+	+	3		
King wrasse					+	+	+	1		
Western foxfish					+	+	+	1		
Breaksea cod					+	+	+	1		
Inshore reef ass. herbivore						+	+	3		
Inshore reef ass. omnivore						+	+	3		
Inshore reef ass. zoobenthos feed.						+	+	3		
Inshore ass. carnivore	+	+	+	+		+	+	3		
Inshore sand ass. omnivore	+							3		
Inshore seagrass ass. omnivore		+	+	+				3		
Inshore seagrass ass. zoob. feed.		+	+	+				3		
Inshore benthopelagic carnivore	+	+	+	+		+	+	30		
Inshore pelagic zooplankton feed	+	+	+	+		+	+	30		
*NDR reef ass. herbivore					+	+	+	3		
NDR reef ass. omnivore					+	+	+	3		
NDR reef ass. carnivore					+	+	+	3		
NDR reef ass. zoobenthos feed.					+	+	+	3		
NDR reef aa. zooplankton feed					+	+	+	30		
NDR sand ass. omnivore	+							3		
NDR sand ass. carnivore	+							3		
NDR sand ass. zoobenthos feed.	+							3		
NDR seagrass ass. omnivore		+	+	+				3		
NDR seagrass ass. carnivore		+	+	+				3		
NDR benthopelagic carnivore	+	+	+	+	+	+	+	3		
NDR pelagic zooplankton Feed.	+	+	+	+	+	+	+	30		
Sessile epibenthos					+	+	+	0		
Photo. corals/sponges						+	+	0		
Infauna	+	+	+	+				3		

Table 7.3 Preliminary spatial distribution of the 14 fishing gears settings for the Ecospace model of Jurien Bay Marine Park. Deep zone (>30 m depth is not included in the model and this habitat was used only to define the boundaries of the marine park).

Fishing Gear	Sa	SeR<10m	SeR>10m	Se	LiMa	Re	SubRe	Deep Zone >30m
Rock lobster						x	x	
Beach Seine	x	x		x		x	x	
Droplinning	x	x	x	x	x	x	x	
Gill Netting	x	x	x	x	x			
Handlinning	x	x	x	x		x	x	
Longlinning	x	x	x	x	x	x	x	
Traps						x	x	
Abalone	x							
Rec. Pots						x	x	
Rec. Beach Anglers	x	x						
Rec. Boat Anglers	x	x	x	x	x	x	x	
Rec. Netting	x	x	x	x	x			
Rec. Diving						x	x	
Rec. Spearfishing						x	x	

Sa	Bare sand with sparse seagrass
SeR<10m	Seagrass intersperse with sand patched and some reef <10m depth
SeR>10m	Seagrass intersperse with sand patched and some reef >10m depth
Se	Seagrass meadow
LiMa	Limestone pavement with some macroalgal cover, interspersed with patches of sand and seagrass
Re	Shallow reef plataform
SubRe	Subtidal reef with predominantly macroalgal cover interspersed with sand patches

Dispersal rates

Each of the groups and species considered in the Ecopath model has an aggregated biomass (B_i) and they are not assumed to move within the Ecopath Jurien Bay Marine Park. In Ecospace, however, a fraction of the biomass (B') of each cell is always on the move, according to

$$B' = m \cdot B_i$$

With m having the dimension of length/ time (i.e. km/year) i.e., a velocity or 'speed'. However, m is not a rate of directional migration, as occurs seasonally in numerous fish populations. Rather, m should be regarded as dispersal and seen as the rate (km year^{-1}) of which the organism would disperse from a given ecosystem as a result of random movements (Christensen *et al.*, 2005). As for the absolute value of m to be used in the simulation, we used a default value of 300 km year^{-1} (recommended by Christensen *et al.,* 2005) for all groups with high/medium motion activity (fish groups) and we used a default value of 3 km year^{-1} (Christensen *et al.,* 2005) for those groups with very low motion (sessile groups and non-living groups).

Lobster movement – One of the comments from the September, 2009 steering was regarding movements of rock lobster mentioning that undersized lobsters that are displaced during fishing may move around more than lobsters that are left in place. We agreed with this comment and it was explained that the dispersal rate for adult rock lobsters was estimated based on movement studies using tagged lobsters in WA, where it was showed that they travelled around 50-100 m·day^{-1} (McArthur *et al.,* 2009) . Therefore, we have allowed a movement rate in the model of 3 km·year^{-1}(~8 m·day^{-1}). For Pink Snapper, an average movement rate of 30 km·year^{-1} (~80 m·day^{-1}). For Dhufish, based on its sedentary behaviour, the rate was estimated as 10 km·year^{-1} (~30 m·day^{-1}). The movement rates in the model were revised by experts from CSIRO (Russ Babcock and Matt Vanderklift and Chris Wilcox).

Migration and Advection

In order to represent the migration patterns of key groups in the model such as rock lobster, migration movements were incorporated in the Ecospace model. Those migrating groups considered in the model are displayed in Table 7.4. Also, due to the nature of the plankton groups, it was necessary to incorporate advection movements into the model. Advected groups in the Ecospace model are also presented in Table 7.4.

Ecospace Spatial Management Scenarios

Three different fishing closure areas within the marine park were simulated individually for the rock lobster (Table 7.5). The first scenario involves the current protection of 4% of sanctuaries; the second scenario included an increment of the no-take areas from 4% to 25% of the total area of the park. The third scenario was conducted after removing all the sanctuaries from the model and all areas are open to fishing i.e. no-take areas = 0%. It should be noted that currently, in Scientific Reference Zones, only lobster fishing and recreational fishing from shore are permitted (18% of the park) so some fish have an effective 22% of the park in no-take areas. To assess the possible effects of the simulated sanctuaries, we conducted 20-year simulations starting with biomass, landing rates, fishing mortalities and effort from the Jurien Bay Ecopath model of 2007 baseline. In the case of finfish groups, only scenario number one (no closures) and three (25% closure) are presented in this report. Fishing effort for each of the thirteen fishing gears included in the Ecospace model (Table 7.6) was held constant during the simulations. The results investigated in these analyses were the biomass and catch for the final year of the simulation. Figure 7.3 shows how these different fishing closures were incorporated into the model, displaying a 33% and 50% of no-take areas within the park.

Table 7.4 Preliminary habitat assignment, base dispersal rates, advection and migration of the functional groups in the Ecospace model. Habitats are represented as follow: Sa (Bare sand with sparse seagrass); SeR < 10 m (seagrass intersperse with sand patched and some reef < 10 m depth); SeR > 10m (seagrass intersperse with sand patched and some reef >10 m depth); Se (seagrass); LiMa (Limerstone pavement with some macroalgal cover, interspersed with patches of sand and seagrass); Re (shallow reef platform); SubRe (Subtidal reef with predominantly macroalgal cover interspersed with sand patches); Deep Zone > 30 m (this habitat was not considered in the simulations, just included to define boundaries of the marine park). The NDR in the functional groups refers to 'Non Depth Restricted'.

Group \ Habitat #	Sa	SeR<10m	SeR>10m	Se	LiMa	Re	SubRe	Base dispersal rate (km· year^{-1})	Advected	Migrating
Dolphins	+	+	+	+	+	+	+	300		+
Sea lions	+	+	+	+	+	+	+	300		
Intertidal birds	+	+						30		
Surface diving birds	+	+	+	+	+	+	+	300		
Large coastal sharks	+	+	+	+	+	+	+	300		+
Small coastal sharks	+	+	+	+	+	+	+	300		
Rays	+	+	+	+	+	+	+	3		
Dhufish					+	+	+	3		
Pink snapper		+	+	+		+	+	30		
Balchin grouper		+	+	+		+	+	3		
King wrasse					+	+	+	1		
Western foxfish					+	+	+	1		
Breaksea cod					+	+	+	1		
Inshore reef ass. herbivore						+	+	3		
Inshore reef ass. omnivore						+	+	3		
Inshore reef ass. zoobenthos feed.						+	+	3		
Inshore ass. carnivore	+	+	+	+		+	+	3		
Inshore sand ass. omnivore	+							3		
Inshore seagrass ass. omnivore		+	+	+				3		
Inshore seagrass ass. zoob. feed.		+	+	+				3		
Inshore benthopelagic carnivore	+	+	+	+		+	+	30		
Inshore pelagic zooplankton feed	+	+	+	+		+	+	30		
*NDR reef ass. herbivore					+	+	+	3		
NDR reef ass. omnivore					+	+	+	3		
NDR reef ass. carnivore					+	+	+	3		
NDR reef ass. zoobenthos feed.					+	+	+	3		
NDR reef aa. zooplankton feed					+	+	+	30		
NDR sand ass. omnivore	+							3		
NDR sand ass. carnivore	+							3		
NDR sand ass. zoobenthos feed.	+							3		
NDR seagrass ass. omnivore		+	+	+				3		
NDR seagrass ass. carnivore		+	+	+				3		
NDR benthopelagic carnivore	+	+	+	+	+	+	+	3		
NDR pelagic zooplankton Feed.	+	+	+	+	+	+	+	30		
Sessile epibenthos					+	+	+	0		
Photo. corals/sponges						+	+	0		
Infauna	+	+	+	+				3		

Table 7.5. Preliminary spatial distribution of the 14 fishing gears settings for the Ecospace model of Jurien Bay Marine Park. Deep zone (>30 m depth is not included in the model and this habitat was used only to define the boundaries of the marine park).

Fishing Gear	Sa	SeR<10m	SeR>10m	Se	LiMa	Re	SubRe	Deep Zone >30m
Rock lobster						x	x	
Beach Seine	x	x		x		x	x	
Droplinning	x	x	x	x	x	x	x	
Gill Netting	x	x	x	x	x			
Handlinning	x	x	x	x		x	x	
Longlinning	x	x	x	x	x	x	x	
Traps						x	x	
Abalone	x							
Rec. Pots						x	x	
Rec. Beach Anglers	x	x						
Rec. Boat Anglers	x	x	x	x	x	x	x	
Rec. Netting	x	x	x	x	x			
Rec. Diving						x	x	
Rec. Spearfishing						x	x	

Sa	Bare sand with sparse seagrass
SeR<10m	Seagrass intersperse with sand patched and some reef <10m depth
SeR>10m	Seagrass intersperse with sand patched and some reef >10m depth
Se	Seagrass meadow
LiMa	Limestone pavement with some macroalgal cover, interspersed with patches of sand and seagrass
Re	Shallow reef plataform
SubRe	Subtidal reef with predominantly macroalgal cover interspersed with sand patches

Table 7.6 Five different fishing closures areas (no-take areas) within the Jurien Bay Marine Park simulated individually for rock lobster and commercial finfish groups in the Ecospace model.

	Percentage of No-take areas				
Scenario	1	2	3	4	5
Rock lobster (adult) and finfish groups	None	4% (current)	25%	33%	50%

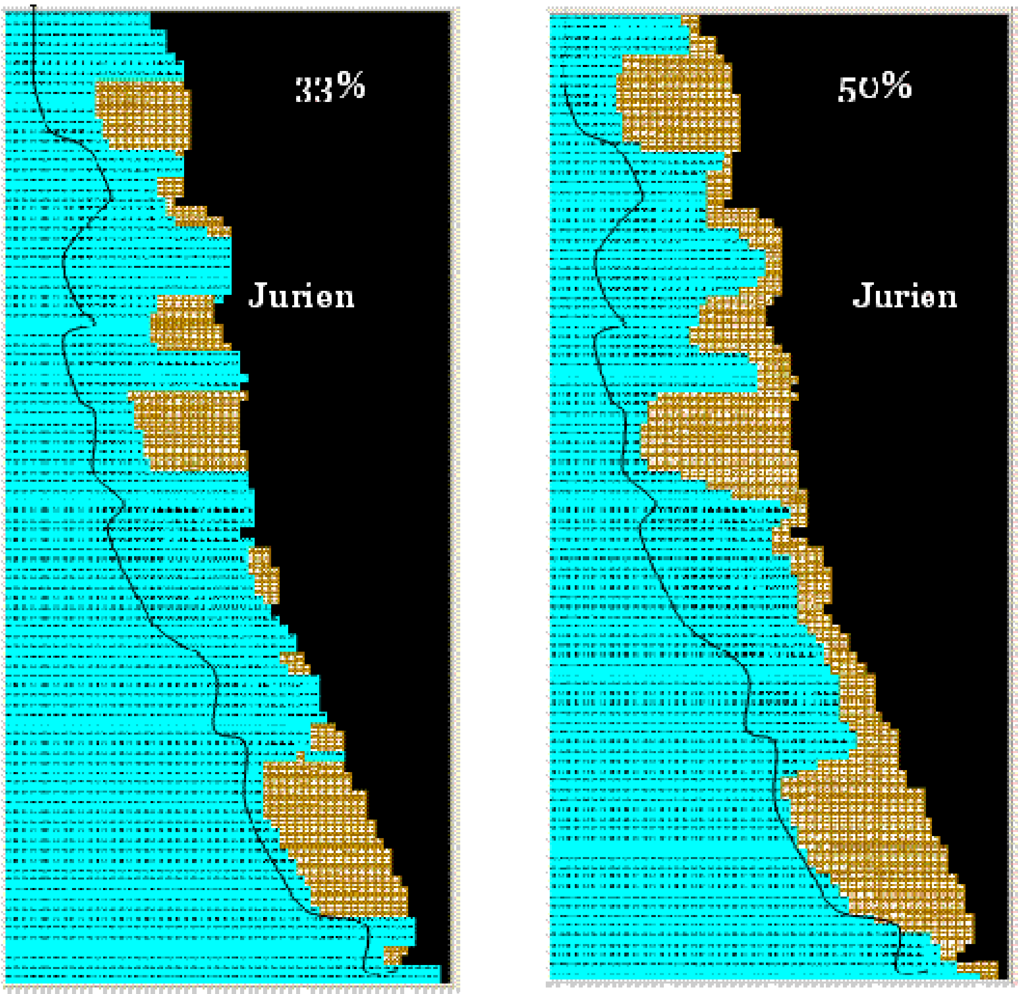


Figure 7.3 Representation of two fishing closure areas in the Jurien Bay Ecospace model. 33% no-take area (left panel) and 50% no-take area (right panel). No fishing for Western Rock Lobster and finfish is allowed within the brown areas (sanctuaries). See text for the other three scenarios simulated.

Summary of key points from the seminar presented in October 20th, 2009 (WA Fisheries and Marine Research Laboratories, Hillarys).

Summary

The results from the quantitative ecosystem modelling of the Jurien Bay Marine Park were presented in a seminar/workshop discussion group at the Department of Fisheries, Research Laboratories on October 14th 2009. The purpose of the meeting was to present feedback on the Ecosim scenarios developed from a meeting of the Steering Committee in July 2008. New results from Ecospace were also presented as well as interviews of fishers, and feedback from the meeting, was used to revise the models in preparation for the Final Report of the project by January 2010. In this summary document from the meeting, we have summarised each of the components presented and provided information on the results from simulating the effects of climate change that were not discussed at the workshop. We have also summarised the discussion from the workshop and indicated how we will take into account the comments from the workshop.

Actions from the workshop are to:

1. Ecosim scenario – change the introduction of the closure from being spread out over 20 years to being introduced over three years.

2. Ecospace – the dispersal rates of Ecospace are under revision by CSIRO experts, e.g. Matt Vanderklift (Benthic ecology; Floreat) and Chris Wilcox (Spatial Dynamic Team, Hobart). Also, it has been planned a series of meeting with other experts from DoF such as Corey Wakefield, David Fairclough, Alex Hesp and Jeremy Prince to tune these movement rates.

3. Ecospace - the results of the Ecospace predictions on biomass of lobster and finfish will be checked through face to face meetings with David Fairclough (Finfish – DoF) and Lachlan McArthur/ (ECU – lobster) and other DoF staff.

4. Local fisher knowledge and building the 1980 Ecopath model – The Department of Fisheries has data in voluntary logbooks and from observers on commercial vessels that may be helpful in looking at the distribution of biomass of lobsters in the past and for the LFK analysis (cross-validation of the relative abundance trends for the last 10-15 years).

5. Further discussions of the model – separate meetings will be arranged with a number of groups (DoF, DEC and Jurien Bay Marine Park Advisory Group) to allow fuller consideration of the model results.

6. Handover of the model – it is planned to provide copies of the model to DoF and DEC and lodge the models on the Ecopath web site (www.ecopath.org). The handover will be discussed with DoF and DEC staff.

Questions and discussion points from the models:

1. **Rock lobster fishing mortality**: Following the meeting, it was felt that simulating the 2008/09 reductions in lobster fishing would be valuable. This was an immediate reduction in the number of pots and the days that could be fished – for the whole fishery it has been estimated that the pot lifts were reduced from about 10 million per season to 4 million per season – this may not translate to a direct 60% reduction in F as the catchability of pots may increase as the saturation of pots is reduced. Figures on pot reductions and relationship to a reduction in F on lobster would need to be checked with Nick Caputi. (WA DoF)

2. Questions regarding Ecopath and Ecosim models:

a) Where do the parameters come from?

This is explained in detail in both the paper submitted to Marine and Fresh Water Research and the draft of the final Milestone Report.

b) What is the effect of inputs on estimated parameters (and their quality)?

The pedigree index (P) built in Ecopath was explained as a first step to measure the amount of local data (i.e. minor uncertainty in the inputs) among the five major categories of the model: biomass, mortality, consumption, diets and catch. The pedigree of an Ecopath input represents the coded statement categorizing the origin of a given input (i.e., the type of data on which it is base), specifying the likely uncertainty associated with the input. There is a pre-defined table in Ecopath for each type of input parameters (Table 7.6). The key criterion used in the model was that input estimated from local data (i.e. fish abundance using underwater visual census) as a rule is better than date from elsewhere, be it guesstimate, derived from empirical relationships or derived from other Ecopath models.

Table 7.6 'Pedigree' index used in the model to describe data origin and assigning confidence intervals based on the origin (*c.i.*) of the four major categories of input parameters of the

model: biomass (B), production/biomass (P/B) and consumption ratios (Q/B); diet composition and catches.

	Parameter: Biomass	**Index**	**Default *c.i,*** (+/- %)
1	'Missing' parameter (estimated by Ecopath)	0.0	n.a.
2	From other model	0.0	80
3	Guesstimates	0.0	80
4	Approximate or indirect method	0.4	50-80
5	Sampling based, low precision	0.7	40
6	Sampling based, high precision	1.0	10
	Parameter: P/B and Q/B		
1	'Missing' parameter (estimated by Ecopath)	0.0	n.a.
2	From other model	0.1	90
3	Guesstimates	0.2	80
4	Empirical relationships	0.5	50
5	Similar group/species, similar system	0.6	40
6	Similar group/species, same system	0.7	30
7	Same group/species, similar system	0.8	20
8	Same group/species, same system	1.0	10
	Parameter: Diets		
1	General knowledge of related group/species	0.0	80
2	From other model	0.0	80
3	General knowledge of same group/species	0.2	80
4	Qualitative diet composition	0.5	50
5	Quantitative, but limited diet composition	0.7	40
6	Quantitative, detailed diet composition	1.0	30
	Parameter: Catches		
1	Guesstimates	0.0	>80
2	From other model	0.0	>80
3	FAO statistics	0.2	80
4	National statistics	0.5	50
5	Local study, low precision/incomplete	0.7	30
6	Local study, high precision/complete	1.0	10

The range of P is from 0 for no data coming from the location to 1.0 for all data coming from the location. The pedigree Index for Jurien Bay model was 0.7 and it was calculated using the following expression:

$$P = \sum_{i=1}^{n} \frac{I_{ij}}{n}$$

Where I_{ij} is the pedigree index value for group *I* and parameter *j* for each of the living groups in the ecosystem; *j* can represent either B, P/B, Q/B and Y or diet.

c. How does the model deal with recruitment variability?

In the model, a compensatory recruitment effects are only represented for rock lobster through the 'split pool' representation of the four stages: four stages: post-puerulus, juvenile and adolescent stages. Recruitment is expressed as a flat or dome-shape relationship between numbers of juveniles recruiting to the adult pool versus parental abundance (stock recruitment relation). The mechanism to create this effect in the model is basically to use non-zero feeding time adjustment for the juvenile pool in the Ecopath model (a value of 2.0 was used) combined with fixed time in juvenile stage and high ecotrophic efficiency (a value of 0.95 used, where 1.0 is the maximum theoretical value) being sensitive to changes in predator feeding. This setup allows us to represent density-dependent changes in juvenile mortality rates of the four stages associated with changes in feeding time and predation risk.

In addition, there is a compensation in recruitment considered in the model. Basically, the four stages of rock lobster biomasses allow us to represent in Ecosim, the trophic ontogeny (differential diets for post-puerulus, juvenile, adolescent, and adult stages). To describe these dynamics of split-pool populations, the Ecosim parameters. For rock lobster (the only split pool in the model), the stages were set to produce an 'emergent' stock-recruitment relationship with a strong compensatory increase in juvenile survival rate as adult lobsters (spawning stock) decline (otherwise less eggs would mean less recruits on average, no matter how variable the survival rate might be). The setting of the split pool parameters for rock lobster (Table 7.7) were defined during the first workshop of Jurien Bay (2006) and incorporated into the Ecopath input parameters. In order to get a compensatory mortality changes in the model, the mortality rate of juvenile group was set relatively high and the adolescent group has a small proportion of the mortality accounted for fishery effects. Given these Ecopath conditions, Ecosim can simulate direct (as opposed to just predator-prey) compensatory changes in juvenile recruitment through three alternative mechanisms or hypothesis:

1) Simple density-dependence in juvenile production rate by adults, due to changes in adult feeding rates.
2) Changes in duration of the juvenile stage and hence in total time exposed to relatively high predation risk
3) Changes in juvenile foraging time (and hence exposure to predation risk) with changes in juvenile feeding rates.

Table 7.7 Input parameters of the four stages of rock lobster in the Ecopath model. These input parameters were defined to simulate a compensation for the recruitment relationship in the model (see text above for details).

Rock lobster	Biomass (tonnes· km^{-2})	Mortality (P/B; year^{-1})	Consumption (Q/B; year^{-1})
post-puerulus	5.9	2.7	28.5
juvenile	23.5	1.6	5.7
adolescent	10.3	1.2	4.3
adults	1.1	2.1	4.0

d. How does the model deal with variation in prey species?

Changes in variation of species or groups in the trophic model as result of a reduction of stock size by natural causes (i.e. climate change) or fishing can be represented in the model through a variety of specific hypothesis about compensatory mechanisms. In general, these mechanisms are divided into two categories:

a) Direct: with changes caused over short time scales (one year) by changes in behaviour of organisms, whether or not there is an ecosystem-scale change due to the nature of change.
b) Indirect: with changes over longer time due to ecosystem-scale responses such as increased prey densities and/or reduced predator densities.

3. **Questions regarding Ecospace**:

a) **Concerns of dispersal rates effect on the model.**

In the model, the dispersal rate (*m*) is not a direct migration; rather, it should be regarded as the rate (km · year^{-1}) the organism would disperse as result of random movements. In the model, the aggregated biomass (B_i) of each group/species is assumed to move within the area covered by the model. A fraction of the biomass (B') of each cell in the map is always on the move, wherein

$$B' = m\ B_i$$

with m having the dimension of length/time (km · year^{-1}) i.e. a velocity or 'speed'. The default value of *m* in the model is 300km/year

Lobster movement – One of the comments regarding movements in the model was that undersized lobsters that are displaced during fishing may move around more than lobsters that are left in place. We agreed with this comment and it was explained that the dispersal rate for adult rock lobsters was estimated based on movement studies using tagged lobsters in WA, where it was showed that they travelled around 50-100 m·day^{-1}(McArthur *et al.,* 2009) . Therefore, we have allowed a movement rate in the model of 3 km·year^{-1}(~8 m·day^{-1}). In the case of Pink Snapper, an average movement rate of 30 km·year^{-1}(~80 m·day^{-1}). For Dhufish, based on its sedentary behaviour, the rate was estimated as 10 km·year^{-1} (~30 m·day^{-1}). The movement rates in the model were revised by experts from CSIRO (Russ Babcock and Matt Vanderklift) and have been sent for a second checking to Chris Wilcox (Spatial Dynamic Team, CSIRO-Hobart). Also, it has been planned a series of meeting with Corey Wakefield, David Fairclough, Alex Hesp and Jeremy Prince to tune these movement rates.

b) **Results from the management zones:**

There were also concerns about some of the biomasses predicted by the model under different no-take areas. The results from the model showed that 4% sanctuary zones improved the biomass a reasonable amount for lobster – a view was that this result should have been close to the no sanctuaries scenario. Some comments pointed out that the effect of 4% of sanctuaries gave similar results to 25% of sanctuaries. Regarding this comments, the scale of the figure in the seminar may have confused the audience because the increases in lobster biomass under the various scenarios are approximately proportional to the amount of MPA in the different scenarios e.g. a 4% increase in lobster biomass under 4% MPA. The increase of lobster biomass in the 25% sanctuary zone scenario was ~38%

c) **Regarding Pink Snapper – How does the model handle a strong recruitment pulse from outside the boundaries of the Ecospace model?**

Recruitment variability does not occur explicitly in the Ecospace model. However, Ecospace uses the biomass and fishing mortalities (F) and compensatory recruitment (see question 3c) as specified in the Ecopath and Ecosim models. In Ecospace, the F's are distributed using a simple 'gravity model', where the proportion of the total fishing effort allocated to each cell is assumed to be proportional to the sum over groups of the product of the biomass, as well as the catchability and profitability of fishing the target groups.

APPENDIX 8. Local Fisher's Knowledge

METHODS

The project is incorporating the perceptions, historical anecdotes and environmental knowledge of fishers from the Jurien Bay region through the data collected by means of twenty semi-structured interviews applied in the region of Jurien Bay (including Green Head and Cervantes). The questionnaire was designed to gain information about the resources, abundances, gear and fishing sites in the region, based on the memory of fishers of different age groups. Because the fishers' use of common names for fish, it was included a picture of the species/groups of the principal species of sea mammals, birds, commercial and non commercial fish, sharks and crustaceans reported to live in the area. The questions covered the following aspects:

- Personal information (name, age, date, location).
- Fishing experience.
- Fishing areas and seasons for main target species.
- Estimation of largest animal caught during 1980s (e.g. Dhufish, lobster)
- Fishing gear.
- Percentages of discards.
- Estimations of illegal and unreported fishing (if any).
- Past abundances by five-year intervals from 1980 to 2005 for the major groups considered in the model.
- Possibility of local exticntions
- Perspective of their future as fishers.
- Impact of the fishing closure areas.

The Personal Information was stored with a unique identifier (Mr. Lozano-Montes), in a separate data file to the data collected from the interview. The personal information was used to follow up any later questions about the interview results if they are necessary.

Data were collected through semi-structured interviews with fishermen in the Jurien Bay region. The survey was completed on the beach and boat ramps of Jurien Bay, Green Head and Cervantes. It focused on interviewing people who began to fish 20 to 30 years ago or who were government employees in the region. In most cases, the interviewees were selected by snowball sampling (Berg, 2001), a method that relies on referrals from initial subjects to generate additional subjects. People were interviewed individually and at the end of the interview and it was explained that the fisher's identity would not be revealed and the information would remain confidential. Written consent was obtained for each interview, after explaining the purpose of the interview and its confidentiality. The questionaire followed technical and ethical recomendations proposed by Bunce *et al.,* 2000 and it was approved (July, 2006) by the Human Research Ethics Committee of Murdoch University. The information provided by questionnaires along any additional commnets was processed to ensure anonymity, according to the requirements of Human Research Ethics Committee of Murdoch University. The inetrviews lasted between 60-90 minutes using paper questionairies and leaving space for most relevant phrasesanecdotes and parts. Also, this field work followed technical and ethical recommnedations proposed by Bunce *et al.*, 2000. following these recommendations, the interviews were conductewd in private and most of them, after the fishers accomplished their activites.

Two field trips to Jurien Bay region were done in order to build the LFK database. Currently, the LFK database consists of twenty interviews, but we intend to increase the number to at least thirty in the close future in order to reduce uncertainty in the perceived abundances and trends reported the fishermen. All the interviews were performed individually and mainly during the afternoon, just after the fishers completed their work and met to socialize. The location of the interviews was variable; in some cases on the beach, boats or in the fishers' homes. At the beginning of each interview, the project and its goals were explained, emphasizing the need to obtain perceptions of the marine park during the 1980s. This resulted in younger fishers suggesting older retired colleagues to interview. They, in turn, introduced me to older fishers in their houses. The field trip followed technical and ethical recommendations proposed by Bunce *et al.,* (2000), which suggest that interviews be conducted in a respectful manner and minimize the disruption to people's routines. Following these recommendations, the interviews were conducted in private after the fishers accomplished their activities.

The interviews aimed at gathering detailed information about more than 40 groups of organisms over the past 20 years, but the number and type of interviews can bias results. Each interview is unique and it is possible that, in another situation, the same person could have given slightly different answers (Flick, 1998). In addition, fishers were aware that their opinions would be published in this report and possibly in a scientific journal, and therefore, it is possible that they gave 'socially desirable' answers about the fishing closures in the marine park or increased their estimates of past abundances. The information provided by questionnaires along with any additional comments was processed to ensure anonymity, according to the requirements of Human Research Ethics Committee of Murdoch University, Western Australia. The time estimated to complete this interview was between 60-90 minutes and the fisher was be free to stop or quit the interview at any time. At the end of the interview, it was mentioned and read it that the information provided has no risk for the fisher's identity or privacy and it is confidential. The interviewer will keep and store the interview information at least for five years and no one will have access to this information. There is written consent for the interview, where it expalined the purpose of the ineterview and its confidentially. This interview was applied to the fishing communities of Jurien Bay, Cervantes and GreenHead located inside of Jurien Bay Marine Park.

Representativeness and Validity

The interviews aimed at gathering detailed information about more than 30 groups of organisms over the past 20 years, but the number and type of interviews can bias results. Each interview is unique and it is possible that, in another situation, the same person could have given slightly different answers (Flick, 1998). In addition, fishers were aware that their opinions would be published in a technical report and possibly in a scientific journal, and therefore, it is possible that they gave 'socially desirable' answers about the fishing closures and increased or decrease their estimates of past abundances.

Moreover, results from a small number of interviews can be biased (Yli-Pelkonen and Kohl, 2005), and it is noted that the LFK results from the Jurien region are based on a relatively small number of interviews (n = 20); this is less than 5% of the fishers' population. Moreover, given the wide experience (more than 500 years of combined experience) and deep perspectives of the interviewees on marine resources, the results of the LFK analysis presented in this section can at least serve as a preliminary estimate of historical changes in the region.

For each of the functional groups of organisms included in the interviews, an index of relative abundance compared to current status was assigned as: increasing (+1), decreasing (-1), or stable (0), for five years periods from 1980 to 2000. The average relative abundance of the living functional groups in each five-year period was calculated according to the perception of the LFK. All the fishermen interviewed were considered 'experts'; i.e. no weighting by experience was applied and the abundances estimated by 'old or expert' or 'young or novice' fishers and their perceptions of abundance were given the same weighting.

The relative abundance time series (relative to 2005) from the interviews was converted into absolute abundance, assuming the same average and amplitude of change as the stock assessment data so that it could be incorporated into the 2005 trophic Ecopath models of the Jurien Marine Park. This process was employed only for those species without published references of their past abundances (i.e., sea mammals and non-commercial species). In the case of rock lobster, its biomass during 1990s was estimated from direct local sampling under a depletion biomass analysis. Time series of Western Rock Lobster biomass was provided by the Department of Fisheries, WA.

Modifying P/B and Q/B ratios

The total mortality (P/B) for several of the model groups (Pink Snapper, Dhufish, Foxfish, sharks, king wrasses, break ea cod and Baldchin Grouper) was lower in 1980 than in 2005 because they were fished less heavily in 1980s. Full explanations and sources of information employed to calculate P/B values for the 2005 model are in Appendix 5. Not surprisingly, the most significant changes in P/B between 1980s and 2005 related to highly exploited large fish such as Pink Snapper, Dhufish, Baldchin Grouper, Breaksea Cod and Foxfish. In some cases, such as marine turtles, the LFK revealed that these organisms were fished in the region during the 1980s. Mortality imposed by former turtle fishing resulted in a decrease of % in the total mortality of sea turtles from 0.068 (1980 model) to 0.05 (2005 model). The rate of consumption per unit of biomass per year (Q/B) may have been lower in the past due to the larger individuals present in the populations of the 1980s, and less so in the 2005 (according to LFK records). A few small changes in Q/B were also needed in the 1980s model during the balancing process. Overall, the Q/B of only 12 groups out of 80 was modified less than 20%.

The diet matrix from the 2005 Jurien model described in Appendix 5 was used as a base for the trophic links and diets needed to built the 1980s model. This decision was taken based on the quality and quantity of diets reported in the marine park, where the 2005 diets represented the best approach to rebuild the past trophic interactions in the region. It was assumed that predator preferences have changed very little in the past 20 years and that the changes in these interactions reflect the changes in abundances of the prey (i.e., increasing their vulnerabilities to predation during high abundances and vice versa.

One problem had to be overcome before simulating dynamics of the marine park from the 1980s to 2005 is related to the prey-predator interactions in the past. There is no reliable diet information from the 1980s. Both Ecopath and Ecosim simulations are highly sensitive to the initial diet matrices, since these determine the base predation mortality rates and the rates of effective search for prey by predators. This issue was addressed by using the 2005 Ecopath model as an initial state including its diet matrix (with the best scientific information available). The main benefit of this approach is that (unknown) diet composition and biomasses for the 1980s model remain consistent with those implied by the 2005 model.

Summary of the interviews applied to twenty fishers of the Jurien Bay region during 2008-2009.

Murdoch University

Centre Fish and Fisheries Research

South St, Murdoch, Western Australia 6150

Project: *Evaluating how food webs and the fisheries they support are affected by fishing closures in Jurien Bay, temperate Western Australia.*

FRDC Project Number: 2006/038

Principal investigator: Professor Neil Loneragan (Murdoch University); co-investigators: Russ Babcock (CSIRO), Hector Lozano-Montes (CSIRO) and Jeff Dambacher (CSIRO).

e-mail Neil Loneragan: N.Loneragan@murdoch.edu.au

e-mail Hector Lozano-Montes: Hector.Lozano-Montes@csiro.au

School of Biological Sciences and Biotechnology

Murdoch University

Phone: +618-9360-6453

Fax: +618-9360-6303

Interview explanation:

The objective of this semi-structure interview is to obtain information from the fishers of Jurien Bay Marine Park related to the principal fishing areas, gears used and an undestanding of past abundances of the principal species living in the region. This information will be combined with more formal surveys and scientific information in order to construct a food web model for the 1980s period in order to evaluate the trophic interaction among predators, preys and fisheries and the impact of fishing closures in the marine park. The time estimated to complete this interview is between 60-90 minutes and you are free to stop or quit the interview at any time. The information provided has no risk for your identity or privacy and it is confidential; the interviewer (Mrs. Patricia Rojo-Diaz or Mr. Hector Lozano-Montes) will keep and store the interview information at least for five years and no one will have access to this information. This interview will be applied to the main fishing communities located inside of Jurien Bay Marine Park. If you require a copy of this interview, please ask Mrs. Rojo-Diaz or Mr. Lozano-montes and they will provide it.

If you have any complaint, concern or question about this interview or about the information provided, please call or send an e-mail to the address provided below. If you require a copy of this interview including the cover letter, please ask Mr. Lozano-montes or Mrs. Rojo-Diaz and they will provide it.

If you wish to talk to an independent person about your concerns you can contact MurdochUniversity's Human research Ethics committee on 9360 6677 or email ethics@murdoch.edu.au.

If you have any complaint, concern or question about this interview or about the information provided, please call or send an e-mail to the address provided below. If you require a copy of

this interview including the cover letter, please ask Mr. Lozano-montes or Mrs. Rojo-Diaz and they will provide it.

If you wish to talk to an independent person about your concerns you can contact MurdochUniversity's Human research Ethics committee on 9360 6677 or email ethics@murdoch.edu.au.

Participant

I have read the participant information sheet, which explains the nature of the research and the possible risks. The information has been explained to me and all my questions have been satisfactorily answered. I have been offered a copy of the information sheet to keep.

I am happy to be interviewed as part of this research. I understand that I do not have to answer particular questions if I do not want to and that I can withdraw at any time without consequences to myself.

I agree that research data gathered from the results of the study may be published provided my name or any identifying data is not used. I have also been informed that I may not receive any direct benefits from participating in this study.

I understand that all information provided by me is treated as confidential and will not be released by the researcher to a third party unless required to do so by law.

___________________________________ ______________________

Signature of Participant Date

Chief Investigator

I have fully explained to ______________________________ the nature and purpose of the research, the procedures to be employed, and the possible risks involved. I will provide the participant with a copy of the Information Sheet if they would like this.

___________________________________ ______________________

Signature of Participant Date

___________________________________ ______________________

Print Name Position

Personal Information

Name (optional):

Age (optional):

Date:

Location:

Fishing Experience:

Are you a:

1. Commercial fisher (   ) or recreational fisher (   ).

2. If commercial fisher: In what fishery are you working: ______________________

3. Are you a boat owner (   ) / rent (   )/ or working in a cooperative (   ).

4. What is the percentage of the total value of this fishery spent in gears?

5. What is the percentage of the total value of your fishery spent on sailing (i.e. fuel, permits, etc)?

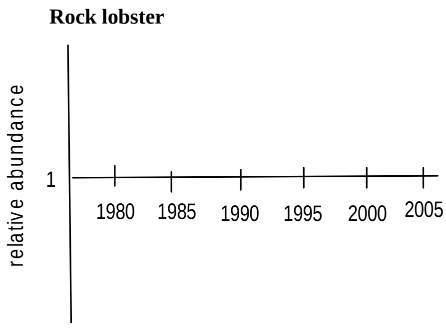
6. What is the percentage of profits?
7. Type of boat ___________ Length __________ Engine_________________
8. Main Target species:

9. Fishing Areas (see attached map):
10. Fishing seasons for main target species: (a)
 ____
 (b) ____
 (c) ____

11. What gears are you using? ____
12. In which year did you begin to fish? _____________
13. Last season fishing __________
14. Number of years fishing? (0-5) (5-10) (10-20) (20-30) (30-40) (40+)
15. Number of generations their family has been fishing?
16. Always in this region?
17. What percentage of the catch is discarded?
 a) little (less than 10%) ________
 b) moderate (10-40%) ________
 c) high (> 40%). _____________

The following questions need to be applied for the principal species / groups of fish, seabirds and marine mammals living in the marine park

23. The abundance of **rock lobster** has increased in the last:
 a) 5 years…… [<1x], [no change], [1-3x], [3-10x], [>10x]
 b) 10 years…... [< 1x], [no change], [1-3x], [3-10x], [>10x]
 c) 20 years…… [< 1x], [no change], [1-3x], [3-10x], [>10x]
 d) 30 years…… [< 1x], [no change], [1-3x], [3-10x], [>10x]



24. Has the abundance of **rock lobster** diminished in the last:
 a) 5 years…….[<50%], [10-50%], [>10%], [no change]
 b) 10 years…...[<50%], [10-50%], [>10%], [no change]
 c) 20 years……[<50%], [10-50%], [>10%]. [no change]
 d) 30 years……[<50%], [10-50%], [>10%], [no change]
25. The abundance of **Dhufish** has increased in the last:
 a) 5 years…… [<1x] , [no change], [1-3x], [3-10x], [>10x]
 b) 10 years…...[< 1x] , [no change], [1-3x], [3-10x], [>10x]
 c) 20 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]
 d) 30 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]

26. Has the abundance of **Dhufish** diminished in the last:
 a) 5 years…….[<50%], [10-50%], [>10%], [no change]
 b) 10 years…...[<50%], [10-50%], [>10%], [no change]
 c) 20 years……[<50%], [10-50%], [>10%]. [no change]
 d) 30 years……[<50%], [10-50%], [>10%], [no change]

27. The abundance of **Pink Snapper** has increased in the last:
 a) 5 years…… [<1x] , [no change], [1-3x], [3-10x], [>10x]
 b) 10 years…...[< 1x] , [no change], [1-3x], [3-10x], [>10x]
 c) 20 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]
 d) 30 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]

28. Has the abundance of **Pink Snapper** diminished in the last:
    a) 5 years…….[<50%], [10-50%], [>10%], [no change]
    b) 10 years…...[<50%], [10-50%], [>10%], [no change]
    c) 20 years……[<50%], [10-50%], [>10%]. [no change]
    d) 30 years……[<50%], [10-50%], [>10%], [no change]

29. The abundance of **Baldchin Grouper** has increased in the last:
    a) 5 years…… [<1x] , [no change], [1-3x], [3-10x], [>10x]
    b) 10 years…...[< 1x] , [no change], [1-3x], [3-10x], [>10x]
    c) 20 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]
    d) 30 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]

30. Has the abundance of **Baldchin Grouper** diminished in the last:
    a) 5 years…….[<50%], [10-50%], [>10%], [no change]
    b) 10 years…...[<50%], [10-50%], [>10%], [no change]
    c) 20 years……[<50%], [10-50%], [>10%]. [no change]
    d) 30 years……[<50%], [10-50%], [>10%], [no change]

31. The abundance of **king wrasse** has increased in the last:
    a) 5 years…… [<1x] , [no change], [1-3x], [3-10x], [>10x]
    b) 10 years…...[< 1x] , [no change], [1-3x], [3-10x], [>10x]
    c) 20 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]
    d) 30 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]

32. Has the abundance of **king wrasse** diminished in the last:
    a) 5 years…….[<50%], [10-50%], [>10%], [no change]
    b) 10 years…...[<50%], [10-50%], [>10%], [no change]
    c) 20 years……[<50%], [10-50%], [>10%]. [no change]
    d) 30 years……[<50%], [10-50%], [>10%], [no change]

33. The abundance of **Breaksea cod** has increased in the last:
    a) 5 years…… [<1x] , [no change], [1-3x], [3-10x], [>10x]
    b) 10 years…...[< 1x] , [no change], [1-3x], [3-10x], [>10x]
    c) 20 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]
    d) 30 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]

34. Has the abundance of **Breaksea cod** diminished in the last:
    a) 5 years…….[<50%], [10-50%], [>10%], [no change]
    b) 10 years…...[<50%], [10-50%], [>10%], [no change]
    c) 20 years……[<50%], [10-50%], [>10%]. [no change]
    d) 30 years……[<50%], [10-50%], [>10%], [no change]

35. The abundance of **Western fox fish** has increased in the last:
    a) 5 years…… [<1x] , [no change], [1-3x], [3-10x], [>10x]
    b) 10 years…...[< 1x] , [no change], [1-3x], [3-10x], [>10x]
    c) 20 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]
    d) 30 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]

36. Has the abundance of **Western fox fish** diminished in the last:
    a) 5 years…….[<50%], [10-50%], [>10%], [no change]
    b) 10 years…...[<50%], [10-50%], [>10%], [no change]
    c) 20 years……[<50%], [10-50%], [>10%]. [no change]
    d) 30 years……[<50%], [10-50%], [>10%], [no change]

37. The abundance of **herring** has increased in the last:

a) 5 years…… [<1x] , [no change], [1-3x], [3-10x], [>10x]
b) 10 years…...[< 1x] , [no change], [1-3x], [3-10x], [>10x]
c) 20 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]
d) 30 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]

38.Has the abundance of **herring** diminished in the last:
a) 5 years…….[<50%], [10-50%], [>10%], [no change]
b) 10 years…...[<50%], [10-50%], [>10%], [no change]
c) 20 years……[<50%], [10-50%], [>10%]. [no change]
d) 30 years……[<50%], [10-50%], [>10%], [no change]

39.The abundance of **whiting** has increased in the last:
a) 5 years…… [<1x] , [no change], [1-3x], [3-10x], [>10x]
b) 10 years…...[< 1x] , [no change], [1-3x], [3-10x], [>10x]
c) 20 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]
d) 30 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]

40.Has the abundance of **whiting** diminished in the last:
a) 5 years…….[<50%], [10-50%], [>10%], [no change]
b) 10 years…...[<50%], [10-50%], [>10%], [no change]
c) 20 years……[<50%], [10-50%], [>10%]. [no change]
d) 30 years……[<50%], [10-50%], [>10%], [no change]

41.The abundance of **mullets** has increased in the last:
a) 5 years…… [<1x] , [no change], [1-3x], [3-10x], [>10x]
b) 10 years…...[< 1x] , [no change], [1-3x], [3-10x], [>10x]
c) 20 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]
d) 30 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]

42.Has the abundance of **mullets** diminished in the last:
a) 5 years…….[<50%], [10-50%], [>10%], [no change]
b) 10 years…...[<50%], [10-50%], [>10%], [no change]
c) 20 years……[<50%], [10-50%], [>10%]. [no change]
d) 30 years……[<50%], [10-50%], [>10%], [no change]

43.The abundance of **sand trevally** has increased in the last:
a) 5 years…… [<1x] , [no change], [1-3x], [3-10x], [>10x]
b) 10 years…...[< 1x] , [no change], [1-3x], [3-10x], [>10x]
c) 20 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]
d) 30 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]

44.Has the abundance of **sand trevally** diminished in the last:
a) 5 years…….[<50%], [10-50%], [>10%], [no change]
b) 10 years…...[<50%], [10-50%], [>10%], [no change]
c) 20 years……[<50%], [10-50%], [>10%]. [no change]
d) 30 years……[<50%], [10-50%], [>10%], [no change]

45.The abundance of **yellowtail kingfish** has increased in the last:
a) 5 years…… [<1x] , [no change], [1-3x], [3-10x], [>10x]
b) 10 years…...[< 1x] , [no change], [1-3x], [3-10x], [>10x]
c) 20 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]
d) 30 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]

46.Has the abundance of **yellowtail** kingfish diminished in the last:
a) 5 years…….[<50%], [10-50%], [>10%], [no change]

b) 10 years…...[<50%], [10-50%], [>10%], [no change]
c) 20 years……[<50%], [10-50%], [>10%]. [no change]
d) 30 years……[<50%], [10-50%], [>10%], [no change]

47. The abundance of **flatheads** has increased in the last:
a) 5 years…… [<1x] , [no change], [1-3x], [3-10x], [>10x]
b) 10 years…...[< 1x] , [no change], [1-3x], [3-10x], [>10x]
c) 20 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]
d) 30 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]

48. Has the abundance of **flatheads** diminished in the last:
a) 5 years…….[<50%], [10-50%], [>10%], [no change]
b) 10 years…...[<50%], [10-50%], [>10%], [no change]
c) 20 years……[<50%], [10-50%], [>10%]. [no change]
d) 30 years……[<50%], [10-50%], [>10%], [no change]

49. The abundance of **rays** has increased in the last:
a) 5 years…… [<1x] , [no change], [1-3x], [3-10x], [>10x]
b) 10 years…...[< 1x] , [no change], [1-3x], [3-10x], [>10x]
c) 20 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]
d) 30 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]

50. Has the abundance of **rays** diminished in the last:
a) 5 years…….[<50%], [10-50%], [>10%], [no change]
b) 10 years…...[<50%], [10-50%], [>10%], [no change]
c) 20 years……[<50%], [10-50%], [>10%]. [no change]
d) 30 years……[<50%], [10-50%], [>10%], [no change]

51. The abundance of **large sharks** has increased in the last:
a) 5 years…… [<1x] , [no change], [1-3x], [3-10x], [>10x]
b) 10 years…...[< 1x] , [no change], [1-3x], [3-10x], [>10x]
c) 20 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]
d) 30 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]

52. Has the abundance of **large sharks** diminished in the last:
a) 5 years…….[<50%], [10-50%], [>10%], [no change]
b) 10 years…...[<50%], [10-50%], [>10%], [no change]
c) 20 years……[<50%], [10-50%], [>10%]. [no change]
d) 30 years……[<50%], [10-50%], [>10%], [no change]

53. The abundance of **small sharks** has increased in the last:
a) 5 years…… [<1x] , [no change], [1-3x], [3-10x], [>10x]
b) 10 years…...[< 1x] , [no change], [1-3x], [3-10x], [>10x]
c) 20 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]
d) 30 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]

54. Has the abundance of **small sharks** diminished in the last:
a) 5 years…….[<50%], [10-50%], [>10%], [no change]
b) 10 years…...[<50%], [10-50%], [>10%], [no change]
c) 20 years……[<50%], [10-50%], [>10%]. [no change]
d) 30 years……[<50%], [10-50%], [>10%], [no change]

55. The abundance of **sea lions** has increased in the last:

a) 5 years…… [<1x] , [no change], [1-3x], [3-10x], [>10x]
b) 10 years…...[< 1x] , [no change], [1-3x], [3-10x], [>10x]
c) 20 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]
d) 30 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]

56. Has the abundance of **sea lions** diminished in the last:
a) 5 years…….[<50%], [10-50%], [>10%], [no change]
b) 10 years…...[<50%], [10-50%], [>10%], [no change]
c) 20 years……[<50%], [10-50%], [>10%]. [no change]
d) 30 years……[<50%], [10-50%], [>10%], [no change]

57. The abundance of **dolphins** has increased in the last:
a) 5 years…… [<1x] , [no change], [1-3x], [3-10x], [>10x]
b) 10 years…...[< 1x] , [no change], [1-3x], [3-10x], [>10x]
c) 20 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]
d) 30 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]

58. Has the abundance of **dolphins** diminished in the last:
a) 5 years…….[<50%], [10-50%], [>10%], [no change]
b) 10 years…...[<50%], [10-50%], [>10%], [no change]
c) 20 years……[<50%], [10-50%], [>10%]. [no change]
d) 30 years……[<50%], [10-50%], [>10%], [no change]

59. The abundance of **octopus** has increased in the last:
a) 5 years…… [<1x] , [no change], [1-3x], [3-10x], [>10x]
b) 10 years…...[< 1x] , [no change], [1-3x], [3-10x], [>10x]
c) 20 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]
d) 30 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]

60. Has the abundance of **octopus** diminished in the last:
a) 5 years…….[<50%], [10-50%], [>10%], [no change]
b) 10 years…...[<50%], [10-50%], [>10%], [no change]
c) 20 years……[<50%], [10-50%], [>10%]. [no change]
d) 30 years……[<50%], [10-50%], [>10%], [no change]

61. The abundance of **Roe abalone** has increased in the last:
a) 5 years…… [<1x] , [no change], [1-3x], [3-10x], [>10x]
b) 10 years…...[< 1x] , [no change], [1-3x], [3-10x], [>10x]
c) 20 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]
d) 30 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]

62. Has the abundance of **Roe abalone** diminished in the last:
a) 5 years…….[<50%], [10-50%], [>10%], [no change]
b) 10 years…...[<50%], [10-50%], [>10%], [no change]
c) 20 years……[<50%], [10-50%], [>10%]. [no change]
d) 30 years……[<50%], [10-50%], [>10%], [no change]

63. The abundance of **sea birds** has increased in the last:
a) 5 years…… [<1x] , [no change], [1-3x], [3-10x], [>10x]
b) 10 years…...[< 1x] , [no change], [1-3x], [3-10x], [>10x]
c) 20 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]
d) 30 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]

64. Has the abundance of **sea birds** diminished in the last:
    a) 5 years…….[<50%], [10-50%], [>10%], [no change]
    b) 10 years…...[<50%], [10-50%], [>10%], [no change]
    c) 20 years……[<50%], [10-50%], [>10%]. [no change]
    d) 30 years……[<50%], [10-50%], [>10%], [no change]

65. The abundance of **seagrass** has increased in the last:
    a) 5 years…… [<1x] , [no change], [1-3x], [3-10x], [>10x]
    b) 10 years…...[< 1x] , [no change], [1-3x], [3-10x], [>10x]
    c) 20 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]
    d) 30 years……[< 1x] , [no change], [1-3x], [3-10x], [>10x]

67. Could you remember the size and year of biggest lobster caught?
68. Where did you catch it?
69. Do you consider that your catches were higher in the past (1980s) than the catches in the present?
70. Were the abundance of seabirds and marine mammals higher than today?
71. Do you have any example of this trend?
72. Is any species disappeared during your career?
73. In your opinion, what is the future of fisheries in Jurien Bay:

    a) Better
    b) Worse
    c) Same
    d) Do not know

74. In your opinion, what is the impact of fishing closure areas in this marine park?

    a) Positive
    b) Negative
    c) No effect

75. Would you like that your son became a fisherman?

APPENDIX 9. Optimum Fishing Strategies

METHODS

The bioeconomic analysis presented in this section is using the fishing optimization routine incorporated in Ecopath with Ecosim 5.2 software (Christensen *et al*., 2000; 2004). This modelling framework allows the modeller to change the relative fishing mortalities using the multi-dimensional Davidson-Fletcher-Powell search algorithm included in the *Ecosim* 'policy search' routine. This routine will seek an optimum solution based on the weighting assigned to the objectives of the scenario in question (Walters *et al.,* 2002; Christensen *et al*., 2004). The search iteratively changes the fishing mortality of all the gears employed (a total of eight included in the model) in the scenario.

The fishing optimization presented in this report is an exploratory approach to maximize four of the critical 'objective functions' considered for management of marine ecosystems defined in Ecosim and recommended by Christensen *et al.,* (2004). These objectives are defined as follow:

1. Maximize fisheries rent, i.e., profits from sale of catch (each species has a market price) after deducting the costs of fishing (both fixed and variable). The objective is to focus on the fishing efforts of the most lucrative species (e.g. Western Rock Lobster).
2. Maximize social benefits, defined here as direct employment in the fisheries. For each gear type or fishery sector, the relative number of jobs per catch value is specified in the model, and the optimization favours the most labour intensive gear. The benefits of this objective are calculated as numbers of jobs relative to the catch. The relative number of jobs per fishing gear was estimated based on the opinion of two commercial rock lobster fishermen of Jurien Bay interviewed in April, 2008. The social variables involved in this analysis need to be improved.
3. Maximize ecosystem structure or 'Ecological' value. This objective is based on the Ecopath network analysis presented in section 8.1 of this report and it refers to the ecosystem 'maturity' concept described by Odum (1971 and 1988) in which mature systems are dominated by large, long-lived organisms. Optimization for ecology often implies a reduction in the fishing effort for all gear types in order to maximize the biomass of the groups that receive a user-set weighting value (Christensen *et al.,* 2004). The biomasses used during the optimization corresponded to those incorporated into the 2005 Jurien Bay Ecopath model.
4. Maximize rebuilding of species: This objective reflects the external pressure on policy makers and stakeholders to preserve or rebuild the population of charismatic or indeed any given species (e.g. sea turtles, dolphins, sea lions). Fishing mortalities across gear types are adjusted to maximize the biomass of groups that receive a high weighting value from the user. This objective was not considered in the simulation because it is recommended for those systems with heavily depleted species (Christensen *et al.,* 2005).

This fishing optimization search also allows the modeler to specify the weights for one or more of the above objectives functions, based on the management priorities established for each of the scenarios. Basically, by changing relative fishing mortalities, the multi-dimensional Davidson-Fletcher-Powell search algorithm in Ecosim 'policy search' routine will seek the optimum solution based on the weighting assigned to the objectives (Walters *et al*., 2002; Christensen *et al.,* 2004). The search iteratively changes the fishing mortality of all the gears employed (fourteen for the Jurien Bay model) to maximize the objective specified (or a mix of the four objective) over a simulation of the 20 years. Basically, this optimum search maximizes the chosen objectives and provides a forecast of economic values, numbers of jobs, catches and biomasses at the end of the simulation. The catches, discards, fishing efforts data were provided by the Department of Fisheries, WA. Market prices were estimated from the local market in Jurien Bay, WA (April, 2008). This routine will maximize profits and they are calculated based on the catch (catch · price, by species) less the cost of fishing (fixed + variable cost). Also, the cost of sailing is involved in the calculation of profits and it is a multiplier of variable cost, reflecting distance from port/landing place. It could be affected by other factors such as wind or currents (Christensen *et al.*, 2005). The following paragraphs define the main costs, profits, and market and non-market prices involved in the model.

Fixed cost represents the cost of operating a fleet unit defined in the Ecopath model. In the Jurien Bay model, the fixed costs were represented by those that are independent of effort at the fleet scale such as the costs of management, licenses, capitalization and insurance.

Variable costs are a function of the effort. They are typically represented by gear costs, but not for costs that depends on spatial effort allocation, e.g. sailing costs.

Spatially-related variable costs: these costs depend on spatial effort allocation and directly related to sailing costs in the model.

Profits: this variable represents the percentage of the total value and it is calculated from the total value less all costs. This variable cannot be entered directly in the model.

Market prices: this variable is defined in Australian dollars per kilogram based on the price on the beach found in Jurien Bay in March, 2008.

Non-market price: this price represents the value of a resource in the ecosystem, e.g. for non-exploitative uses (Christensen *et al.,* 2000; 2004). This variable in the model is expressed in monetary units per unit of biomass. In the model, a high non-market value was assigned to groups such as corals, sponges, dolphins, sea turtles, sea lions.

In the case of the most profitable fleet in Jurien Bay, the Western Rock Lobster (WRL), its income and expenditures were estimated on an average catch per pot (approx $25/kg) and the average number of pots in the water across all MFL holders provided by Andrew Wizard (Personal communication, August, 2008). The income and operating costs (including bait, fuel, repairs and maintenance, anchorage, labor) and depreciation on capital items (including pots, boats, dinghies, sheds, vehicles) and the actual WRL licenses were also provided by Andrew Winzer (Personal communication, August, 2008). For the other seven commercial gears, the profits and costs were estimated using the experience and opinion of fishermen interviewed in Jurien Bay (from March, 2008 to July, 2009).

The optimization routine will maximize profits and they are calculated based on the catch (catch · price, by species) less the cost of fishing (fixed + variable cost). Also, the cost of travelling is involved in the calculation of profits and it is a multiplier of variable cost, reflecting the distance from the port/landing place. This cost could be affected by other factors such as wind or currents (Walters *et al.,* 2002). Tables 9.1 and 9.2 display the profits, costs and prices (and non-market prices) of the species or functional groups caught for the eight commercial fleets in the model. These estimations have been improved with the suggestions provided by local Jurien Bay fishermen in March, 2009. The fifteen scenarios designed to this exploratory analysis of the optimization of the fisheries are presented in Table 9.3. These scenarios were categorized by economic, ecological and ecological criteria. Each scenario runs for 10 years from 2006 to 2016.

Table 9.1 Estimated costs and profit of each of the fleet in the Jurien Bay model, estimated as percentages of the value of the total landings by fleet. Some of these estimated were calculated based on the interviews with local fishermen of Jurien Bay in March, 2009.

Fleet	Fixed cost (%)	Effort related cost (%)	Travelling related cost (%)	Profit (%)
Rock lobster	5	5	30	50
Beach Seine	2	30	55	13
Droplinning	10	20	60	10
Gill Netting	10	20	60	10
Handlinning	2	20	60	18
Longlinning	2	20	60	18
Traps	5	20	60	15
Abalone	1	20	40	39

Table 9.2 Market prices of the commercial species exploited in Jurien Bay. These prices are expressed in Australian dollars per kilogram based on the price on the beach found in Jurien Bay in March, 2008. The non-market price represents the value of a resource in the ecosystem, e.g. fro non-exploitative uses. A relative high value of non-market price was assigned to charismatic species such as sea turtles, corals, sponges, dolphins, sea lions.

Group Name	Rock lobster $ AU/kg	Beach Seine $ AU/kg	Droplinning $ AU/kg	Gill Netting $ AU/kg	Handlinning $ AU/kg	Longlinning $ AU/kg	Traps $ AU/kg	Abalone $ AU/kg	Non-Market Price
Dolphins									8
Sea lions									6
Intertidal birds									3
Surface diving birds									3
Large coastal sharks			7.50	7.50	7.50	7.50			
Small coastal sharks			8.50	8.50	8.50	8.50			
Rays			4.50	4.50		4.50			
Dhufish		40.00	40.00	40.00	40.00				
Pink snapper		20.00	20.00	20.00	20.00	20.00			
Balchin grouper		17.00	17.00	17.00	17.00				
King wrasse		10.00	10.00	10.00	10.00				
Western foxfish			6.50	6.50	6.50	6.50			
Breaksea cod					10.00	10.00			
Inshore reef ass. herbivore		2.50	2.50		2.50				
Inshore reef ass. omnivore			4.50	4.50	4.50				
Inshore reef ass. zoobenthos feed.		3.50	3.50	3.50	3.50				
Inshore ass. carnivore		8.00							
Inshore sand ass. omnivore		3.80	3.80	3.80	3.80				
Inshore seagrass ass. zoob. feed.				4.00	4.00				
Inshore benthopelagic carnivore		5.50		5.50	5.50	5.50			
NDR reef ass. herbivore				2.20		2.20			
NDR reef ass. carnivore			4.00	4.00	4.00				
NDR reef ass. zoobenthos feed.		8.00							
NDR sand ass. carnivore				8.00					
NDR sand ass. zoobenthos feed.			8.00		8.00				
NDR benthopelagic carnivore		5.50	5.50	5.50	5.50				
Sessile epibenthos									1
Photo. corals/sponges									10
Large Crabs							15.00		
Cuttlefish				3.50		3.50			
Squid		1.50	1.50	1.50					
Octopus	18.00						18.00		
Lobster Adult	50.00								
Sea turtles									10
Roe abalone								120.00	

Table 9.3 Scenarios designed in the exploratory analysis of the optimization of the fisheries in Jurien Bay. The fifteen scenarios were categorized by economic, social and ecological criteria. Each scenario runs for 10 years from 2006 to 2016.

Objective	Scenario														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Relative weighting														
Economic (profits)	1	2	4	6	10	0	0	0	0	0	0	0	0	0	0
Social (# jobs)	0	0	0	0	0	1	2	4	6	10	0	0	0	0	0
Ecological (total biomass)	0	0	0	0	0	0	0	0	0	0	1	2	4	6	10

APPENDIX 10. Climate Change Impacts

METHODS

To explore the effects of fishing and climate change on marine ecosystems we use the mass-balanced ecosystem model of Jurien Bay presented in this report as example of the potential responses of marine ecosystems in Western Australia to climate change (i.e. ocean warming). The effect of climate change on the food web of Jurien Bay was evaluated by downscaling changes in primary productivity. The environmental conditions for the pelagic primary production models were obtained from the Commonwealth Scientific and Industrial Research Organisation's (CSIRO) Mark 3.5 coupled atmosphere-ocean General Circulation Model (GCM, Hirst *et al.,* 2000, Gordon *et al.,* 2002). The relative change in pelagic primary production at 2100 predicted by this Mark 3.5 model for the Jurien Bay region (30°S) was an increase of about 11% (Fig. 10.1). This change in pelagic primary production was used as a driver to run the dynamic food web model (Ecosim model) of Jurien Bay (structure and input parameters of the model are presented in Appendix 5. Ecosim dynamic simulations were carried out to simulate the impact of increasing pelagic primary production by 11% over 100 years on both the secondary production and fisheries of Jurien Bay. This approach represents our first attempt to incorporate environmental factors into the food web of Jurien Bay in order to gain a better understanding of how changes in this primary production can influence small marine ecosystems in Western Australia.

CSIRO MK 3.5: A primary production model

By using the changes in primary production from the primary producer MK 3.5 model (Fig. 10.1), we investigated how changes in the physical climate affected the rate of primary production in marine food webs of Jurien bay and the effect of this change on its fisheries. To predict climate impacts on the physical environment, we use the Commonwealth Scientific and Industrial Research Organisation's Mark 3.5 coupled atmosphere-ocean GCM (Hirst *et al.,* 2000, Gordon *et al.,* 2002). We predict future changes in phytoplankton production in the Jurien region by using a nutrient-phytoplankton-zooplankton (NPZ) model that is forced by the CSIRO Mk3.5 GCM (Hirst *et al.,* 2000, Matear *et al.,* 2000, Oschlies & Schartau 2005). This GCM model provides a global coverage of physical changes in environmental variables driven by projected greenhouses emissions in Australia. Brown *et al.*, 2009 combined this GCM with a nutrient-phytoplankton-zooplankton-detritus (NPZD) model to estimate the changes in phytoplankton productivity in Australia. In addition, the NZPD model describes the flux of nitrogen between inorganic and organic dissolved states, its uptake by phytoplankton and the consumption of phytoplankton by zooplankton. This model captures the major climate-driven processes that impact phytoplankton production (Sarmiento *et al.,* 2004) such as light and nitrogen availability and the temperature dependence of physiological rates. Ocean warming and light supply changes driven by changes in cloud cover, wind and the depth of the mixed layer directly impact phytoplankton production. Warming can also increase ocean stratification, by heating surface waters faster than at depth and thus, enhancing ocean stratification. This impacts availability of nutrients in surface waters where light is available for photosynthesis.

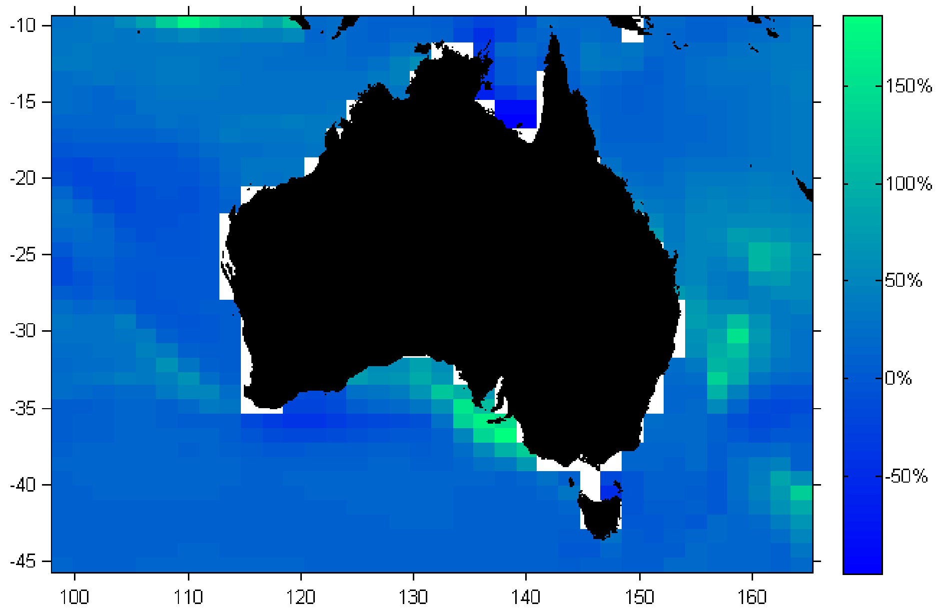


Figure 10.1 Predicted relative percent change in phytoplankton production from the 2000-2004 mean to 2100 mean for the Australasian region. According to the CSIRO Mk 3.5 global climate model (GMC), the phytoplankton production is predicted to generally increase around 11% in the region of Jurien Bay (30°S).

Under the IPCC A2 scenario, the NPZD model predicted a small increase of nutrients (generally <10%) in most of the Australian regions (Brown *et al.*, 2009). This increase in nutrients is predicted to cause an increase in phytoplankton production rate in most areas of Australia (Fig. 10.1). In coastal models, increased nutrient availability and temperatures also increased the primary production rate of macroalgae and benthic microalgae, but decrease primary production of seagrasses due to enhanced epiphyte growth on photosynthetic seagrasses blades (Brown *et al.*, 2009). Changes in large-scale oceanographic processes, such as basin-scale circulation patterns, also affect supply of nutrients to the Australian region. Details of this model are presented in Brown *et al*., 2009. The changes in predicted primary production (mainly phytoplankton) by the NPZD model in the region of Jurien Bay were used to drive the mass-balanced Ecopath model of this marine park.

Predicted primary production change using the Ecosim model

The structure and input parameters and calibration of the Ecosim model of Jurien Bay is presented in Appendix 5. As mentioned in previous in Appendix 4, Ecopath & Ecosim models are grounded in general ecological theory and have proved to capture real ecosystem dynamics in different ecosystems (Walters *et al.*, 2005). We used the Ecosim model of Jurien Bay to investigate the response of this ecosystem to primary production changes by forcing a linear change of the 11% of increment rate of primary production over 100 years predicted by the MK 3.5 model. Also, we designed six scenarios to explore which of the main primary producers has the strongest influence in the food webs of Jurien Bay. Each scenario involved a 11% of change of the biomass of each of the six primary producers groups in the model. These six scenarios were run for 100-year period and the total biomass and total catch predicted at the end of the scenario were used to evaluate the impact.