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An Evaluation of Management Strategies for Line Fishing in the Ningaloo Marine Park

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Final Report for Ningaloo Reef Project 3.2.3 Biodiversity Assessment, Ecosystem Impacts of Human Usage and Management Strategy Evaluation

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List of Figures

List of Tables

1. EXECUTIVE SUMMARY

This project explored the effects of managing recreational fishing in the Ningaloo Marine Park. The project used simulation techniques known as Management Strategy Evaluation (MSE) to explore the effectiveness of current management arrangements, and the consequences of a range of alternative management actions, and alternative future scenarios, on the management of a major recreational target species on Ningaloo Reef, spangled emperor (*Lethrinus nebulosus*). The results of the scenarios are examined against the objectives set out by management and other stakeholders in the park.

The simulation model that was used is known as ELFSim (Effect of Line Fishing Simulator). ELFSim is a decision support software system designed to evaluate options for conservation and harvest management, and includes a number of key components: a population dynamics model of the target species that captures the full life history (including larval dispersal, reproduction, development, and habits) of that species, a model of fishing dynamics that captures the exploitation pattern due to fishing behaviour, and a management model that simulates the implementation of management actions. ELFSim was developed for other coral reef fisheries where commercial fishing is the primary fishing activity. In this project we developed a simulation model of recreational fishing dynamics. This model was agent-based, meaning that individual recreational fishing boats were represented in the model, and a range of management measures were tested on the ability to manage these virtual recreational fishers.

The project started by first evaluating the effects of the current management arrangements operating in the park on spangled emperor biomass using the ELFSim model. Current management arrangements include sanctuary zones implemented by the Department of Environment and Conservation (DEC) and regulations on fishing activities in the Marine Park and state waters by the Department of Fisheries, Government of Western Australia (DoFWA). Spangled emperor was the focal species of this study as it is a primary targeted species in the Ningaloo Marine Park and Gascoyne Coast Bioregion and is used by DoFWA as an indicator species to monitor effects of fishing on the inshore demersal (0 to 250 m depth range) suite of scalefish species (Marriott et al. 2010a).

The effect of the current sanctuaries was compared to the sanctuaries previously implemented in simulation space, and the effects of the current bag limit of 4 fish, and effort levels on biomass, inside and outside the sanctuaries, on the biomass, catch and catch rates were examined. In these simulations, marginally less biomass was seen across the entire marine park under the previous sanctuary arrangement compared to the most recent implementation of sanctuaries. However, the amount of biomass protected under the current sanctuaries was almost 3 times that under the previous sanctuaries. The result reflected that although a greater proportion of spangled emperor population biomass was protected under the new (current) sanctuary zones, fishing was also demonstrated to become more concentrated in areas outside of those sanctuary zones in the model, resulting in greater simulated depletion of spangled emperor biomass in those areas, outside of the sanctuary zones. Removing the bag limits in the model simulations resulted in about a 5% reduction in biomass, while an assumed increase in effort was the biggest single factor of reducing the biomass more than 10% than under current conditions. Combining the two management options compounded the effects. The corresponding effects on the catch was that increased effort and reduced bag limit led to higher retained catches. Doubling the effort however did not double catch, and so it was more difficult to catch fish under increased effort, as catch rates declined. Catches and catch rates however could be increased, at least initially, by removing bag limits in the model, which correspondingly led to an overall reduction in spangled emperor biomass in the park.

Under the simulated current management arrangements fishing pressure was greatest, and biomass lowest, around Exmouth, because most of the effort was assumed to be concentrated in this area. Implementation of the current closures appears to have had a greater effect around Coral Bay than around Exmouth or Tantibiddi Creek in the north. Although bag limits tended to have an effect throughout most of the park, in the vicinity of Exmouth (10-15 nautical miles) bag limits appeared to have little effect mainly because the model assumed there was a high concentration of effort in this area, and any fish discarded would tend to be taken subsequently by other fishers.

In work shown in this report, we derived, from a stakeholder workshop, potential future management actions. These included the effect of increasing the extent of no-take sanctuary zones (2 alternative strategies; see Fig 4), and prohibiting fishing from shore into sanctuary zones, where it is permitted under the current Marine Park Management Plan.

The effectiveness of the alternative management actions in the simulation model were measured against the management objectives of the stakeholders. Management objectives were classified according to ecological (conservation) objectives, or social and economic objectives. For example, in the workshop setting stakeholders proposed a conservation objective that, with more than 75% probability, the spawning biomass in the sanctuaries should be above 75% of pre-exploitation level. The simulation results showed that restricting shore fishing into sanctuary zones had the biggest effect on the spawning biomass in the sanctuaries and achieved the conservation objective, set by the stakeholders, in 100 out of 100 trajectories of the model. Alternatively, if a catch limit was imposed on the recreational fishers, and effectively enforced, while still allowing fishing in sanctuaries from shore, only 10 simulations out of 100 achieved the stakeholder objective. Thus, restricting shore-based fishing in sanctuaries was best able to achieve the management objective of conserving biomass in the sanctuaries, while imposing the catch limit (and allowing shore fish to occur) did not.

The implementation of shore fishing in sanctuaries in the model, conservatively, assumed that the amount of fishing effort from shore was similar to that of boat-based fishing. Because the management strategy that restricted fishing from shore in the sanctuaries had one of the largest effects, particularly on the conservation objectives (performance indicators), and because most of the other management strategies assumed fishing occurred in the sanctuaries from shore-based activities, those management strategies did not achieve the conservation objectives set out.

The other management actions examined included expanding the sanctuary zones, adding an education program, and increasing the compliance monitoring on the fishery. Changing the sanctuary zones in the model had a marginal effect on the biomass across the entire park, but mainly affected the distribution of biomass between the sanctuary and non-sanctuary zones. The reason is that when sanctuary zones are expanded to cover a greater amount of area, then fishing is precluded from an increased number of areas in the Marine Park, leading to fishing effort becoming concentrated in the remaining areas open to fishing, and increased fishing pressure reduces fish population biomass locally, in those areas. The management strategies that were proposed to combat infringement were marginally effective mainly because a relatively small amount of infringement was assumed in the model, and without more data on why and the degree to which infringement occurs, it is difficult to compare these to the other management actions.

In general, the results showed that current management arrangements perform adequately against the range of ecological and social objectives. However, for other management actions, the results showed the inherent trade-off that exists between the ecological objectives and the social objectives. For example, restricting fishing in sanctuaries from shore did well to achieve the conservation objectives, but did not achieve the social objectives as well as other management strategies. Imposing catch restrictions, increasing compliance monitoring and implementing an education program to reduce infringement also performed well against both social and ecological objectives, but explicit consideration of the feasibility, likely effectiveness and cost of implementing the simulated management strategies are uncertainties that our analysis did not consider. Such factors are likely to be extremely important for any realistic implementation of these management actions.

Lastly, we also examined the effect of a selection of management strategies under alternative projected future scenarios. Three management strategies, including; (i) simulating current management conditions in the park (reference strategy), (ii) allowing “increased (fishing) effort” and (iii) capping total catch from the stock (catch limit), were examined. Each of these strategies were simulated for the following potential future scenarios: (i) hypothesized effects of climate change through on-going effects on the life history of spangled emperor, (ii) potential mortality events from cyclones, (iii) improved access to fishing the reef from Coral Bay, and (iv) further developments in fishing technology that improve the capacity to find and catch fish. Under the alternative future scenarios the management strategy that was most likely to achieve the objectives involved capping the catch. The management strategy that allowed effort to increase was best at achieving the social objective of maximizing catches, including the catch of large fish. Although the simulations indicated that as an effective strategy for future alternative scenarios the catch limit strategy may need to be used for indirectly limiting the overall level of catch of spangled emperor from this sector. Such a strategy may not be practical however, and may instead rely on a combination of strategies limiting effort, or something else quite novel and resource intensive to limit catches (like pink snapper tags in Freycinet Estuary in Shark Bay, WA for implementing a recreational TAC). Of course such a strategy is also species specific and does not limit potential sustainability risks for other species, despite the use of spangled emperor as an indicator species for the suite of demersal scalefish species in the Gascoyne Coast Bioregion.

The power of management strategy evaluation is that it can capture and simulate the full actions that are made by management. This could help determine the efficacy of fisheries management procedures that include assessment models estimating the state of the population, and the decision-making process. This offers management a powerful tool to be able to test their management practice(s) in the simulation setting before they implement them in reality.

1.1 Date

December 2010

1.2 Project Title & Number

Ningaloo Reef Project 3.2.3 Biodiversity Assessment, Ecosystem Impacts of Human Usage and Management Strategy Evaluation

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1.5 Dates covered

May 2007 – December 2010

2. KEY FINDINGS AND RECOMMENDATIONS

2.1 Objectives and Outcomes-Key Findings

A range of broad objectives and management questions were developed for this project in the context of the Ningaloo Marine Park Management Plan. These are outlined below.

2.1.1 Public Policy Statements (NMP Management Plan)

Investigate the applicability and benefits of implementing a management strategy evaluation approach to support performance assessment and adaptive management. The applicability and benefits of the management strategy approach were investigated, and the results of various management strategies were compared against management objectives developed with stakeholders.

Formulate performance measures and targets for key recreational species that will ensure ecologically sustainable recreational fishing in the reserves. In stakeholder workshops performance indicators were developed as they related to each stakeholder objective. These are reported in the final report.

Undertake research to support the development of management targets for commercially and recreationally targeted finfish species and assess the appropriateness of current management controls. Current management controls were examined in the mid-term report (Little et al. 2009). The contents of this report focused on the recreational fishing as this is the primary extractive activity in the park. It also focused on spangled emperor (*Lethrinus nebulosus*) which is a primary targeted species that is used by DoFWA as an indicator of wider fishing impacts in the marine park. Results looked at the current sanctuary zones compared to the zonation previously implemented, and at the effect of using bag limits in managing the fishery.

2.1.2 Management objectives

Assess the impact of existing management strategies on key target fish species and biodiversity

Current management controls were examined in the mid-term report (Little et al. 2009). The contents of this report focused on the recreational fishing because it is the primary extractive activity in the park and are summarised in the Executive Summary above. We did not examine the management of biodiversity explicitly, but only indirectly as fisheries management in the park a key primary targeted fish species, spangled emperor (*Lethrinus nebulosus*), as a surrogate and an indicator of wider fishing effects in the marine park.

2.1.3 Management Questions

Four management questions developed for this project and how this project addressed them are:

What are the implications of various management scenarios on fish populations?

We investigated several alternative management scenarios on spangled emperor in the marine park. These included eight management strategies under what is thought as current environmental conditions (Table 6), and a subset of three of those management strategies under six potential alternative future scenarios (Table 7).

What are appropriate performance measures for the park's key ecological values

Performance measures are related to the management objectives. We held stakeholder workshops to elucidate the management objectives from stakeholders, and consequent performance measures as they relate to fisheries management, particularly of spangled emperor (Table 5). We did not explore the objectives of other key ecological values as they were thought to be beyond the scope of this project.

What are indicators for the current major pressures on target species, particularly relating to fishing and tourism

The indicators of major fishing pressures on spangled emperor developed in consultation with stakeholders are presented in Table 5. Ideally, fishing pressure would have been best captured by its effect on the simulated spawning biomass of the spangled emperor population, but at present this quantity can not be accurately estimated. Therefore, more relevant indicators for monitoring fishing pressure, given current data availability, that were simulated in the model were CPUE, catches, as well as the average age and average length in the catches.

Are management targets for values and associated monitoring methods sensitive enough to trigger management responses in manner that is timely enough to protect the condition of the values

Many of the proposed management strategies showed little difference to the indicators (objectives), and so they were able to achieve or not achieve the proposed objectives equally. There was little difference for example between “Increased compliance monitoring” and “Education program” management strategies across all indicators (objectives). We also found that some of the indicators pertaining to length and age of fish were not sensitive enough to discriminate among management strategies. This should be investigated further.

2.1.4 Outputs

Evaluation of appropriate indicators and performance measures to supporting management objectives- significant pressures associated with fishing and tourism

The results show the effectiveness of various management strategies against the objectives (indicators) associated with fishing on Ningaloo Reef.

Development of integrated data products and modelling framework relating ecological and socio-economic processes in Ningaloo to impacts on key target fish species and biodiversity

Integrated data product developed for this project is a model (ELFSim framework) used for management strategy evaluation, and decision support on Ningaloo Reef. Models results were generated and also represent data products available.

Asess, test and ultimately improve the effectiveness of management and monitoring strategies for key target fish species

The results of the assessment and evaluation of the management strategies are provided and summarised in this report.

2.1.5 Research Objectives

Key questions relevant to this subproject were provided in a NRP Workshop (February 2006).

1. To develop performance measures for some of the region’s key ecological values (related in particular to target species and behaviour of fishers).

2. To develop indicators for current major pressures on target species, particularly relating to fishing and tourism (the latter through the CSIRO Flagship Cluster).

3. To simulation test the effectiveness of management and monitoring strategies (including indicators and performance measures) in managing key target species of the region.

4. To develop a project data management framework consistent with WAMSI’s cross-nodal information management requirements.

5. To transfer information and tools to management agencies and other NRP and CSIRO Cluster projects (subject to approval by third party IP holders where appropriate).

6. Production of integrated reports detailing project findings and linking to relevant inputs provided by other NRP projects and the CSIRO 'Ningaloo Cluster'.

Accordingly this sub-project was structured to provide five main outputs aimed at integrating and extending the outputs of other subprojects presented here as well as projects in the NRP and Ningaloo WfO Collaborative Cluster.

Output 1. A project consultative committee was established with members from the relevant state departments, the NRP, the CSIRO Wealth from Oceans Flagship, and other stakeholder groups. Extensive stakeholder engagement was taken to derive the operational management objectives and strategies examined in this report.

Output 2. Develop and evaluate appropriate indicators and performance measures to supporting management objectives will be developed in consultation with the relevant management agencies (Objectives 1 and 2). These were to be framed around the natural values of the Ningaloo region and the potentially significant pressures associated with fishing and tourism. Indicators were developed from stakeholder engagement and assigned based on the management objectives determined from stakeholder workshops (see 3.7 Appendix).

Output 3. Integrated data products and a modelling framework (ELFSim) was to be developed relating selected ecological and socio-economic processes in the Ningaloo region (Objective 3). Quantitative modelling would provide a means to assess and examine the effectiveness of management and monitoring strategies for a key target species in the region. Quantitative modelling developed for this project have been developed (ELFSim framework) and used for management strategy evaluation, and decision support on Ningaloo Reef. Models results were generated and represent data products available.

Output 4. Model outputs, as well as data collated to drive or calibrate the model, are to be managed by CSIRO and made available online to management agencies and other NRP and CSIRO Cluster projects (Objectives 4 and 5). Subject to Deed of Confidentiality and Non-Disclosure signed by CSIRO for DoFWA's data, which stipulates that written approval is required before DoFWA's data [data and data derived from the data collected by DoFWA] is published.

Output 5. Midterm and final reports were developed detailing key findings and linking management relevant outputs from other NRP projects (Objective 6). These reports were not to replicate those of other projects but, within NRP resource constraints, aim to present key findings within a unified framework oriented towards management needs. To most effectively capture input made available from other NRP activities, this reporting was to be scheduled following reporting by other projects by a few months. Reports were completed on time.

2.1.6 Operational Management Objectives

The fisheries (Dept Fisheries WA) and conservation (Dept. Environmental Conservation) management agencies were consulted extensively in this project. In order to align the efforts of DoFWA and this project, members of DoFWA were invited to the project team and contributed extensively to the production. Operational management objectives for recreational fishing are covered in detail in this report. There is no commercial fishing in the Ningaloo Marine Park.

Management objectives, strategies and indicators were developed in the context of the Ningaloo Marine Park Management Plan. These management details address a broad range of ecological, social and conservation issues. Measures implemented include: sanctuary (i.e., no fishing) zonation for 34% of the park; facilitation of comprehensive research and monitoring programs; instigation of education and information programs; regulation of recreational use to ensure sustainability; and integration of management of the marine environment and the adjoining coastal lands.

2.1.7 Key findings

The key findings of this project were:

1. As a conservation management tool, the results of the mid-term report (Little et al. 2009) found that sanctuaries work to conserve fish populations, but when used as a fisheries management tool, the concentration of effort outside sanctuaries counteracts the beneficial population effects of the sanctuaries. Thus, when managing for exploited populations, if sanctuaries are to be implemented then ideally their implementation should be combined with other methods of reducing fishing pressure.

2. The current sanctuaries are likely conserving a greater amount of the fish biomass than the previous zones.

3. The biggest factor in controlling fishing pressure is fishing effort. Fishing effort however can be difficult to control. The use of bag-limits as a strategy for controlling fishing effort was demonstrated in simulation results.

4. Spawning biomass was put forth by stakeholders as a key indicator of the target species status in the model, but in reality it is very resource intensive to estimate this quantity reliably. Therefore, alternative indicators for fishing pressure for use are CPUE, catches, as well as the average age and average length in the catches as indicators were also used as indicators in the simulation.

5. Some of the indicators pertaining to length and age of fish were not sensitive enough to discriminate among the management strategies. This should be investigated further.

6. Infringement (e.g. illegal fishing in sanctuary zones, exceeding bag limits) is important and may lead to reduced biomass, particularly in the protected sanctuary zones. It is unknown whether the levels in the model were accurate depictions of reality.

7. The biggest factor in achieving the conservation objectives, particularly for the sanctuary zones was the allowance of fishing in sanctuaries from shore. Such activity strongly affected the biomass in the sanctuary zones. We assumed a conservative estimate that the amount of shore based fishing was equal to recent boat based fishing effort. More information on the effects of shore based fishing in the sanctuaries is warranted.

8. Making predictions of the future scenarios is difficult everywhere. The scenarios we proposed ranged from broad scale environmental changes across the fishery to small-scale changes of expanding boat ramp capacity. The assumed effects of environmental

pressure on the natural mortality of spangled emperor had the biggest effect on the fishery. However, the cause of such effects is not well understood and so there is a great amount of uncertainty attached to these results. Relatively small-scale changes in fishing effort, catches and spangled emperor population biomass associated with expanded boat ramp capacity at Coral Bay did not affect the wider park to a great degree in the simulations.

Management Frameworks

Provide basis for evaluating current management strategies and their effectiveness in protecting target fish species given the historic and current level of fishing pressure

The basis for evaluating the current management strategies was to determine if they could achieve the various conservation and social objectives set out in a workshop by the stakeholders. In addition, a further subset of these strategies was examined under a range of different future scenarios.

Assist in setting targets and identifying the best management strategies that will achieve them for target fish species

The final report documents the targets (Table 5) and management objectives developed through consultation with stakeholders, and tested alternative management strategies against those objectives.

Education

Demonstrate the links between fishing, fish populations and management strategies to gain support for current or additional management strategies

Consultation with stakeholder groups in the workshop setting was essential to educating them about management strategy evaluation. The workshop detailed the simulation model and its use, including ways management actions can be implemented in it. Appendix 3.7 documents the stakeholders who attended the final stakeholder workshop in which the objectives (Table 5) and management strategies (Tables 6 and 7) were developed and finalised.

Surveillance & Enforcement

Identify whether compliance with regulations is an issue

Compliance with regulation might be an issue in the recreational fishery but we lacked data documenting the degree to which infringement of fisheries regulations (boats fishing in the sanctuaries, and keeping more than the bag limit) actually occur. Results showed that with a modest amount of infringement in the simulations (i.e. a compliance rate of 95%) resulted in slightly lower biomass than if an education or enforcement strategies were implemented.

Management Intervention

Identify where alternative management strategies, including direct intervention may be required

The factor identified in simulations done for the final report that led had the biggest effect on the spawning biomass, particularly in the putatively protected sanctuaries, was the ability to fish in the sanctuaries from shore. We assumed a conservative estimate that the amount of shore based fishing was equal to recent boat based fishing effort, and found that shore based fishing activities had a relatively large effect in the simulations. More information on the effects of shore based fishing in the sanctuaries is warranted.

Research

Will identify important features of the biology of fish species and human exploitation that lead to significant population changes and may point to further information required to improve model

The results have identified future empirical and modelling research required. These include updating the model with current data as it comes in. This may involve changing the fishing behaviour in the model as data on the recreational use in the park becomes available. Further, a need for research into the effects of shore fishing in the sanctuaries was highlighted as important in results of the simulations.

Monitoring & Evaluation

Provide basis for development of management targets, performance indicators and temporal/spatial scale to set up monitoring programs

The model that was developed for this project is the basis on which different monitoring, assessment and decision rules can be tested. This is an area that has been identified for potential future research collaboration between CSIRO and DoFWA.

2.2 Implications for Management - Recommendations

1. When managing for exploited populations, the use of sanctuaries needs to be combined with other methods of reducing fishing pressure.

2. Some of the indicators pertaining to length and age of fish were not sensitive enough to discriminate among the management strategies. This should be investigated further.

3. The indicators developed in this projected should be related to the fisheries management procedures being developed for the Gascoyne region (Wise et al. 2007, Marriot et al. 2010a). The procedures being developed include assessment models estimating the fishing mortality relative to natural mortality,

and decision procedures that use these estimates to achieve fishery management objectives. This feedback management strategy should be tested in the MSE model, and possibly show the accuracy of the assessment method and efficacy of the management procedure.

4. The effect of fishing in sanctuaries from shore should be reviewed and examined in greater detail as this has had a major effect on the conservation status of the target species in the sanctuary zones in simulation results. This demonstrates a need to collect accurate measurements of fishing infringement rates within the marine park.

5. The biggest factor in controlling fishing pressure is fishing effort and the use of bag-limits was demonstrated to provide a small means of control. Many other potential strategies are available, however, and the effectiveness of these could be explored in isolation or in combination using the procedures demonstrated in this report.

2.3 Other Benefits

This project has developed a simulation harvest model for a recreational fishery. Simulation models in the past have traditionally focussed on commercial fishing activity but there is increasing demand for such model of recreational fishing. This project leads the way in simulation modelling for recreational fisheries.

2.3.1 Tools, Technologies and Information for Improved Ecosystem Management

This project has developed a decision support tool for fisheries management. There are future plans to collaborate in the testing of assessment models, and decision procedures.

2.3.2 Forecasting for Natural Resource Management Decisions

There are future plans for using this model to test the fisheries management procedures (assessment and decision procedures) being developed for the Gascoyne Coast Bioregion (Wise et al. 2007, Marriott et al. 2010a).

2.3.3 Impacts

This work has brought together DoFWA, and CSIRO scientists to formulate the model and its use. It has done this within the context set by DEC in the management strategies, and objectives that they had and were interested in. It has thus provided a nexus for interaction among the research interests in the marine park.

2.4 Problems Encountered

As always with modelling projects, getting data in a timely manner from other aspects of the larger program were encountered. This included obtaining data that could help parameterise the behavioural model of the recreational fishing and other activities. To obtain fisheries data we signed a confidentiality agreement with DoFWA relatively early in the project, which greatly helped in development of the project. Updating recreational fishing data in the model is possible in the future as new data become available.

3. AN EVALUATION OF MANAGEMENT STRATEGIES FOR LINE FISHING IN THE NINGALOO MARINE PARK

3.1 Introduction

This body of work examined management strategies for line fishing, the main extractive activity permitted in the Ningaloo Marine Park, as a result of recreation by local residents and tourists. It consisted of the implementation of the ELFSim computer software, calibration of this software using data from the Western Australia Department of Fisheries (DoFWA) and specification and identification of management objectives and indicators of management performance, as well as selection and testing of potential management strategies in collaboration among stakeholders. Implementation of such a management strategy evaluation was discussed with WA agency staff in workshops in May 2006 in August and September 2006, November 2008 and April 2010. These workshops elicited and identified clear needs of management agencies.

In this report we describe:

- background to the project within the context of the larger NRP
- the Management Strategy Evaluation (MSE) approach, which is planned to be used as a general framework for the study and integrated management of Ningaloo Marine Park
  - a general outline of the ELFSim software and its role in MSE
  - the analyses and assumptions we have performed to apply ELFSim to the Ningaloo Marine Park, and the data we have used to derive values for the parameters of the model
  - results of simulating the effects of management strategies suggested in consultation with stakeholders

3.1.1 Background

The Ningaloo Research Program

The main objectives of the Ningaloo Research Program were:

• “to underpin protection and management of the Ningaloo Coast by providing a good understanding of the conservation needs of the area, and how those needs can best be met”;

• “to support the World Heritage nomination of the Ningaloo Marine Park and North West Cape”;

• “to boost efforts to conserve threatened species, including the whale shark”

The “Integration for Management of Ningaloo’s Marine Environmental Resources” project will make a major contribution to these objectives by:

- increasing system understanding through development of an integrated modelling framework and the provision of explanatory reports supplemented with input from other NRP projects,

- providing tools to assist management agencies to identify effective management strategies in meeting selected management objectives, and

- providing tools that can be adapted to support threatened species risk assessments and evaluations of alternative management approaches.

3.1.2 Integration for Management of Ningaloo’s Marine Environmental Resources

The aims of this project have been to:

- Seek from management agencies a clear exposition of their decision support needs through meetings, correspondence and workshops, and reach agreement with these agencies on which of these the project can address on time and within budget.

- Develop integrated data products and a modelling framework relating key ecological and socio-economic processes in the Ningaloo region. These products and tools will be designed to support assessment of risks associated with recreational fishing and environmental trends (e.g. climate variability and change) in the region. They will also be used to evaluate existing and alternative management strategies in terms of identified management objectives in simulation space.

- Lead and coordinate the completion of a number of integrated reports summarising and linking findings across the NRP and the CSIRO ‘Ningaloo Cluster’, with an emphasis on relevance to management.

- Transfer information and tools to management agencies and other NRP and CSIRO Cluster projects.

Achievement of these objectives involved bringing a broad range of physical, biological and socio-economic information and process understanding being developed through the NRP and the CSIRO ‘Ningaloo Cluster’ into an integrated framework. This facilitated collation and interpretation of data gathered both historically and through the NRP. It also provided an effective interface with management through development of tools that directly address needs such as risk assessment, performance assessment, and management strategy evaluation (e.g. multiple-use zoning, fishing effort controls, new monitoring regimes).

Project outputs included:

- Software tools to support integrated management, including treatment of important elements of ecosystem models, socio-economic models, management strategy evaluation models, and output visualisation.

- Performance assessment of existing zoning and monitoring against management objectives under a range of environmental and socio-economic scenarios.
- Evaluations of a range of potential future management and monitoring strategies identified through consultation with management agencies.
- Identified indicators and associated targets to meet management objectives.
- Mid-term and final reports detailing project findings and incorporating outcomes and products supplied by other projects of the NRP.
- Scientific papers in international journals.
- Web accessible data and metadata.
- Integrated data products to ensure compatibility with government agencies and other research providers.

This project has been one of the suppliers of integrated data products to management. It will utilise data archiving and distribution systems based on Geodatabase technology and interface with the Department of Environment and Conservation Marine Information System Network. (Subject to Deed of Confidentiality and Non-Disclosure signed by CSIRO for DoFWA's data, which stipulates that written approval is required before DoFWA's data [data and data derived from the data collected by DoFWA] is published.) Metadata will be generated for all data produced by this project.

3.1.3 Management Strategy Evaluation

One of the big challenges for contemporary Australian society is the management of competing human uses of, and impacts on, natural and transformed ecosystems. Growing urbanisation, as well as industrial and tourism development have increased the need for government to broker a balance among the activities of many users of the natural and built environment. In meeting this challenge, governments have encouraged an increasingly prominent role for science to provide information and analytical methods for supporting policy and management decisions. In the past the tendency has been to use scientific advice on an ad hoc basis. The growing requirement for scientific knowledge in collective decision-making has prompted scientific research agencies to seek better ways of providing scientific support.

Among the barriers to the uptake of scientific knowledge in collective decision-making processes is the frequent lack of a broad decision framework within which stakeholders and management agencies can assess merits and implications of particular scientific advice. Accordingly, it is to a broad decision framework that scientists have turned their attention in attempting to communicate with a widening range of stakeholders. Such a framework requires active participation of stakeholders (including management agencies) and facilitates the generation of ideas, identification of problems and approaches for solving them, as well as anticipation of real-world impacts. It necessarily spans diverse fields ranging from biophysical, social and economic sciences, to jurisdictional, political, institutional and managerial processes.

In response to this evolution of the context in which scientific advice is provided, CSIRO Marine and Atmospheric Research has developed an integrated management strategy evaluation (MSE) framework. The purpose of the integrated MSE framework is to advance the science and tools used to characterise, monitor, predict and manage ecosystems at the whole-of-ecosystem level, by recognising links across socio-economics, physics, biogeochemistry, trophodynamics, population and community ecology, and interactions across time and space scales. Integrated MSE has been applied successfully to fisheries, and has recently been developed for providing a scientific decision support for multiple use management of coastal regions and estuaries.

The design of the integrated MSE framework has been guided by the need to tackle a combination of theoretical, methodological and technical questions. Although to date, integrated MSE has been mainly applied to coastal and marine ecosystems, the supporting computer software is specified so that it can be readily applied in other situations. It is, therefore, adaptable to a wide range of collective decision problems in terrestrial, coastal and marine regional ecosystems that are subjected to human impacts.

MSE Methods

The integrated MSE framework uses process-based mechanistic numerical models to emulate environmental, social and economic conditions and processes associated with the state of an ecosystem and its evolution in response to natural forcing and human use. It makes use of observations and generates data that can be displayed as maps (GIS shape files), images (digital photography and pictures) and numerical values recorded over time.

Critical to integrated MSE is the clear definition of two main elements: Strategies and Scenarios. In addition, agreed indicator variables describing the outcomes and allowing confrontation of these outcomes with pre-stated objectives is required.

•Strategies.

A strategy is a deliberate existing or planned course of action by one or more people. It may be a management strategy that constrains human use in order to achieve environmental, social and economic objectives. It may be a monitoring strategy (or program) designed to observe and measure the state of the ecosystem through time and space in order to build a set of environmental, social and economic indicators. It may be a business or private strategy aimed at achieving business outcomes or personal advantage. It may be a particular set of policy instruments or governance arrangements. It may also be a combination of these and other types of strategies.

•Scenarios.

A scenario is a hypothesised future trajectory of external forces on either the system itself or a computer representation (or model) of the real system. Uncertainty in knowledge usually leads to several alternative scenarios of the system, which include the natural ecosystem and relevant components of human society. These scenarios represent alternative hypotheses about the current state of nature and how the system evolves in response to exogenously determined natural events and human actions.

•MSE Outputs.

For each combination of a strategy and scenario, the MSE provides output data in the form of indicator variables. The display of these data may then be used to compare and contrast similar displays for different combinations of strategy and scenario.

3.1.4 Context of the MSE application: the Current Management Plan for the Ningaloo Marine Park

Current management objectives, strategies and targets for the Ningaloo Marine Park are documented in CALM and MPRA (2005). These management details address a broad range of ecological, social and conservation issues. Measures implemented include: sanctuary zonation for 34% of the park; facilitation of comprehensive research and monitoring programs; instigation of education and information programs; regulation of recreational use to ensure sustainability of marine resources; and integration of management of the marine environment and the adjoining coastal lands.

The management plan (CALM and MPRA 2005) is directed broadly at conservation of ecological and social values. These values are specified to include: species and communities of species conservation status; key endemic species; key structural organisms of the ecosystem; exploited species and communities; key physical and chemical components of the ecosystem; and major cultural and aesthetic, recreational and economic attributes. Although all the strategic objectives related to conservation, science and education, public participation, recreational use and commercial uses are important, we focus in this project on a selection of specific management objectives that can be addressed and quantified within our modelling framework.

Research, monitoring and the management of fishing within and outside of the Ningaloo Marine Park in Western Australia falls under the jurisdiction of the Department of Fisheries, Western Australia (DoFWA; Fletcher and Santoro, 2010). Current research and monitoring activities conducted by the DoFWA within the Marine Park include assessments of the stock status of the demersal scalefish resource from inshore waters (20-250 m deep) of the Gascoyne Coast Bioregion (from Shark Bay to Exmouth Gulf, inclusive) and characterising each of the fishing sectors (commercial, recreational, indigenous) that exploit this resource. Information from this work is being used to develop DoFWA policy for implementing Integrated Fisheries Management strategies in the Bioregion (Marriott *et al.* 2010 a, b). The spangled emperor, which is the focal species of this report, is also one of three indicator species currently monitored and assessed by the DoFWA for this purpose. Results from this report will be available to DoFWA and DEC managers to assist with the development of suitable management strategies, and will likely be particularly useful for addressing the complexities in jurisdictional arrangements among government departments for managing fishing activities within the Marine Park.

Additionally, although this project concentrates on management objectives related to line fishing, future work could address objectives related to other ecological and social aspects of the Ningaloo Marine Park.

The NRP modelling projects were established to provide information that may help in the judgement of whether actual or proposed management strategies are likely to achieve specific management objectives. This modelling work is relevant to a suite of management objectives, and the strategies designed to achieve them, contained in the Ningaloo Management Plan. The following objectives and associated strategies from the management plan (Table 1) provide the focus for our MSE modelling work.

Table 1 Management objectives and associated management strategies from the Ningaloo Management Plan (CALM and MPRA 2005) relevant to MSE modelling in the NRP and CSIRO Ningaloo Cluster projects.

Page	Management Objective	Management Strategy
p. 29	To ensure the diversity and abundance of coral reef communities in the reserves are not significantly impacted by human activities within the reserves.	1. Zoning for various permitted uses. 2. Assess the nature, level and potential impacts of human activities. and recreational fishing in particular, on coral communities. 6. Educate users of the reserves about … the potential detrimental effects of … walking, collecting, anchoring and boating activities. 7. Implement a mooring plan. 3. - 5., 8. – 10. Undertake research and monitoring activities to assess ecosystem dynamics under human-use, climate-change and extreme event pressures.
p. 31	To ensure that important filter feeding communities are not significantly impacted by human activities in the reserves	1. Zoning 2.– 4. Undertake research, monitoring and mapping activities.
p. 35	To ensure the species diversity and biomass of soft sediment communities within the reserves are not significantly impacted by human activities in the Park	1. Zoning 2.-3. Undertake research and monitoring activities to assess community dynamics and human impacts on them.

	Management Objective	Management Strategy
p. 37	To ensure seagrass and micro-algal communities are not disturbed as a result of human activities in the reserves.	1. Zoning 2.– 4. Undertake research, education, and monitoring activities to characterise seagrass and microalgal communities and mitigate the effects of human activities.
p. 43	To ensure the species diversity and abundance of seabird, shorebird and migratory bird species in reserves are not significantly impacted by human activity.	1. Zoning 2.– 4. Undertake research and monitoring activities to characterise bird distribution and abundance and to assess the impact on them of vehicles and human activities.
p. 46	To ensure the species distribution and abundance of finfish species are not unacceptably impacted by recreational and commercial fishing in the reserves.	1. Zoning 2.– 4. Undertake research and monitoring programs to assess finfish diversity and abundance, to identify species requiring protection, to establish management targets and to implement measures to progressively reduce bycatch of finfish and other species in the reserves.
p. 48	To gain an understanding of the invertebrate diversity and abundance throughout the reserves to facilitate long-term management.	1. Zoning 2.– 4. Undertake research and monitoring programs to assess invertebrate diversity and abundance, to identify species requiring protection, to amend notices under the WC Act and FRM Act as necessary, to establish management targets and to implement measures to progressively reduce bycatch of invertebrates in the reserves.

	Management Objective	Management Strategy
p. 51-57	To ensure whale sharks migrating through the reserves and manta rays, whales and dolphins in the reserves are not disturbed by boating, interactive tours, snorkelling and other human activities in the reserves.	1. Implementation of the Whaleshark Interaction Management Program No. 27 2. Develop codes of conduct and education programs to reduce impacts of human activities. 3. Undertake research and monitoring programs to characterise migratory patterns and the impacts of human activities on these, to consider licensing arrangements for commercial activities and to consider changes to existing management arrangements as necessary.
p. 59	To ensure turtles in the reserves are not significantly disturbed by foxes or recreational activities on beaches.	1. Continue the fox control program. 2. – 7. Undertake research and continue monitoring programs to determine locations of turtle aggregation sites and rookeries and to ensure that human activities do not impact turtle population dynamics on spatial patterns.
p. 60	To ensure dugong in reserves are not significantly disturbed by human activity.	1. – 3. Undertake research and continue monitoring programs to determine human impacts and the state of dugong populations in the reserves and the adjacent Exmouth Gulf and to determine the extent and level of sustainable indigenous hunting of dugong.

	Management Objective	Management Strategy
p. 73	1. To ensure that recreational fishing in the reserves is managed in a manner that is consistent with maintaining the reserves' values. 2. To maintain the ecological values of the reserves that are important to recreational fishing.	1. Zoning. 2. – 9. Undertake research, education, and surveillance programs to ensure compliance with zone restrictions and other management regulations, to determine management targets, to record recreational catch and effort data and to implement a community monitoring program for key target species in the reserves.
p. 79	1. To ensure that commercial fishing in the reserves is managed in a manner that is consistent with maintaining the reserves' values. 2. To maintain the ecological values of the reserves that are important to commercial fishing.	1. – 4. Undertake research and monitoring programs to support development of management targets, to assess the levels and effects of commercial fishing (particularly the marine aquarium fishing) in the reserves and to review the effectiveness of existing management controls.

These selected objectives and strategies provided the foundation for discussion with management agencies, resource users, and the general public about other potentially valuable objectives or strategies.

3.1.5 The ELFSim software

ELFSim is a decision support tool (Little et al. 2007) designed to evaluate options for conservation and harvest management. It includes a number of key components.

- A (meta) population dynamics model of target species that captures their full life history (including larval dispersal, reproduction, development, and habits).

- A spatial effort allocation model that captures the exploitation pattern due to fishing behaviour.

- The ability to account for harvest by multiple sectors.

- A management model that simulates the implementation of management strategies.

- Output visualisation and run management, for easy scenario testing and interpretation of results.

ELFSim is suited to addressing the “Integration for Management of Ningaloo’s Marine Environmental Resources” because it incorporates the following features.

- It can be used to evaluate the effect of different zone closures on both the stocks and their harvest.

- It can model both sedentary and mobile target species.

- It can model different levels of larval settlement/transport, depending on the target species and, consequently, can account for the potential benefit of specific area closures.

- It can extrapolate fish stock dynamics into the future, subject to simulated fishing pressure which depends on imposed management measures.

- It allows the user to evaluate the consequences of various management options by examining biological and economic performance indicators that are generated from the model.

- It allows the user to specify area closures, gear selectivity and minimum catch size. The user is also able to specify an annual amount of effort to be allocated over the area.

ELFSim operates at a monthly time scale and each simulation consists of two parts. In the first, the biological component uses information from the physical characteristics of individual reefs to determine the population size (and its age-, sex- and size-structure) on each reef given the documented amount of past fishing. In the second part, which projects the reef populations forward in time, the biological component is subjected to simulated fishing pressure, which is in turn subject to management measures imposed by the user. The user is then able to evaluate various management options by examining biological and economic performance indicators that are produced from the model. The duration of the projection period can be set by the users, and was discussed with the consultative committee for the project, as well as with stakeholders.

3.2 Materials and Methods

3.2.1 The Model

The Biological Operating Model

The biological operating model of ELFSim incorporates many of the features of the models of coral trout population dynamics developed by Walters and Sainsbury (1990) and Mapstone *et al*. (1996). Each population is assumed to consist of several sub-populations each associated with a single reef or spatial location. The population dynamics model is age-, sex- and size-structured, assumes that the number of 0-year-olds is related to the size of the reproductive component of the population according to a stock-recruitment relationship, and allows for larval movement. Several sources of process error (Francis and Shotton, 1996) such as variation in natural mortality and larval survival are included in the operating model. The operating model allows for multiple vessel-classes.

The population model allows for movement of larvae but ignores the possibility of movement of animals aged 1 and older. A specific model that incorporates the movement of older animals has been developed that requires age data across spatial locations (Little et al. 2008). However, given recent information on the lack of spangled emperor movement (Moran et al. 1993, Pillans et al. 2009), and so we did not employ this process in the model we used.

The equations below assume that the parameters determining natural mortality, fecundity, sex-change and growth are common to all reefs. The software that implements the model has the functionality to allow these parameters to depend on reef.

Basic population dynamics

The resource dynamics are modelled using the equations:

$$N^{r,k}_{y+1,a} = \begin{cases} N^{r,k}_{y+1,a} & a = 0,1 \\ N^{r,k}_{y,12,a-1}\, e^{-Z^{r,k}_{y,12,a-1}} & a = 2,\ldots,x-1 \\ N^{r,k}_{y,12,x-1}\, e^{-Z^{r,k}_{y,12,x-1}} + N^{r,k}_{y,12,x}\, e^{-Z^{r,k}_{y,12,x}} & a = x \end{cases} \qquad (1)$$

where $N^{r,k}_{y,a}$ is the number of fish of age *a* in growth group *k* on reef *r* at the start of year *y* (individual in a growth class remain in the class for their entire life),

$N^{r,k}_{y,m,a}$ is the number of fish of age *a* in growth group *k* on reef *r* at the start of month *m* of year *y* (by definition $N^{r,k}_{y,1,a} = N^{r,k}_{y,a}$):

$$N^{r,k}_{y,m+1,a} = N^{r,k}_{y,m,a}\, e^{-Z^{r,k}_{y,m,a}} \qquad (2)$$

$Z^{r,k}_{y,m,a}$ is the total mortality on fish of age *a* in growth group *k* on reef *r* during month *m* of year *y*:

$$Z^{r,k}_{y,m,a} = M^{r}_{y,a}/12 + \sum_{v}(F^{r,k}_{y,m,a,v} + F'^{r,k}_{y,m,a,v}) \qquad (3)$$

$M^{r}_{y,a}$ is the instantaneous rate of natural mortality on fish of age *a* during year *y,*

$F^{r,k}_{y,m,a,v}$ is the fishing mortality on fish of age *a* in growth group *k* on reef *r* during month *m* of year *y* by vessel-class *v*,

$F'^{r,k}_{y,m,a,v}$ is the fishing mortality caused by effort that discards fish age *a* in growth group *k* on reef *r* during month *m* of year *y* by vessel-class *v*,

D is the fraction of fish that are retained following capture

R is the fraction of fish that die after being discarded, and

x is the maximum age considered (taken to be a "plus group").

0-year-olds

All fish are born as females (Marriott et al. 2010b). The number of 0-year-olds on reef *r* at the start of year *y* is determined from a contribution from spawning on reef *r* and from a contribution from all reefs:

$$N_{y,0}^{r,k} = K^k \left[st\, \tilde{f}^r\, S_y^r + (1-st) c^r\, BL_y^r \right] \tag{4}$$

where S_y^r is size of the reproductive component of the population on reef *r* at the start of year *y* (taken to be the biomass of mature females – also referred to as the spawner biomass):

$$S_y^r = \sum_{a=1}^{x} \sum_k f_{L_{k,a}}\, w_{L_{k,a}}\, N_{y,a}^{r,k} \quad (1 - P_{L_{k,a}}) \tag{5}$$

$$\tilde{f}^r = \frac{N_{0,0}^r}{S_0^r}$$

$$c^r = \frac{N_{0,0}^{r'}}{\sum_{r'} N_{0,0}^{r'} \Omega^{r',r}}$$

S_0^r is the size of the reproductive component of the population on reef *r* at pre-exploitation equilibrium,

$N_{0,0}^r$ is the number of 0-year-olds on reef *r* at pre-exploitation equilibrium.

st is the fraction of the larvae that settle on reef *r* that originated from reef *r*,

$L_{k,a}$ is the length of a fish of age *a* in growth group *k*,

K^k is the fraction of larvae that fall into growth group *k*,

w_L is the mass of a fish of length *L*,

f_L is the fraction of animals of length *L* that are mature,

P_L is the probability that a fish of length *L* is male,

BL_y^r is the background supply of larvae to reef *r* from all reefs during year *y*:

$$BL_y^r = \sum_{r'} \tilde{f}^{r'}\, S_y^{r'}\, \Omega^{r',r} \tag{6}$$

c^r is the scaling factor for reef *r* to account for variation in background larval supply among reefs, and

$\Omega^{r',r}$ is the fraction of larvae that move from reef r' to reef *r*.

The values in the larval dispersal matrix, Ω, are proportional to the fraction of larvae that move from reef r' to reef *r* because the value for c^r provides an overall scaling factor. The values in the larval dispersal matrix are determined using one of three approaches:

"Uniform" distribution of larvae: $\Omega^{r,r'} = 1$.

Pre-specified. The values for the $\Omega^{r',r}$ are determined directly from models of larval movement.

Distance-based distribution of larvae: $\Omega^{r,r'} = \exp(-A \times d(r,r') - B)$ where the function $d(r,r')$ is the distance between the centres of reefs *r* and r' (in degrees).

The model assumes that there is no contribution of recruits from outside the set of modelled reefs, i.e. the population is closed to recruitment and migration to or from outside the modelled reef system and there is no density-dependence in the spawner-recruit relationship. Thus, a reduction in spawning biomass at one reef will cause a corresponding proportional reduction in the contribution to recruitment from that reef to all other reefs. It is important to note that for spangled emperor, and many other demersal scalefish species, such processes (i.e., localized depletion versus recruitment) can occur, and can be simulated, at different spatial scales with this model.

The bulk of the analyses are based on using the distance-based approach (approach c) because a uniform distribution of larvae is unrealistic, particularly when the model is applied to a large geographic area, because of the influence of currents and tides on larval behaviour. Use of larval dispersal rates determined from models of larval advection and larval behaviour are clearly desirable but these are unavailable at present.

The value of c^r depends on the larval dispersal matrix. The value of c^r is recalculated annually for scenarios in which the larval dispersal matrix is based on the model of larval advection and behaviour, and hence varies among years. The fraction of the animals that are mature, f_L, and the fraction of animals that are male, P_L are determined from logistic functions of length (Marriott et al. 2010b).

Recruitment to reefs

$$N_{y+1,1}^{r,k} = N_{y,0}^{r,k}\, e^{-M_{y,0}-\beta^r (U_{y+1}^r/U_0^r - 1)}\, e^{\varepsilon_y^r - \sigma_r^2/2}\, e^{\sum_i x_{y,i} \exp(\omega_p\, dist(r,c_i))} \tag{9a}$$

$$U_{y+1}^r = \sum_k (N_{y,0}^{r,k}\, e^{-M_{y,0}} + \sum_{a=2}^{J} N_{y+1,a}^{r,k}) \tag{9b}$$

$$\varepsilon_y^r = \tau_r\, z_y + \sqrt{1-\tau_r^2}\, z_y^r \tag{9c}$$

where

β^r is the density-dependence parameter for reef *r*,

U_0^r is the value of U_y^r at pre-exploitation equilibrium,

J is the maximum age of a 'juvenile',

z_y, z_y^r are random deviates from $N(0;\sigma_r^2)$,

σ_r^2 is the overall inter-annual variation in larval abundance,

τ_r is the correlation in larval abundance among reefs,

$x_{y,i}$ is the magnitude of the *i*'th 'recruitment pulse' during year *y*, generated from the normal distribution, $N(0;1^2)$,

ω_p is the parameter that determines the spatial extent of a 'recruitment pulse', and

c_i is the center of the *i*'th 'recruitment pulse'.

Given the formalism adopted, 'recruitment pulses' can lead to higher or lower than expected survival rates from age 0 to age 1. The centres for the 'recruitment' pulses are distributed randomly over the Marine Park. Note that if the model is run for a subset of the reefs, it is possible that the centres for some of the 'recruitment pulses' may fall outside the area considered in the model. 'Recruitment pulses' do not form part of the base-case analyses.

The value for the parameter β^r is determined by solving the system of equations for a pre-specified value for the steepness of the stock-recruitment recruitment, *h* (Mapstone et al. 2004). Steepness is defined after Francis (1992) to be the fraction of the (average) pre-exploitation number of 1-year-olds to be expected when the spawner biomass is reduced to 20% of its (average) pre-exploitation level.

Natural mortality

The model used to determine natural mortality by age and year allows for differences in the mean value of natural mortality among ages, variability in natural mortality over time, the impact of catastrophic events, and time-trends in natural mortality:

$$M_{y,a}^r = (M_{y-1,a}^r)^{\tau^M} (M'_{y,a}\, e^{\varepsilon_{y,a}^M - (\sigma^M)^2/2})^{\sqrt{1-(\tau^M)^2}} \qquad \varepsilon_{y,a}^M \sim N(0;(\sigma^M)^2) \qquad \text{(10a)}$$

$$M'_{y,a} = \begin{cases} M_a + M_c\,\eta_y & \text{if } y \le y_{fst} \\ M_a + M_{fin,a}\frac{(y-y_{fst})}{(y_{fin}-y_{fst})} + M_c\,\eta_y & \text{if } y_{fst} < y < y_{lst} \\ M_a + M_{fin,a} + M_c\,\eta_y & \text{otherwise} \end{cases} \qquad \text{(10b)}$$

where

M_a is the expected rate of natural mortality on animals of age a,

σ^M is the parameter that determines the extent of temporal variation in natural mortality,

τ^M determines the extent of temporal correlation in natural mortality,

y_{fst} is the year in which the natural mortality rate begins to change,

y_{lst} is the year after which the natural mortality rate ceases to change and remains constant,

$M_{fin,a}$ is the amount by which natural mortality changes for an animal of age a,

M_c is the amount by which natural mortality increases during a catastrophic event,

η_y is a random variable that is 1 with probability p_c and 0 otherwise, and

p_c is the probability of a catastrophic event.

Equation (10) allows for catastrophic events (such as the impact of a cyclone) to increase natural mortality on all fish by M_c yr^{-1}. The probability of a catastrophic event is assumed to be p_c (base-case value zero). The value of η_y is independent of reef so that it is assumed that a catastrophic event has the same impact across all of the reefs included in the model. Time-trends in natural mortality cause natural mortality for age *a* to increase from M_a to $M_a + M_{fin,a}$ over the years y_{fst} to y_{lst}. This formulation provides a framework within which some of the possible impacts of global climate change on the dynamics of the fishery can be investigated. The base-case trial ignores the possibility of climate change. The base-case values for the remaining parameters that determine natural mortality (M_a, σ^M and τ^M) are listed in Table 2.

Growth

The growth of an individual is assumed to be governed by the von Bertalanffy growth equation:

$$L_{k,a} = \ell_\infty^k (1 - e^{-\kappa^k (a - t_0^k)}) \qquad (11)$$

Variation in growth among individuals is modelled by assuming that the parameters κ, ℓ_∞ and t_0 differ among growth groups but that all animals in a growth group grow according to the same growth curve. The values for the parameters that determine growth (i.e. the values for κ, ℓ_∞ and t_0) and those that determine the proportion of 0-year-olds in each growth group (i.e.

the values for the K^k) are determined by fitting a model to data collected on length-at-age, after accounting for gear selectivity (Annex 3).

Mass as a function of length is determined using the standard allometric equation:

$$w_L = b_1 (L)^{b_2} \qquad (12)$$

where b_1, b_2 are the parameters of the relationship between length and mass (Table 2).

Catches

The catch (in mass) of fish from reef *r* during month *m* of year *y* by vessel-class *v*, $C^r_{y,m,v}$, is computed using the equation:

$$C^r_{y,m,v} = \sum_{a=0}^{x} \sum_{k} \frac{w_{L_{k,a+(m-0.5)/12}} \, D_{L_{k,a+(m-0.5)/12}} \, F^{r,k}_{y,m,a,v}}{Z^{r,k}_{y,m,a}} N^{r,k}_{y,m,a} (1 - e^{-Z^{r,k}_{y,m,a}}) \qquad (13a)$$

$$F^{r,k}_{y,m,a,v} = V_{L_{k,a+(m-0.5)/12}} \, F^r_{y,m,v} \qquad (13b)$$

where

V_L is the selectivity of the gear on fish of length *L*,

D_L is the fraction of animals of length *L* that are retained following capture,

$F^r_{y,m,v}$ is the fishing mortality applied to reef *r* by vessel-class *v* during month *m* of year *y*,

$$F^r_{y,m,v} = D q^r_v \, (B^r_{y,m} / B^r_0)^{\phi} \, E^r_{y,m,v} \, e^{\varsigma^r_{y,m,v} - \sigma^2_{\varsigma}/2} \qquad (14)$$

$B^r_{y,m}$ is the biomass on reef *r* at the start of month *m* of year *y* available to the fishery (the exploitable biomass):

$$B^r_{y,m} = \sum_{a=0}^{x} \sum_{k} w_{L_{k,a+(m-0.5)/12}} \, D_{L_{k,a+(m-0.5)/12}} \, V_{L_{k,a+(m-0.5)/12}} \, N^{r,k}_{y,m,a} \qquad (15)$$

B^r_0 is the value of $B^r_{y,m}$ at the pre-exploitation equilibrium level,

ϕ is a parameter that permits catchability to be density-dependent,

$E^r_{y,m,v}$ is the effort applied by vessel-class *v* on reef *r* during month *m* of year *y*:

$\varsigma^r_{y,m,v}$ is a factor to account for random variation in catchability ($\varsigma^r_{y,m,v} \sim N(0;\sigma^2_{\varsigma})$), and

q_v^r is the catchability coefficient for vessel-class *v* and reef *r*.

The fishing mortality that is caused by fishing effort that discards fish is calculated as

$$F'^{r,k}_{y,m,v} = Rq_v^r\,(B^r_{y,m}/B^r_0)^{\phi}\,E'^{r}_{y,m,v}\,e^{\varsigma^r_{y,m,v}-\sigma^2_\varsigma/2}$$

and the “fully selected” fishing mortality associated with fishing effort that discards fish

$$F'^{r,k}_{y,m,a,v} = V_{L_{k,a+(m-0.5)/12}}\,F'^{r}_{y,m,v}$$

where

$E'^{r}_{y,m,v}$ is the effort in which fish were discarded by vessel-class *v* on reef *r* during month *m* of year *y*.

If catch and effort data are available for reef *r*, the catchability coefficients for each vessel-class are computed using the formula:

$$q_v^r = \exp\Big(\sum_y\sum_m \ell nF^r_{y,m,v} \Big/ \sum_y\sum_m \ell n\{E^r_{y,m,v}(B^r_{y,m}/B^r_0)^{\phi}\}\Big) \qquad (18)$$

where the summations over year are restricted to the years for which effort data are available. This approach cannot be applied to reefs for which there are no catch and effort data. Therefore, the catchability coefficient for a reef for which there are no catch and effort data is taken to be the catchability coefficient for the closest reef.

Harvest Model

Several harvest models have been developed for ELFSim (Little et al. 2004, Little et al. 2008). Recently we have developed an individual based model to simulate the spatial fishing behaviour of individual recreational and charter fishing vessels (Little et al. 2008).

A vessel dynamics module was developed to operate within ELFSim and simulate the movement, reef selection processes, and fishing activities of individual vessels. The basic approach is to simulate vessel behaviour and hence effort dynamics using an agent-based model. Agent-based models attempt to determine the combined behaviour of a collection of individuals (Uchmański and Grimm 1996, Grimm 1999, Lempert 2002). In this case, the individual agents that are simulated are fishing vessels. Individual vessels in the model operate according to their own perspective and accumulated knowledge using models of their decision-making processes. Agent-based models are particularly effective when the number of agents is small, agents show non-uniform behaviours and the combined behaviour of individuals exhibits characteristics that are not easily identified by more aggregated models. These agents have heterogeneous characteristics like location and port of origin (boat ramp). They have different fishing efficiencies, make decisions based on rules, learn from past experiences and may use information from a range of external sources.

The harvest model operates on a daily time-step within each monthly time-step at which the remainder of ELFSim operates. Through the model, effort can respond dynamically to daily changes in fishing conditions (e.g. catch rates on individual reefs) and management arrangements (e.g. area and seasonal closures). The model incorporates progressive discounting of historical catches, with more recent experiences and personal information being more important than historical information or fleet-wide experience when making decisions. Catch expectations therefore are specific for each vessel for each reef for each month of the year and are 'learnt' by the fishers or 'forgotten' if a reef is not visited for some time. It is assumed that at the start of each day the vessels start from a particular port (e.g. Exmouth, Tantabiddi Creek, Coral Bay).

Consistent with previous work on effort dynamics, the vessel dynamics model is based on the concept of utility (usually measured as CPUE), where fishers are assumed to fish in locations where they would expect to obtain the highest CPUE (utility). At each daily time step a decision is made where to fish. This is done by selecting a location (reef) based on the (normalised) distribution of expected CPUE, i.e. the probability of vessel *b* fishing on reef *r*, in any day is given by

$$P_{b,r} = \frac{p\overline{CPUE}_{b,r} - cd_{b,r}}{\sum_r p\overline{CPUE}_{b,r} - cd_{b,r}}$$

$\overline{CPUE}_{b,r}$ is the historical average CPUE experienced by boat *b* on reef *r*, and is calculated as

$$\overline{CPUE}_{b,r} = \delta\overline{CPUE}_{b,r} + \frac{C}{E}$$

p is the price of fish

c is the cost of moving to fish per unit distance

$d_{b,r}$ is the distance between the location of boat *b* and reef r.

δ is a discount factor

Based on this formulation the vessels are constrained to fish at locations they have fished in the past. We have also introduced the ability of boats to explore new fishing locations (reefs). With a 1% probability a vessel will choose a reef location based only on distance from port, and not on catch rate. The probability that a vessel will choose a reef in this manner is calculated as,

$$P'_{b,r} = \frac{e^{-5d_{b,r}}}{\sum_r e^{-5d_{b,r}}}$$

Each vessel allocates fishing effort on a daily basis, $E^{r}_{y,m,b,d}$, by selecting a location at random from either $P_{b,r}$ or $P'_{b,r}$. Since the duration of fishing varies from day to day, however, the daily effort is assumed to be influenced by stochastic fluctuations, which result in an effective effort $\tilde{E}^{r}_{y,m,b,d}$ that is used to calculate fishing mortalities, such that

$$\tilde{E}^{r}_{y,m,b,d} = \varepsilon_d E^{r}_{y,m,b,d}$$

where

ε_d represents the daily variability in fishing expressed as a log-normal random variate $\varepsilon_d \sim \mathrm{e}^{N(0,\sigma^2)-\sigma^2/2}$, and σ^2 is equal to 1.

Simulating Bag Limits

Vessels in the model are subjected to management limits in the daily number of fish they can keep (bag limit). To handle this, the catch (in numbers) is calculated for each vessel fishing in any given day. If this number is greater than the specified bag limit, then the effort for the day of fishing is divided into effort expended in catching the bag limit, and the remaining effort expended on fishing, but with fish being released after capture.

This is done by finding the proportion of the daily effort that will catch the bag limit on a given reef by a given vessel $\hat{E}^{r}_{y,m,b,d} = x\tilde{E}^{r}_{y,m,b,d}$, and assuming that all fish caught with the remaining effort that day were discarded $E'^{r}_{y,m,b,d} = (1-x)\tilde{E}^{r}_{y,m,b,d}$.

In every month the effort that is passed from the harvest model to the biological model is summed across all vessels and all days of the month as,

$$E^{r}_{y,m,v} = \sum_{b\in v}\sum_{d}\hat{E}^{r}_{y,m,b,d}$$

$$E'^{r}_{y,m,v} = \sum_{b\in v}\sum_{d}E'^{r}_{y,m,b,d}$$

These values are used to calculate fishing mortalities on the population of reef *r* in month *m* of year *y*.

Inshore (shore-based) fishing effort

The harvest model thus far has only included boat-based fishing, by attempting to capture the fishing behaviour and location choice across all of Ningaloo Reef, but being constrained by distance (cost) and catch rates. Because there is also a substantial amount of shore-based recreational activity in the area, we attempted to capture the fishing removals that might take place from such associated activities (e.g. camping). We therefore compiled a list of camping sites along the coast (Table 3), and assigned effort to adjacent coastal reefs and fish sub-populations according to the relationship

$$E_i = C_{camp} e^{-\alpha d}$$

where E_i is the inshore (shore-based) effort assigned to coast reef *i*

C_{camp} is the capacity of the camp (lacking information on these we assumed that a default value of 1.0)

α is a parameter associated with the cost of fishing (default value of 1.0) as distance d from the camp.

Effort was allocated similar to the offshore allocation model. A set amount of effort was specified, and days of effort were assigned by randomly selecting a reef and allocating to it E_i effort until none of the pre-specified effort was left to allocate. By default we assumed that the amount of effort from shore-based fishing was equal to that in offshore or boat-based fishing.

Infringement and compliance

Whether a reef *r*, is open or closed to fishing by vessel-class *v* is defined by its 'management status' or 'compliance', $L^{r,v}$, which ranges between 0 (open to fishing) and 1 (closed), with intermediate values representing closed reefs that experience some level of infringement. Effort assigned to reefs is calculated by multiplying the probability of fishing on a particular reef by (1-$L^{r,v}$). Allowance can be made for spatial (edge effects) and temporal changes to infringement into MPAs (Little et al. 2005). Infringement of bag limits on reef *r* by vessel-class *v* is calculated by modifying the bag limit B with an infringement factor: $B + B(1 - L^{r,v})$. Under full compliance $L^{r,v}$=1 then only the bag limit is taken. If compliance is 0 then up to twice the bag limit could be taken.

3.2.2 Data

The spatial domain in which ELFSim operates, including the Ningaloo Marine Park, was defined in a 1 minute grid (Figure 1). Biological data were obtained from DoFWA (Marriott et al. 2010a; Marriott et al. 2010b; DoFWA, unpublished data) for growth rates, length-weight relations, maturity, sex-change and selectivity relationships, as well as natural mortality (Table 2). In this report we focus on only one target species, the spangled emperor (*Lethrinus nebulosus*).

The spatial distribution and putative amount of habitat for spangled emperor, for each grid, was assigned based on GIS intersections with mapped inter-tidal coral reef habitat. Although spangled emperor are generally considered reef associated species, they are assumed in the model to occur in locations other than the inter-tidal area in the marine park, where they are known to exist from fish catch records. Nevertheless, inter-tidal habitat is used to derive an indicator of habitat, which determines the population carrying capacity for each local population associated with a 1 minute grid. For those grid cells not associated with inter-tidal habitat, an initial value for the amount of habitat and carrying capacity of the local population is determined by selecting a value randomly for the ten closest inter-tidal locations. Since the actual unexploited state of the species is not known but is generally expected to be explored through model sensitivity analysis by the user (see section 3.1.7 and 3.3), the actual values of the species carrying capacity of the different local populations is less important than the relationship among the local populations. As a result, in the current model the spatial distribution of the resource is captured by a combination of the inter-tidal coral reef habitat and catch records (Figure 1).

Charter fishing catch and effort data were obtained from DoFWA at a 5 minute spatial grid scale for the period from 2002 to 2006. These data were disaggregated to the 1 minute spatial scale of the sub-populations based on the amount of assumed habitat distributed among the 1 minute grid cells embedded in each 5 minute grid cell datum. For each grid cell, catch and effort data were hindcast linearly back to zero in 1965, the year in which fishing was assumed to have started (Figure 2). Recreational fishing catch and effort data were obtained for 5 minute blocks in 2007/08 (DoFWA, unpublished data). These data were similarly disaggregated to 1 minute grid cells based on the amount of habitat assumed to exit in each grid cell, and hindcast linearly back to zero in 1965 (Figure 2). Commercial catches were obtained for 1 degree blocks from 1975 to 2005 (DoFWA, unpublished data) and disaggregated to the 1 minute spatial scale of the sub-populations and distributed among grid cells in proportion to the relative amount of assumed habitat within each grid cell. These data were also hindcast back to 0 in 1965 (Figure 2).

These data allow the model to run historically by capturing an assumed spatial pattern of historical fishing, given available data and assumptions stated in this section, including the historical linear-extrapolation of catches and effort (Figure 2). Assuming that there was no or little fishing before 1965, and with an assumed relationship between habitat and reef (grid cell) population size, the model derives a simulated biomass of the local reef populations in 2006. After 2006 the harvest model operates to project the population under different management conditions. For simulation of management strategies involving the sanctuary zoning of the marine park (Figure 3), ELFSim can either partially or totally prevent fishing from occurring in the protected (sanctuary) zones in this projection period.

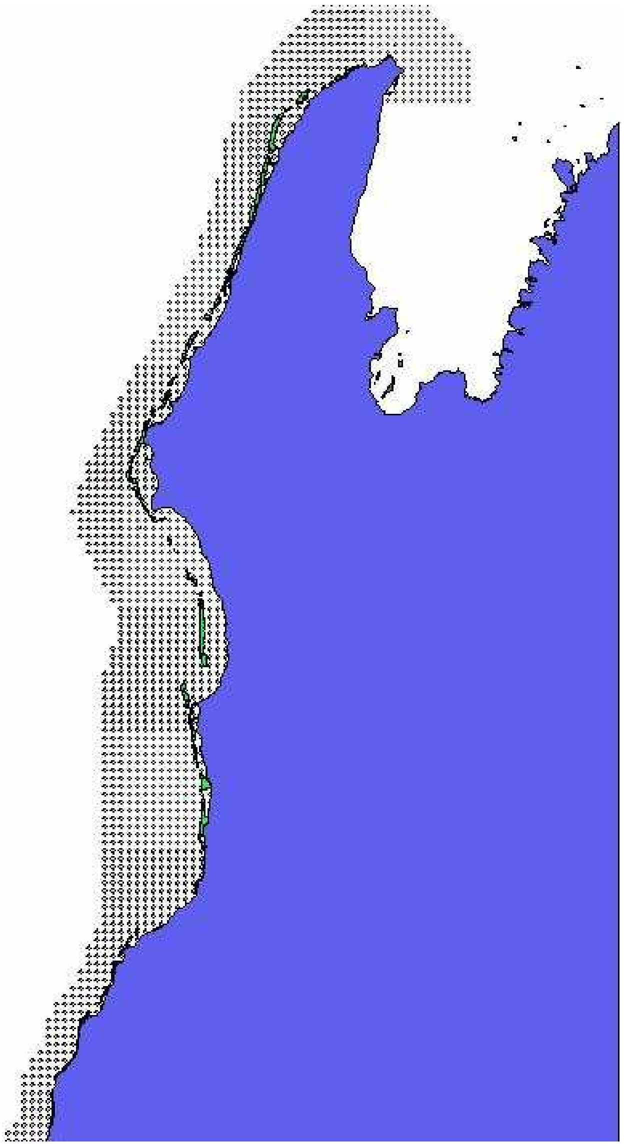
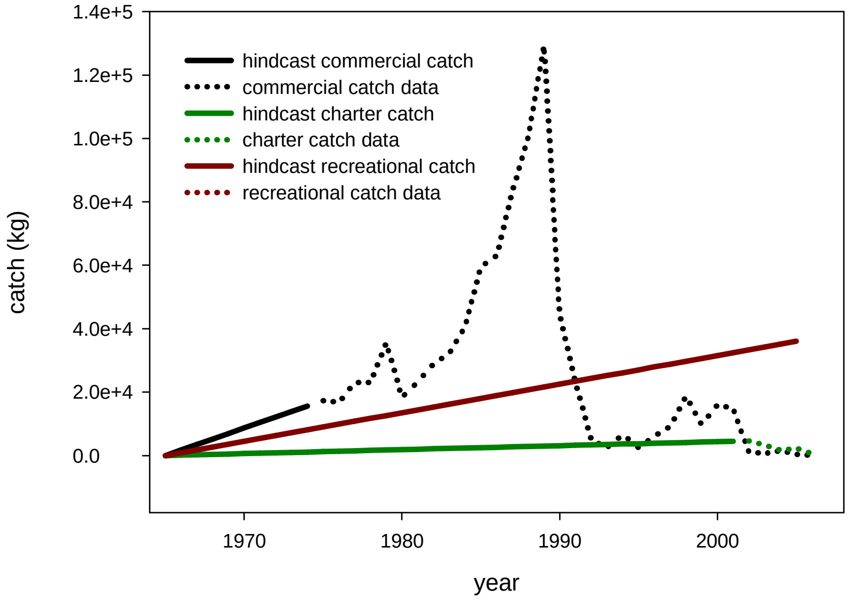


Figure 1 The spatial extent of the area covered by ELFSim including the 1 minute grid cells representing *Lethrinum nebulosus* populations, and the inter-tidal habitat (green).



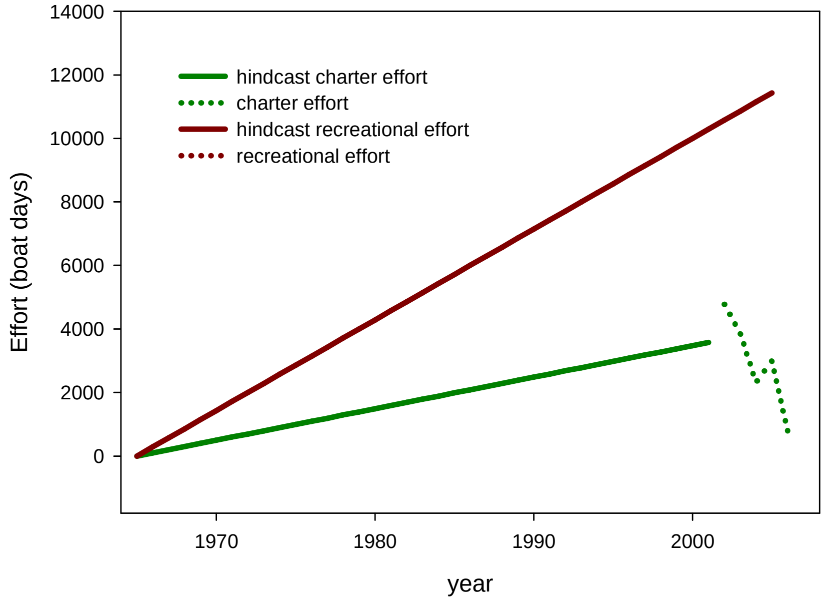


Figure 2 Spatially aggregated a. catch data by fleet and b. effort data.

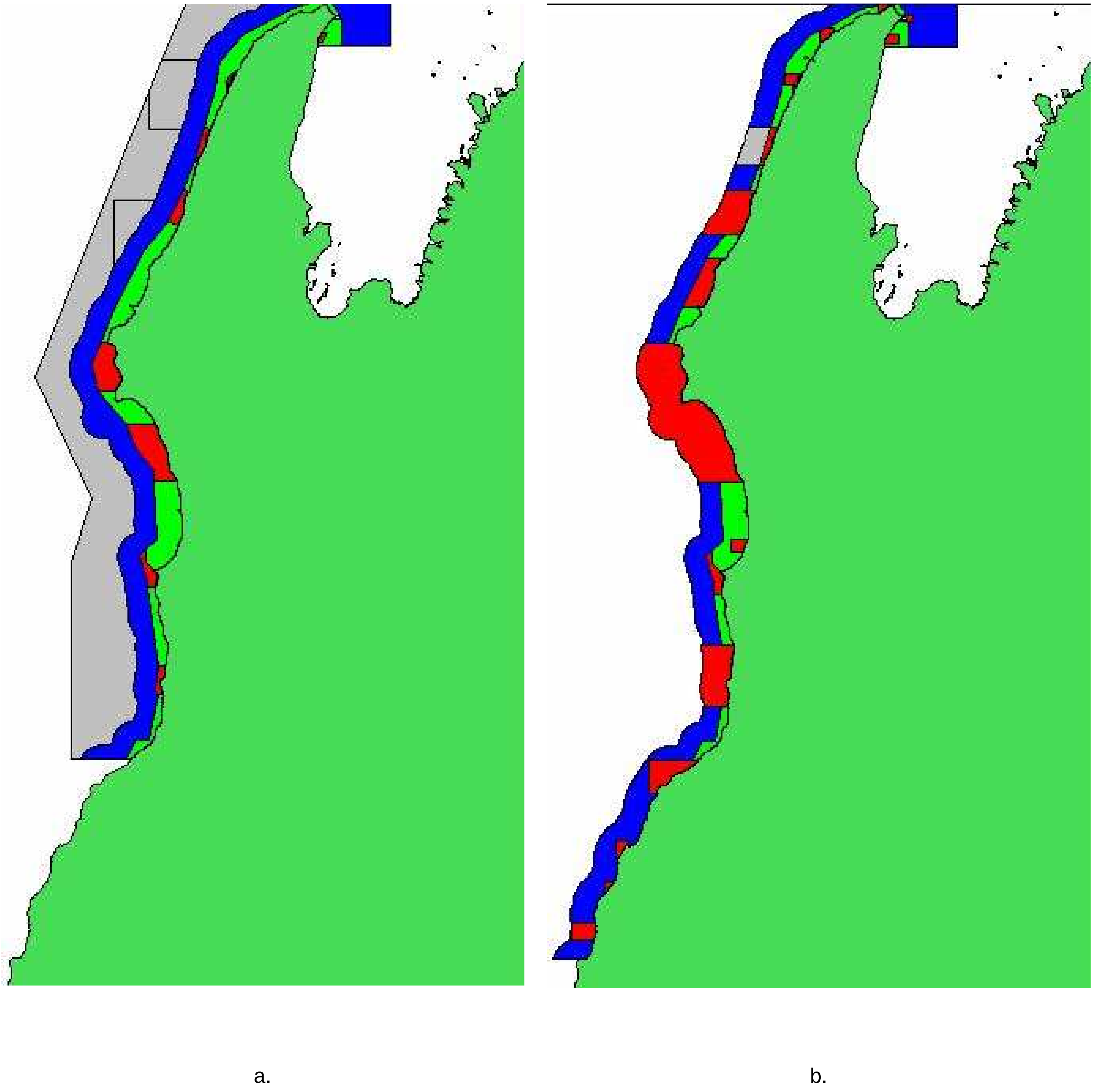


Figure 3 Zoning, with sanctuaries in red used as no-take areas in the model on Ningaloo Marine Park a. 2003, and b. currently, that are used by the management model of ELFSim to constrain vessels in the harvest model (**red**: sanctuary, **blue:**, general use: **green**, recreation,, **grey**: special purpose/commonwealth).

Table 2 Values for the parameters of the biological component of the model (see section 3.2.2).

Parameter	Description	value	Source
M_a	Natural mortality	0.15 yr^{-1}	Marriott et al. 2010b
σ_M	Temporal variation in natural mortality	0.05	Assumed
σ_r	Variation in 0-year-old survival	0.6	Assumed
τ	Spatial correlation in 0-year-old survival	0.5	Assumed
st	Larval self seeding	0.1	Assumed
h	Steepness	0.75	Assumed
b_{1_r}, b_{2_r}	Length-mass parameters	-10.60, 2.84	Marriott et al. 2010b
n_K	number of different growth groups	1	Assumed
K_k	Proportion of animals in growth group *k*	1.0	Assumed
$\ell_{\infty_{r,k}}, \kappa_{r,k}, t_{0_{r,k}}$	von Bertalanffy growth parameters	64.7 cm, 0.258 yr^{-1}, 0.28 y	Marriott et al. 2010b
D	Proportion of fish discarded that die	0.15	Little et al. 2007
R	Proportion of fish caught below MLS that are retained	0	Assumed
L_{MLS}	minimum legal size	41 cm total length	Marriott et al. 2010b
	Length-at-50%- and 95%-selectivity	18 cm; 28 cm	Marriott et al. 2010b
	Length-at-50%- and 95%-maturity	35 cm; 49 cm	Marriott et al. 2010b
	Asymptotic proportion males, Length-at-50% Asymptote - and 95% Asymptote -	0.5; 27.5 cm; 34.5 cm	Marriott et al. 2010b

Initial conditions Biological model

The population is assumed to have been at pre-exploitation equilibrium with the corresponding age- and sex-structure at the start of 1965. This date is arbitrary but guarantees that there is sufficient time from pre-exploitation to the period for which catch and effort data exist to tune the model to those catches. The population sizes (of the target species) and the corresponding age-and sex-structures on each reef at the start of the first year are computed using the following algorithm:

1. The number of 20cm+ animals on reef *r*, n_r, is generated from the lognormal distribution, $LN(I_{1\,l_r}\ \tilde{p}_r, 0.5^2)$where $\tilde{p}_r$ is a measure of the amount of reef habitat and $I_{1\,l_r}$ is a quantity that can be influenced by the geographical distribution of reef *r*. The amount that habitat varies among reefs and is not well known. We therefore allow for user specification of that relationship through a “habitat scalar” parameter to facilitate exploration of different scenarios and tests of the sensitivity of results to variation in habitat extent.

2. The number of 1-year-olds on reef *r* is determined using the formula:

$$N_{r,0,1} = n_r / \sum_{a=1}^{x} \sum_{k} \tilde{N}_{r,k,a} \qquad (19)$$

   where $\tilde{N}_{r,k,a}$ is the age-structure of the pre-exploitation population on reef *r*, expressed as a fraction of the number of 1-year-olds, and the summation over age and growth group is restricted to fish for which $L_{r,k,a} > 20\text{cm}$.

3. The historical period of the model is run with fishing mortality calculated based on historical catches.

The biomass corresponding to the generated value for n_r however, can be such that the population would be extinct prior to the start of the projection period, after all of the historical catch was taken from it. Available catch data, however, are not consistent with such extinctions of target species in Ningaloo Marine Park. Therefore, if such an extinction occurs during the historical period of the model, where the population cannot support the historical catch taken from the reef, the previous value used for the log-normal mean, (i.e. . $I_{1/_r}\ \tilde{p}_r$),), is increased by 5% and steps 1 to 3 are repeated (increasing the mean by 5% increase prevents the model from entering a loop it is unlikely to exit).

This process is repeated until a value for initial biomass is obtained for each reef that precludes extinctions during the historical period.

Initial Conditions Harvest model

At the start of the projection period all vessels start with the same perceived CPUE across different locations (reefs), based on the historical data used in the historical period of the model. As the projection period in the model progresses however, these perceptions diverge under stochastic influences, and the behaviour of individual vessels becomes conditioned on more recent fishing experiences. For the current simulations, a number of vessels were selected for each fleet so that the aggregate effort of the vessels, each operating consistently over the period of a year, would match the aggregate effort that has actually occurred in the fishery. A distribution of fishing vessels across different ports, or boat ramps, was also necessary, based roughly on the calculated effort distribution in different areas of Ningaloo Marine Park (Table 4).

Table 3 Camping grounds distributed along the Ningaloo coast for use in inshore (shore-based) fishing.

Name	Latitude (^{o}S)	Longitude (^{o}E)
Lighthouse Caravan Park	21.8	114.1
Yardie Caravan Park	21.98	114
Reef Retreat"	22.13	113.9
Mandu Mandu	22.15	113.9
Pilgramunna	22.18	113.88
Osprey Bay	22.2	113.85
Boat Harbour	22.37	113.78
Sandy Point	22.38	113.7
Winderabandi Point	22.5	113.7
Ningaloo	22.68	113.68
Cardabia	22.15	113.75
Coral Bay Camp	23.17	113.77
14 mile Camp	23.25	113.75
Elles Camp	23.45	113.73
Stevens Camp	23.45	113.73
Waroora	23.48	113.73
The Lagoon	23.63	113.77
Gnaraloo	23.733	113.5
3-mile	23.75	113.5
Red Bluff	24.03	113.47

Table 4 Number and distribution of fishing vessels in the harvest model, fishing in the different fleets (charter and recreational) from different ports (boat ramps). * Although no charter fishing has been simulated to operate out of Coral Bay, it is acknowledged that Charter vessels currently operate from this port, and often catch and land spangled emperor.

	Fleet	
Port	Charter	Recreational
Exmouth	8	18
Tantabiddi Creek	4	12
Coral Bay	0*	10
Total	12	40

Different scenarios involving level of stock depletion as well as management strategies involving future effort levels, area closures and bag limits, were simulated in the current model runs. Each reef-associated sub-population was assumed to be at pre-exploitation equilibrium with the corresponding age- and sex-structure at the start of 1965. The pre-exploitation sub-population size for each reef was calculated as a function of reef perimeter. A ‘habitat scalar’ parameter is used to convert the product of population density and reef perimeter to the numbers of animals in the unfished sub-populations. The habitat scalar provides a means of setting unexploited population sizes such that after running the operating model from 1965, the actual catches observed are realised in the simulation data. The value of the habitat scalar is arbitrary because we have a poor understanding of the amount of reef that is habitable. Thus, observed catches could be realised with relatively low fishing mortality and a large value for the habitat scalar or, alternatively, with higher fishing mortality and a lower value for the habitat scalar.

When a management strategy is to be applied, the age- and size-structure of each reef sub-population at the start of the first projection year (2007) is determined by running the population from pre-exploitation equilibrium in 1965 to 2006, with random variation in recruitment and natural mortality, and subject to realising the reported catches prior to 2004. However, the allocation of historical catches to reefs in this initialisation can result in population extinctions on individual reefs prior to the projection period. The initialisation process is repeated after incrementing the habitat scalar for that reef by 5% and repeating the projection from 1965 if extinction occurs on a reef. This process is repeated until no extinctions occur. Effectively, this tunes the population model to realise the reported catches prior to the projection period, given the distribution of the resource and fishing effort, under the assumption that local extinctions are unlikely to have occurred in the past, given contemporary regulations and levels of fishing.

Simulating management strategies

Management strategies are implemented during the projection period by varying effort levels, access to areas for fishing, as well as bag limits. Management strategies can be fully implemented at the start of the projection period or, if they include time-varying measures, during the projection period. However, management strategies are always pre-specified, i.e., there is no feedback to change management strategies through the simulation. Evaluations proceed by running the operating model from 1965 to the end of the period for which actual data are supplied (2006) (the initialisation period) and then introducing the desired changes to the parameters that define the management strategy. Random processes in the population dynamics mean that each initialisation will lead to different starting conditions for the projections. The model is then run for a defined projection period (in this case 19 years). Repeating runs with the same management strategy allows an evaluation of the effect of variation in population dynamics and effort allocations on the results for that management strategy. Running the same management strategy when the values for the parameters of the operating model are changed allows an assessment of the robustness of the results to uncertainties or errors in model assumptions. A wide range of reef-specific data can be collected at each time step, including catch and effort for each fleet (commercial, charter and recreational), available biomass, spawning biomass, fishing mortality and size and age measures for the population and catch.

We performed initialisations from 1965 to 2006 in the current simulations under a habitat scalar that depleted the available biomass (totalled across all reefs) to 40% by the end of the historical period, and a second scenario in which the total population was only depleted to about 90% of the pre-exploitation level. These scenarios correspond to a case of a moderately depleted population (depleted scenario), and a relatively unaffected population (unaffected scenario).

3.2.3 Management objectives, management strategies and projection scenarios

Management strategy evaluation (MSE) is a process that attempts to evaluate the effects of management actions in a computer simulation framework so that trade-offs can be identified among management objectives, specified by stakeholders. MSE is comparative rather than prescriptive, seeking to compare likely outcomes from a range of management strategies rather than just prescribe an optimal strategy or decision that should be taken under an existing regulatory framework. The approach thus uses a simulation-based framework consisting of a representation of the resource dynamics and exploitation, within which management actions are implemented and compared.

The central part of an MSE is the computer representation of reality on which to impose the various management activities including regulations, monitoring and assessment procedures. The operating model in this study, ELFSim, provides the MSE framework to examine the trade-offs associated with the performance of alternative management strategies. ELFSim captures the dynamics of the underlying resource and its exploitation.

The framework is able to deal explicitly with a range of sources of uncertainty when showing the consequences of alternative management strategies, including structural and parameter uncertainty, errors in data, estimation uncertainty and management implementation uncertainty. Transparency and trade-offs in performance of alternative strategies in recognition of sources of uncertainty is essential to the approach and acceptance of outcomes from stakeholders.

A key element of MSE involves turning broad conceptual objectives into quantifiable and measurable operational management objectives and related performance indicators.

Fundamental to this approach, therefore, is the identification and representation of stakeholder objectives. Stakeholder engagement in MSE is essential to the acceptance of credible management objectives and strategies that represent the divergent interests of the different user groups.

Facilitated by stakeholder workshops specific operational management objectives, performance indicators and management strategies have been defined. The management objectives that have been identified fall into two broad categories: ecological objectives and social objectives.

Management objectives

In specifying operational management objectives for an MSE three elements are needed: a performance indicator that specifies the quantity of interest, a target for the performance indicator, and a measure of tolerance or acceptance that the indicator must achieve, usually specified as a probability. This section summarizes the way in which key objectives were expressed by the stakeholders (Appendix) involved in the management of Ningaloo Reef recreational fishery, during the dedicated workshops that were held, as part of this project.

Ecological objectives

Stakeholders identified seven ecological objectives. Participants in the workshops expressed two ecological management objectives for the Ningaloo reef recreational fishery effects on spawning biomass of the target species in sanctuaries (Table 5). The first required that spawning biomass in sanctuaries should be above 90% of pre-exploitation spawning biomass 75% of the time. The second required that spawning biomass in sanctuaries should be above 75% of pre-exploitation spawning biomass 75% of the time. In both cases, the performance indicator (spawning biomass in the sanctuaries) was required to meet the target 75% of the time, thus, accounting for the stochastic nature of the processes. In all other management objectives, a tolerance measure assumed a default of 75%. In general, the objectives were not applied to individual reefs, or individual sanctuaries, but applied across reefs in the particular zones (sanctuaries or non-sanctuaries).

Other ecological management objectives involved the length distribution and the age distribution of the spangled emperor population. These management objectives specified that the age distribution of the population in the sanctuaries should approximate the age distribution of an unexploited population and, that the length distribution of the population in the sanctuaries should approximate the length distribution of an unexploited population. Quantitatively we have interpreted these objectives as the mean of the age and length distributions of the population in the sanctuaries should be within the tenth percentile of the unexploited values, 75% of the time.

The remaining ecological objectives pertained to the state of the stock outside of the sanctuaries and the desire that the overall population of the target species does not decline below its current state. This applies to the stock that is perceived by the fishers, defined in the operating model as available biomass, as well as the part of the population that has reproductive potential, namely the spawning biomass. The first of these objectives was specified such that the available biomass outside sanctuaries should be greater than what it was in 2007 (i.e. its status is not degrading), and that the spawning biomass outside sanctuaries is greater than what it was in 2007. The last ecological objective was an aggregate objective over the entire marine park, including both protected and non-protected areas. It specified that the spawning biomass should be more than 40% of the pre-exploitation spawning biomass 75% of the time.

Social objectives

The main social objective of the Ningaloo reef recreational fishery was that a good recreational fishing experience will be maintained. This was interpreted as the total catch (landed and discarded) rate, CPUE, be greater in the future than the most recent value 75% of the time. The second social objective was that there should be a good chance of catching a trophy fish (considered > 50cm). This was interpreted as having one fish in a bag that was more than 50cm, or alternatively that 25% of the catch is > 50cm. There were several other indicators that were thought to be important, but could not be treated as performance measures for the purpose of MSE, as no clear target or reference values for these indicators could be identified in the course of the workshops. They were, however, included as important descriptors of the consequences of alternative management strategies in the output of the model runs. These included the number of days, or trips in which 0 fish are caught, the total landed catch, discards, and the variability in catch. Importantly, we acknowledge that these objectives simplify motivations for recreational fishing (for the purpose of running the simulations) and thus only consider part of the experience. Motivations also vary among different anglers and so each objective reflects a specific value not likely held consistent among them.

The indicator that attempted to capture the variability in catch was assumed to be the day-to-day variability in total (landed plus discard) catch. Calculating the indicator that captured the number of days in which no fish are caught was complicated because of the functional relationship between catch and effort in the model, which entails that a non-zero effort will never result in a non-zero catch. Consequently, catch in a day of fishing will never be zero in the model. Also, because the main form of catch is weight, not numbers, it is possible for the model to report numbers of fish in the catch that are fractional, e.g. 1.5 fish. As a result we have developed an indicator that represents the chance of not catching a fish, as the average number of fish in the catch is less than 1.

Table 5 Management objectives for the recreational fishery on Ningaloo reef.

	Ecological objectives
1.	Spawning biomass in sanctuaries should be above 90% of pre-exploitation spawning biomass 75% of the time
2.	Spawning biomass in sanctuaries should be above 75% of pre-exploitation spawning biomass 75% of the time
3.	Average age in the population = unexploited average age ± 1 year 75% of the time
4.	Average length in the population = unexploited average length ± 10 cm 75% of the time
5.	Available biomass outside sanctuaries> available biomass in 2007
6.	Spawning biomass outside sanctuaries> spawning biomass in 2007
7.	Spawning biomass is greater than 40% of the pre-exploitation spawning biomass 75% of the time
	Social objectives
8.	(landed + discarded) CPUE > (landed + discarded) CPUE in 2007 75% of the time.
9.	25% of the catch > 50cm 75% of the time
	Indicators with no objective or specific target
	Landed catch
	Discards
	Catch variability
	Number of times not catching a fish

Management Strategies

The selection of management strategies to evaluate was also carried out in discussion with stakeholders in the course of the workshops. Several management strategies were selected and their potential consequences, including various environmental, technological and economic conditions, were proposed (Table 6). These included:

1. using the current or an increased network of marine sanctuaries

2. allowing or not allowing fishing to occur from shore in sanctuaries

3. maintaining the current recreational effort, (presumably through a licensing platform for implementation), or allowing it to increase in connection with projected increases in visitor numbers in the region. An alternative strategy is the implementation of a catch limit. This has been proposed as a possible outcome considered in the Gascoyne Bioregion of Western Australia under the Integrated Fisheries Management framework, however the effectiveness and specification of the magnitude of any suitable catch limit depends firstly on having some reliable estimate of the spangled emperor population biomass. Since no reliable estimate of biomass currently exists for Spangled Emperor

in the park, we calculated a hypothetical catch limit as relevant to the context of the MSE simulations. Since only the relative magnitudes of catch and population biomass were important, the simulated catch limit corresponded to the spangled emperor population being at 40% of the pre-exploitation biomass level in 2002, given available data and assumptions for the model (as tailored to this fishery). Accordingly, the value used for the simulated catch limit is not reported here and all results are reported in relative terms: population biomass values are presented as percentages of the simulated pre-exploitation level and catch/discards are presented as percentages of the simulated catch limit;

4. implementing an educational program, which would be expected to reduce infringement into closed areas, and informally reducing the bag limit through the development of a catch and release plan;

5. implementing an enforcement program by having a monitoring vessel patrol the coast, to reduce fishing in the sanctuaries, and catches over the bag limit

A description of the management strategies that were implemented in the simulation model is given in Table 6. Although other management options are included in the model, such as bag limits and minimum legal sizes, changes to these regulations in isolation were thought to be less likely than the other control variables listed as alternative single management measures and, in the interest of having a manageable set of simulations, we did not consider changing them as part of the set of strategies tested. The effect of changing the bag limits was examined in the mid-term report (Little et al. 2009). It is worth noting that the management of fisheries is not typically achieved through the implementation of one or two management measures in isolation, but instead usually involves the implementation of a combination of different strategies, and so the results of MSE simulations presented here should be considered in light of these limitations.

Table 6 Alternative management strategies examined under current conditions and high or low compliance scenario ($L^{r,v}$ is equal to 0.95 or 0.50). All management strategies contain the Reference Strategy conditions unless specified. For the increased sanctuaries we considered two cases whereby the current sanctuary zones were extended. The first zoning was made by creating a large sanctuary in the north and a large sanctuary in the south. The second was made by creating only a single large zone in the north with current zones in the south to remain as they are (Figure 4).

	Management Strategy:							
	Reference Strategy	**Increased Sancts A**	**Increased Sancts B**	**No inshore fishing in sancts**	**Increased effort**	**Catch limit**	**Education program**	**Increased Compliance Monitoring**
Sanctuaries	Current	Increased	Increased					
Fishing from shore in sanctuaries	Allowed			Not allowed				
Effort/Catch Limit	Current effort				Increased	Model determined - fixed		
Education program	None						Included	
Compliance	Current							Increased
Bag limit	Current							
Min. legal size	Current							
Compliance ($L^{r,v}$)	High, low (0.95, 0.50)	High, low (0.95, 0.50)	High, low (0.95, 0.50)	High, low (0.95, 0.50)	High, low (0.95, 0.50)			High, low (0.95, 0.50)
Number of simulations	2	2	2	2	2	2	2	2

For the strategies we developed involving increased sanctuaries (“Increased sancts A”, and “Increased sancts B”), we considered two cases whereby the current sanctuary zones were extended (Figure 4). The first zoning was made by creating a large sanctuary in the north and a large sanctuary in the south. The second was made by creating only a single large zone in the north with current zones in the south to remain as they are (Figure 4).

Projection Scenarios

Management strategies were tested under current conditions in the fishery, where compliance is high and low (Table 6). We also examine the management strategies under different possible future conditions or scenarios (Table 7). Because of the high computational requirements entailed by the multiplication of combinations of strategies and scenarios, we chose to examine a subset of 3 strategies under 6 future scenarios, where compliance is high and low.

The projection scenarios retained for the analysis were thought to be likely conditions experienced in the future. The key drivers of changes in the conditions of the fishery were identified and discussed in the stakeholder workshops. They included:

1. Environmental Pressures as a result of climate change or similar global effect. This was captured by increasing the natural mortality of the species to twice its value by 2025.

2. Environmental Catastrophe, which would be the result of a large detrimental effect such as a cyclone occurring once per year. This is modelled as a spatial effect, such that a location is chosen randomly. The effect is a randomly chosen reduction in recruitment that decreases with distance in such a way that half of the intensity of the effect is felt 40km away;

3. Technology creep occurs such that increased fisher catchability would increase at 5% per year for 10 years

4. Wider footprint, which would result if fishers moved to bigger and more powerful boats, leading to a reduction in the relative cost of moving across the region (by 20% in the simulations);

5. Boat ramp / road upgrade, which would double the number of vessels originating from Coral Bay (with an corresponding increasing in the amount of effort), and thus would be expected to have an effect on localised depletion of the resource

Most of these scenarios were examined in isolation of each other except for the “Environmental Pressure” and the “Technological creep”, which were combined to show the potential effect if both scenarios eventuated.

The total number of different combinations of management strategies and projections scenarios that were examined is 50 (current conditions: 7 strategies & 2 compliance scenarios = 14; projection scenarios: 6 projection scenarios & 3 management strategies & 2 compliance scenarios = 36). For each of these 50, we replicated the projection period 100 times to capture the uncertainty in the population and fishing dynamics.

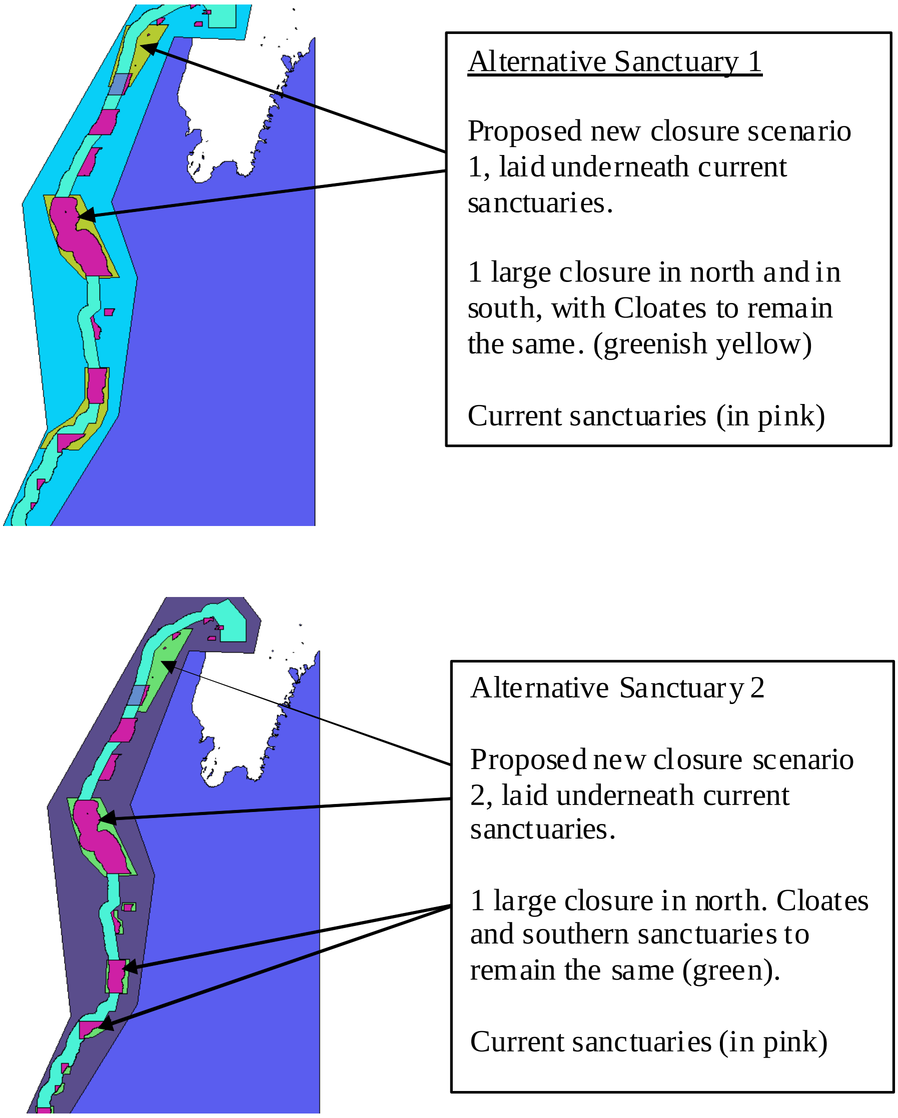


Figure 4 Two alternative sancturary zonings used in the Increased Sanctuaries management strategy.

Table 7 Combinations of management strategies and different potential scenarios for the fishery. Three management strategies were examined for each scenario: Reference Strategy, Increased Effort and Catch Limit. Three management strategies (Reference, Inreased effort, Catch Limit) were used across the different scenarios.

Management Strategy	Scenarios Environmental Pressure	Environmental Catastrophe	Technology Creep	Decreased Costs	Coral Bay upgrade	Env. Pressure + Tech. Creep
Sanctuaries	Current					
Fishing from shore in sanctuaries	Allowed					
Effort/Catch Limit	Reference Strategy (current effort), Increased effort, Catch Limit					
Education program	None					
Compliance	Current					
Bag limit	Current					
Min. legal size	Current					
Compliance ($L^{r,v}$)	High, low (0.95, 0.50)	High, low (0.95, 0.50)	High, low (0.95, 0.50)	High, low (0.95, 0.50)	High, low (0.95, 0.50)	High, low (0.95, 0.50)
Env. Pressure	Yes					Yes
Env. Catastrophe		Yes				
Technology creep			Yes			Yes
Decreased costs				Yes		
Coral Bay upgrade					Yes	
Number of simulations	6	6	6	6	6	6

3.3 Results

The model contains 1544 spangled emperor sub-populations spread across different locations, determined from from the 1 minute grid cells (Figure 1). Simulation results shown for the two depletion scenarios are totalled across these sub-populations and include the available biomass (biomass of legal size that is selected by and available to the hook and line fishing gear) and the spawning biomass (mature females), the biomass status in the areas open to fishing and closed to fishing, the legal catch, effort and CPUE. Results are considered first in terms of the dynamic responses to alternative management strategies. Since we are interested in the long-term effect of management, the results are then displayed based on the status of the selected ecological and socio-economic indicators, in the final year of the simulations. First we present results obtained regarding the effects of management strategies under “Reference Strategy” conditions, where we have simulated the fishery with model inputs that are similar to current fishing and management. Next, we examine the consequences of including the alternative scenarios in terms of the effectiveness of management strategies, with respect to the management objectives identified.

3.3.1 An evaluation of alternative management strategies under current conditions

The time series of simulated spangled emperor spawning biomass is shown in Figure 5. The black curve shows simulated spawning biomass in the historical period in which historical catches are removed from a proposed initial population size. After the final historical year, the sub-populations are projected from 2007 under different management strategies. The management strategies that resulted in the greatest recovery of biomass were the “Catch Limit” and the “No inshore fishing in Sanctuaries”. The spawning biomass under all of the management strategies stabilised by 2025 except under the “Increased effort” management strategy which showed a decline in the spawning biomass to its simulated 2007 level.

The simulated spawning biomasses, both inside and outside of the sanctuaries, are shown in Figure 6 relative to the biomass in the same areas at the start of the projections. In general, the spawning biomass in the sanctuaries was higher and closer to the simulated pre-exploitation level than outside of the sanctuaries. None of the management strategies led to full recovery to simulated pre-exploitation levels in the protected areas because most simulations allowed fishing from shore into all of the sanctuaries. When this was prevented, spawning biomass in the sanctuaries rose to almost 90% of simulated pre-exploitation levels and was continuing to increase at the end of the projected simulation.

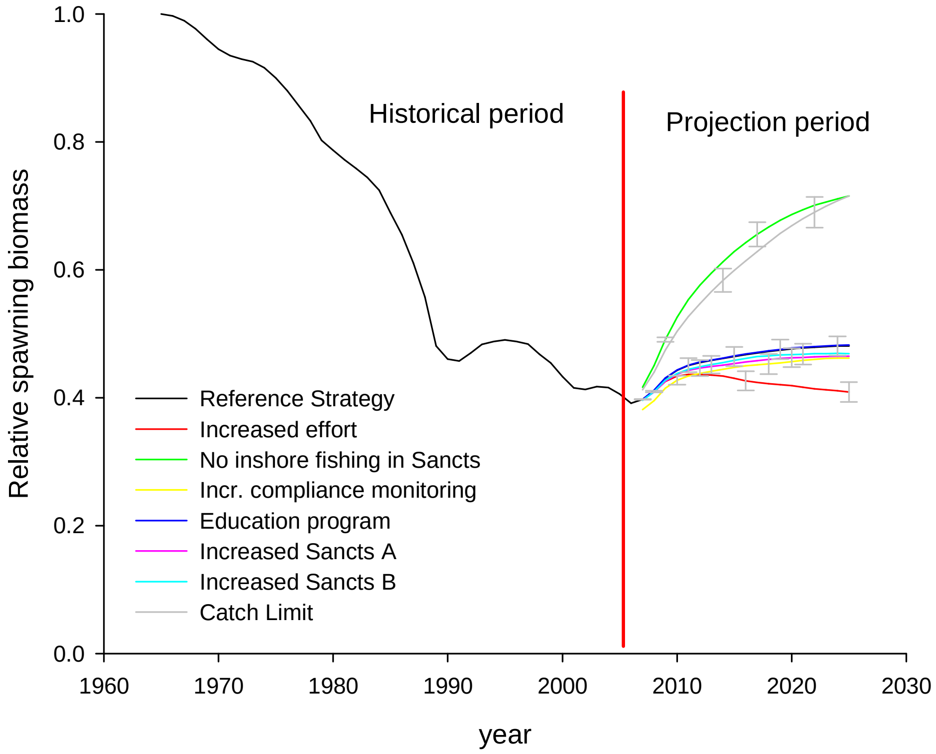


Figure 5 Average spawning biomass across 100 simulations (± SE) relative to the total unexploited spawning biomass projected under different management strategies.

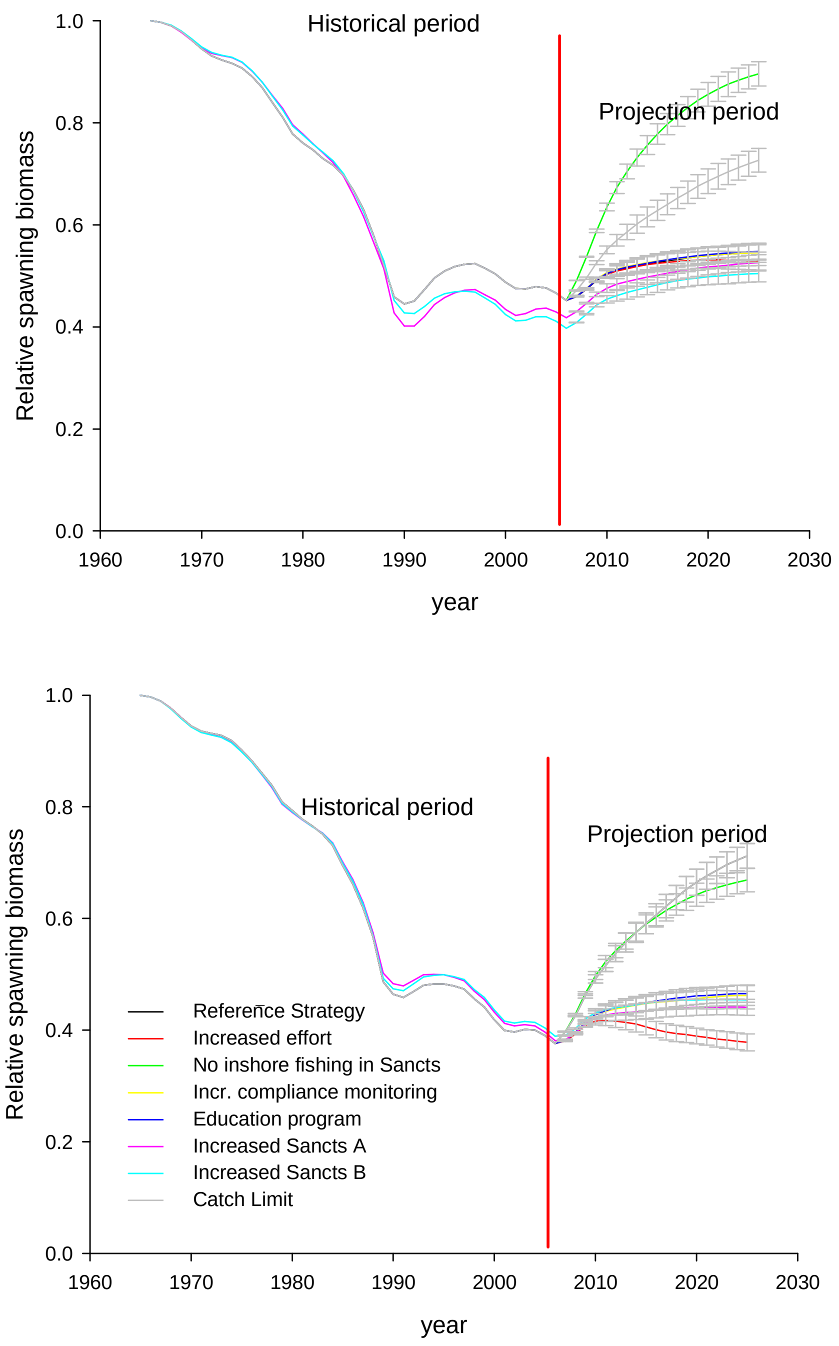


Figure 6 Average spawning biomass across 100 simulations (± SE) in sanctuaries (top) and outside of sanctuaries (bottom) relative to the total unexploited spawning biomass projected, under different management strategies.

Achieving ecological objectives under current conditions

Figure 7 shows probabilities, derived from the model runs, that the ecological objectives, identified prior to running the simulations, were achieved. The evaluation of the proposed management strategies with regards to the ecological objectives inside and outside of the sanctuaries, under current conditions, was that the long-term biomass objectives outside sanctuaries were achieved in all cases except where effort was allowed to increase (Figure 7; top panels). All other management strategies were able to achieve the objectives of both spawning biomass and available biomass being above the 2007 levels more than 75% of the time. In fact, in all management strategies, except “Increased Effort”, spawning biomass and available biomass were above simulated 2007 levels in all simulations (i.e. 100% of the time; Figure 7).

In the sanctuaries, no management strategy achieved the more demanding objective for the spawning biomass to be above 90% of simulated pre-exploitation level by the end of the projection period 75% of the time, and only one management strategy achieved the less restrictive objective of having spawning biomass above 75% of simulated pre-exploitation level by the end of the projection period 75% of the time (Figure 7; bottom panels). The management strategy that achieved this objective, and came closest to achieving the more demanding objective of having spawning biomass greater than 90% of the simulated pre-exploitation level, was the one that banned shore-based (“inshore”) fishing in sanctuaries. Shore-based fishing in the sanctuaries clearly had a large effect on the sanctuary biomass in the model.

These simulation results can also be examined in terms of the status of spawning biomass and available biomass relative to simulated pre-exploitation levels, inside and outside of the sanctuaries (Figure 8). At the end of the historical period, in 2007, the simulated spawning and available biomasses outside the sanctuaries were close to 0.37 of the simulated pre-exploitation level. The simulations showed that all strategies, including the Reference Strategy, led to an improvement on this initial situation, except when effort was allowed to increase (Figure 8). Four of the management strategies produced results comparable to the Reference Strategy, and only two (“No inshore fishing in sanctuaries”, and the introduction of a “Catch Limit”) led to a significant increase in relative spawning biomasses outside of sanctuary zones. These two strategies also led to significant improvement in the levels of average spawning biomass inside the sanctuaries, although this was affected by levels of compliance with bag limits and spatial closures. The ban on shore-based fishing (“No inshore fishing in sanctuaries” strategy) clearly had the strongest impact, leading to an average simulated spawning biomass level inside sanctuaries close to 0.9 of the simulated pre-exploitation level. Outside sanctuaries, the “increased sanctuaries A” strategy produced results that were comparable to the Reference Strategy. However, the effects within sanctuaries were strongly affected by the compliance assumptions: with increased compliance, it led to results equivalent to the Catch Limit strategy while, with limited compliance, it led to poorer results than the Reference Strategy. The “Increased sanctuaries B” strategy, on the other hand, was the poorest performing strategy with regards to spawning biomass in the sanctuaries, under both compliance scenarios. The “Increased compliance monitoring” and “Education programs” led to results that were comparable to the Reference Strategy, both within and outside of sanctuary zones.

The evaluation of the spawning biomass objective across all of the Ningaloo Marine Park (inside and outside of sanctuary zones combined) that spawning biomass be above 0.4 the simulated pre-exploitation level, 75% of the time, showed that all management strategies achieved this objective under a high compliance scenario (Figure 10). Under low compliance, the strategy allowing effort to increase (“Increased effort”) did not meet this objective. All other management strategies were able to achieve the objective in all (i.e. 100%) of the low compliance simulations. The average spawning biomass on all of Ningaloo reef relative to pre-exploitation levels, shown in Figure 11 for the 100 simulations, explains this result. Under the “Increased effort” management strategy, the simulated spawning biomass was 0.4 under 0.95 compliance, and slightly lower under 0.50 compliance levels. All other management strategies led to spawning biomass on the entire Ningaloo reef above 0.4, although only the shore-based fishing ban (“No inshore fishing in sancts”) and the “Catch Limit” strategies entailed a significant increase in relative spawning biomass at this scale (Figure 11).

The evaluation of whether the length and age indicators would lie above the pre-exploitation level, 75% of the time, showed that all management strategies achieved the length objective, but not the age objective (Figure 12). Under a 0.95 compliance level, the only management strategies that achieved the age objective were the “Catch Limit” and “No inshore fishing in sancts”. With higher infringement levels (lower simulated compliance), the latter management strategy did not achieve the average age objective. The average length in the simulations relative to pre-exploitation average length, and average age relative to the pre-exploitation average age are shown in Figure 13. Average lengths were in general more than 90% that of the pre-exploitation average length, while average ages varied among management strategies between 75% and 90% of pre-exploitation average age (Figure 13). The reason why so many of the management strategies met the length objectives, but not the age objectives is that the tolerance for length (10 cm tolerance, with an average fish length in unexploited stocks estimated at 34.84 cm) represented a much larger tolerance ratio than for the ages in the simulation results (1 year tolerance, with an average age in an unexploited stock estimated at 4.69 years).

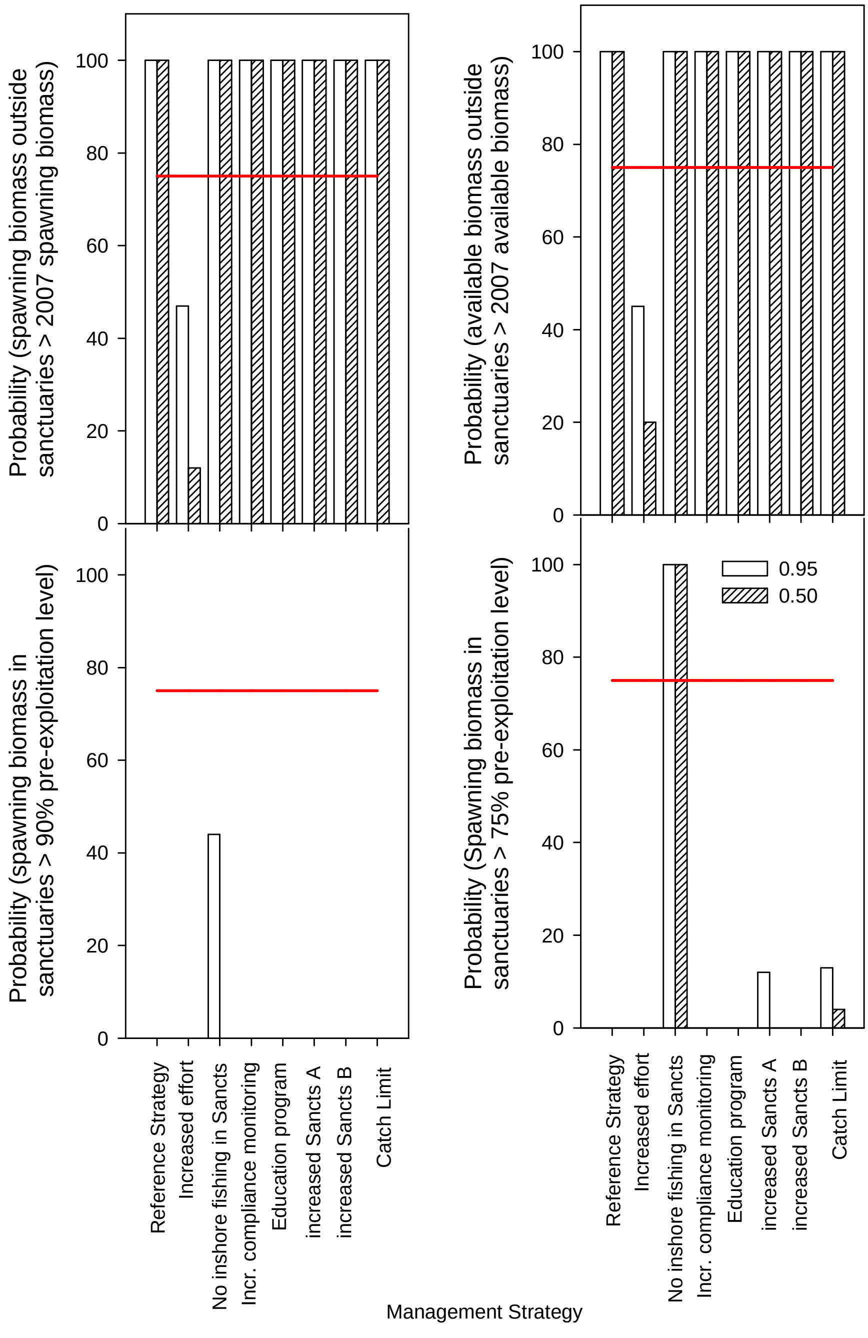


Figure 7 The probability that different management strategies are above the associated reference point (with management objective indicated by the red line) for different performance indicators for spangled emperor (upper left: objective 6, spawning biomass outside sanctuaries, upper right: objective 5, available biomass outside sanctuaries, lower left: objective 1, spawning biomass in sanctuaries, lower right: objective 2, spawning biomass in sanctuaries), under two levels of compliance (0.50 and 0.95).

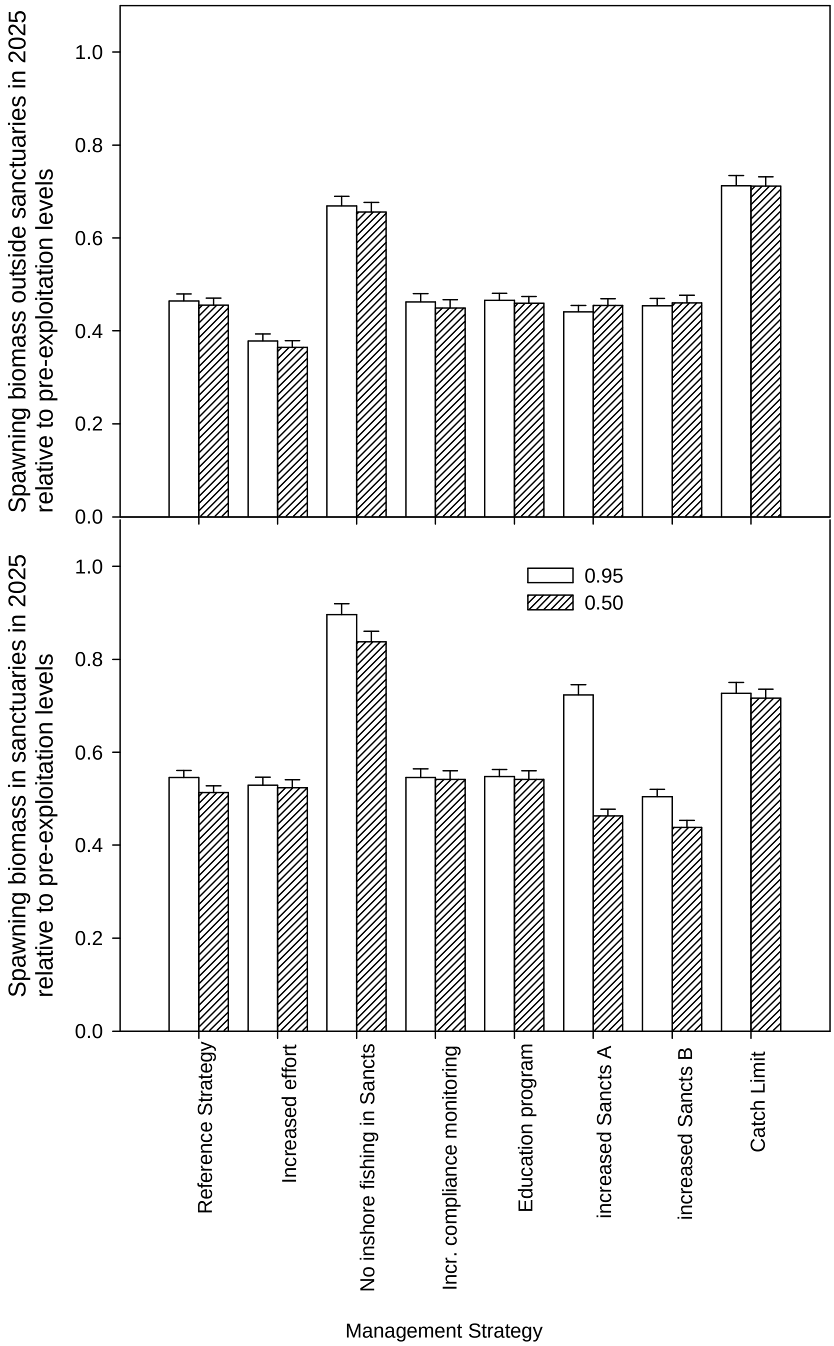


Figure 8 Simulated average (± SE) spawning biomass relative to pre-exploitation, of spangled emperor inside and outside the sanctuaries in 2025 for different management strategies, with two levels of compliance (0.50 and 0.95).

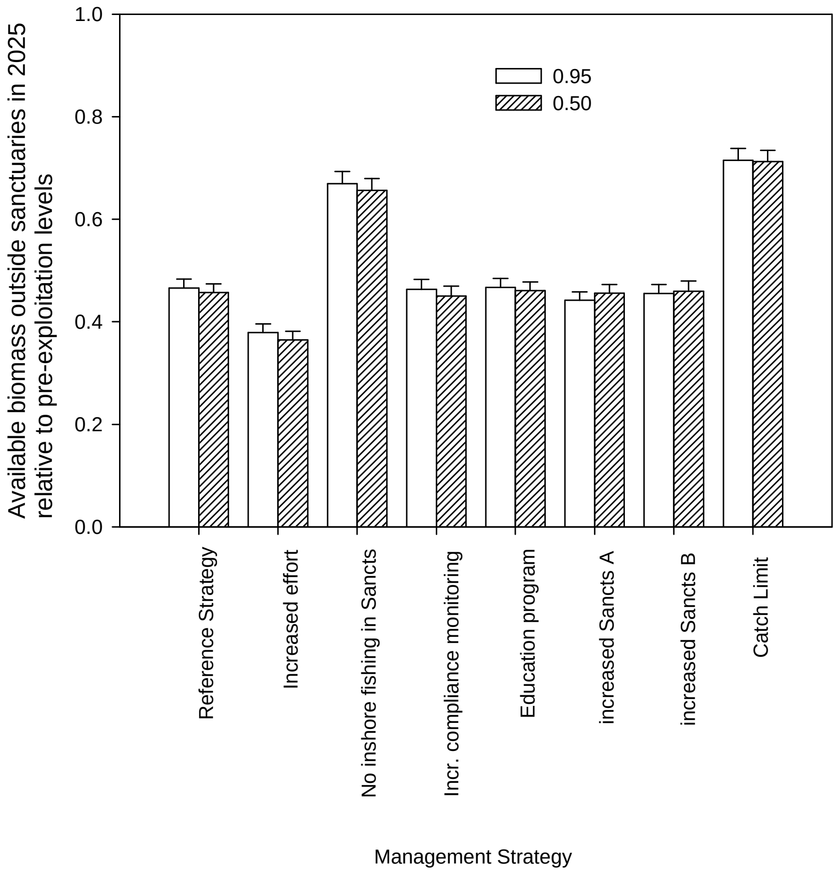


Figure 9 Simulated average (± SE) available biomass relative to pre-exploitation of spangled emperor outside the sanctuaries in 2025 for different management strategies, with two levels of compliance (0.50 and 0.95).

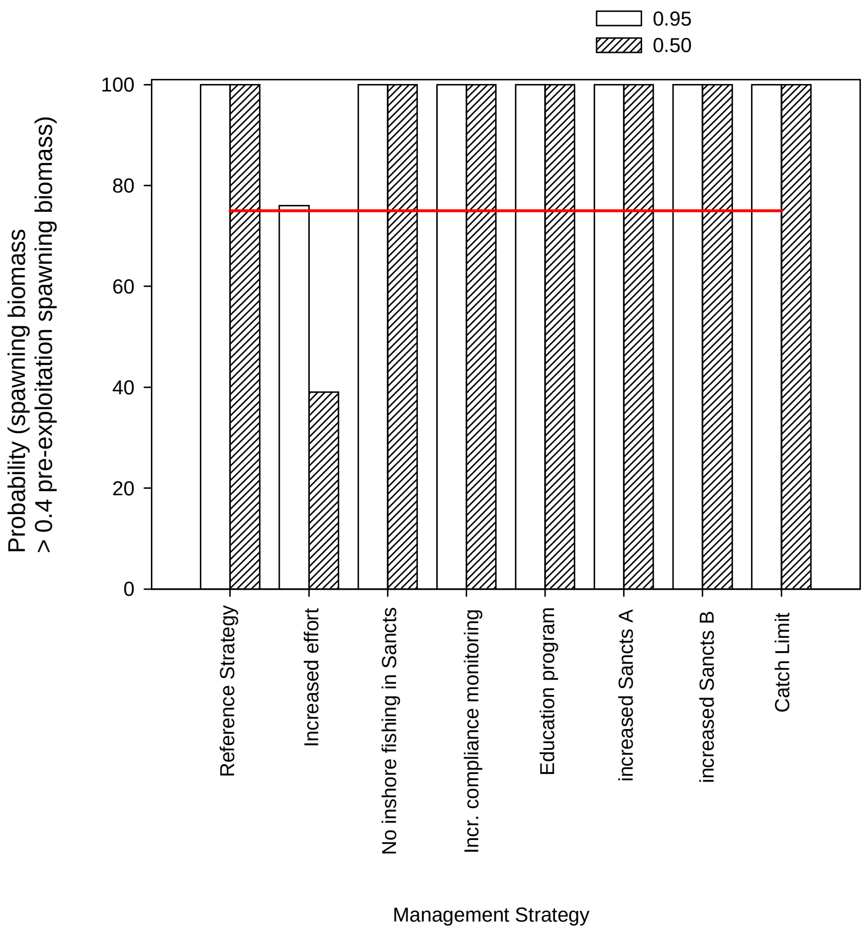


Figure 10 The probability that different management strategies lead to spawning biomass of spangled emperor across all of Ningaloo Reef greater than 40% of pre-exploitation levels, with management objective (objective 7) indicated by the red line, with two levels of compliance (0.50 and 0.95).

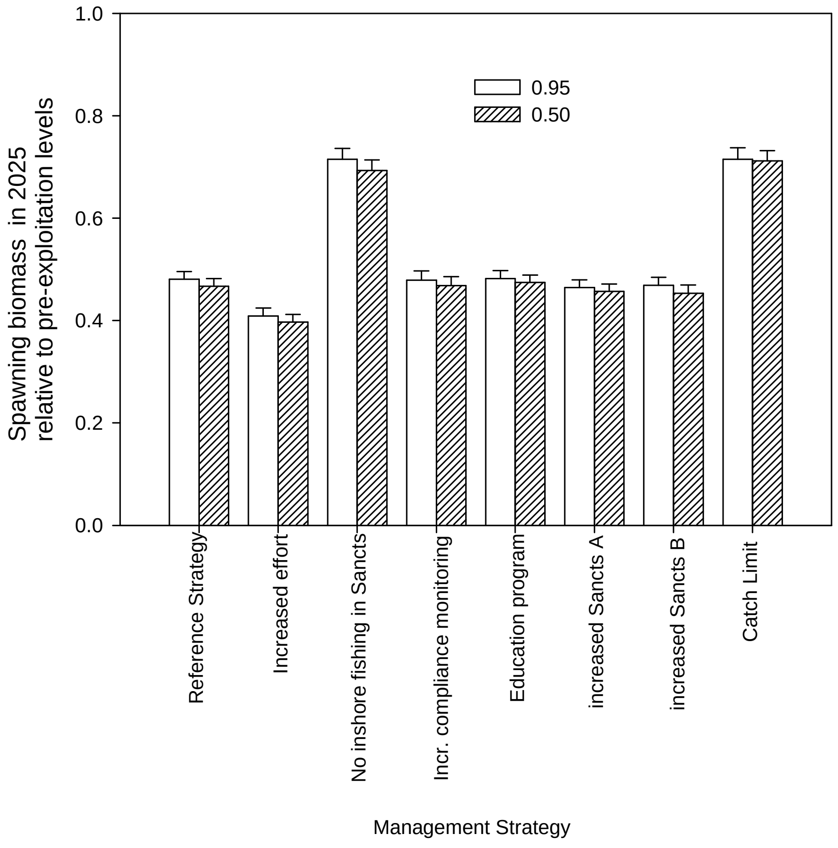


Figure 11 Simulated average (± SE) spawning biomass relative to pre-exploitation of spangled emperor across Ningaloo Reef in 2025 for different management strategies, with two levels of compliance (0.50 and 0.95).

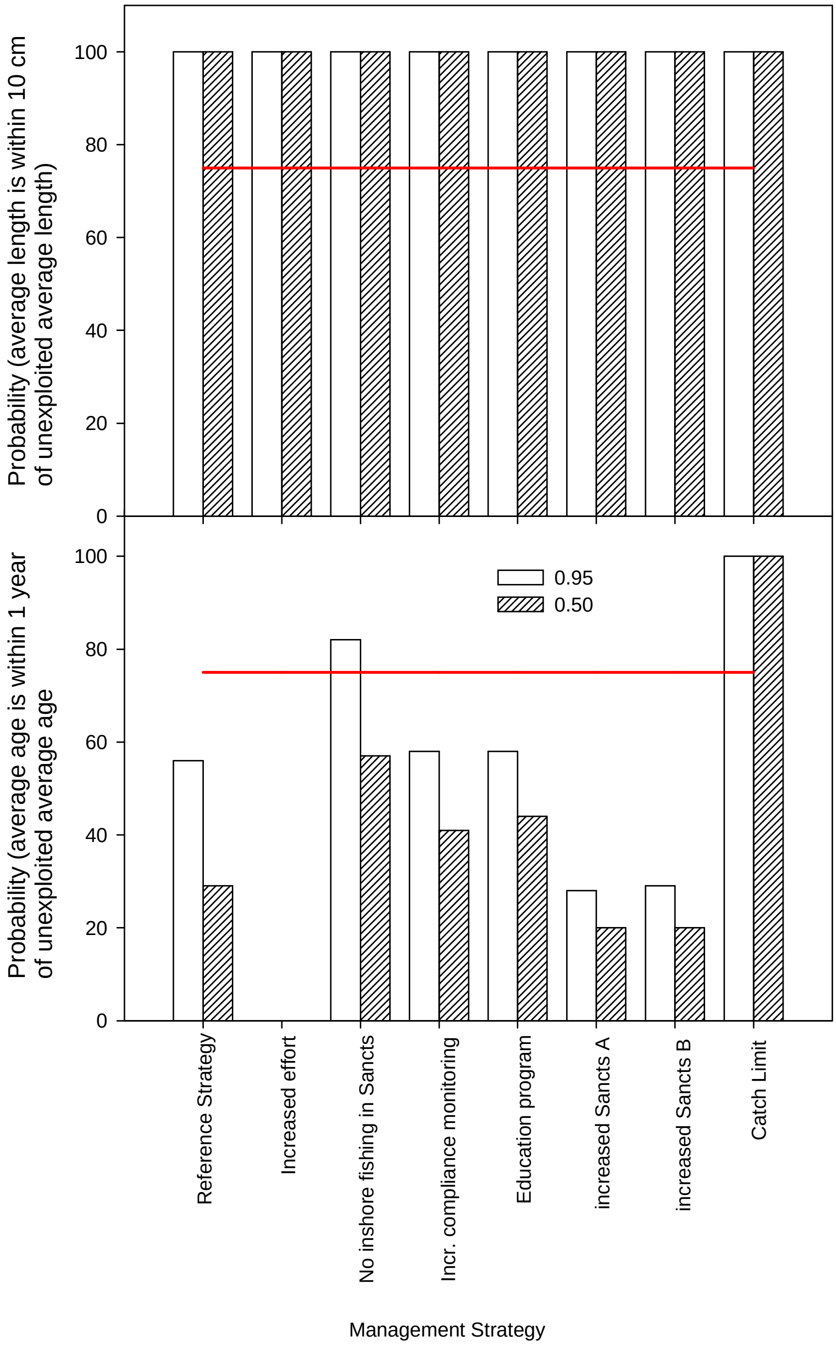


Figure 12 The probability that different management strategies lead to average ages (objective 3) and lengths (objective 4) in the spangled emperor on Ningaloo Reef greater in relation to pre-exploitation levels, with management objectives indicated by the red line, and under two levels of compliance (0.5 and 0.95).

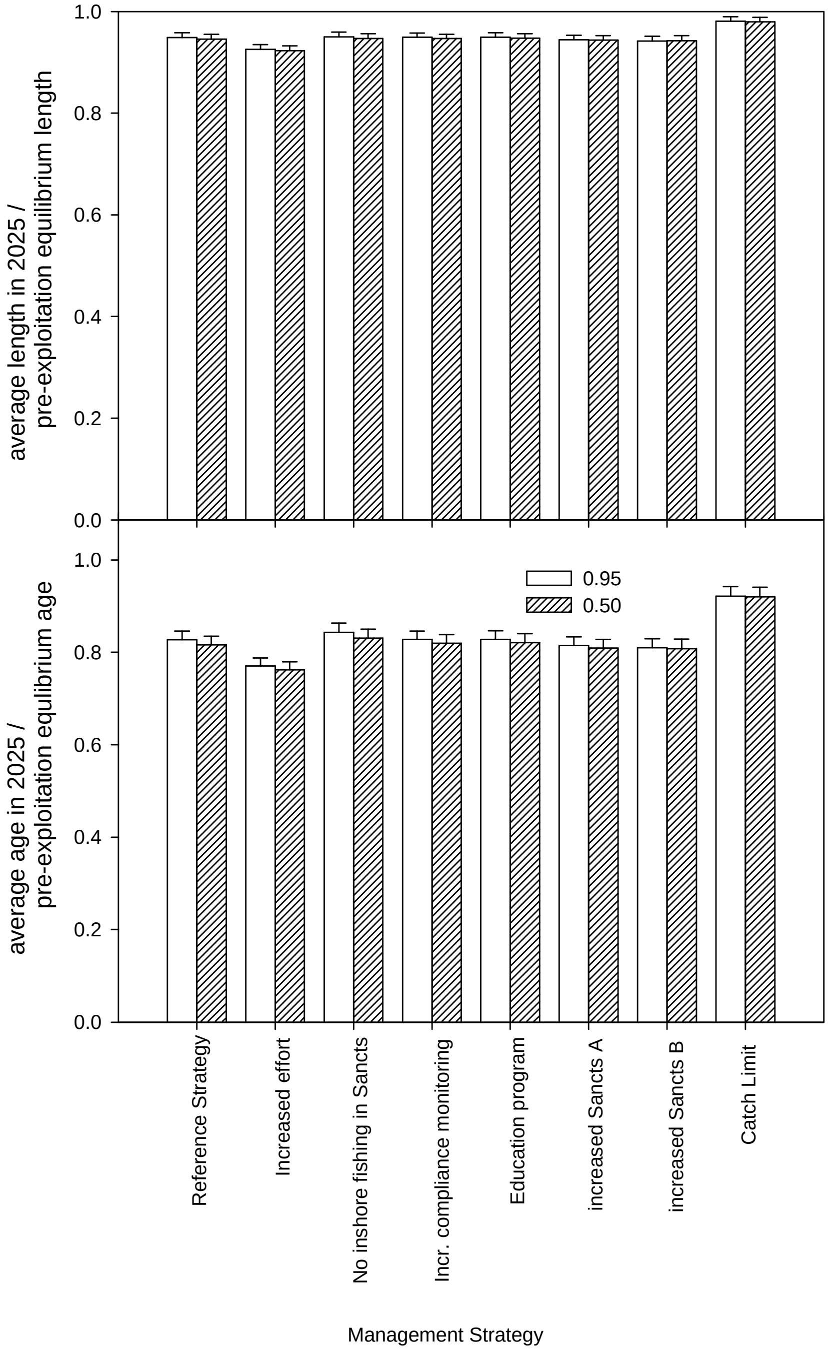


Figure 13 Average simulated length and age of spangled emperor (± SE) relative to equilibrium levels in 2025 for different management strategies, with two levels of compliance (0.50 and 0.95).

Achieving social objectives under current conditions

Evaluation of the proposed management strategies under simulated current conditions indicated that almost all simulated management strategies achieved the specified objectives (Figure 14). These objectives were that more than 20% of the recreational catch is of more than 50cm long fish, 75% of the time, and that catch per unit of effort (CPUE) should be above the 2007 CPUE, 75% of the time. All management strategies achieved the first of these in the simulations: the catch always consisted of more than 25% fish greater than 50cm. The only management strategy not able to achieve the objective of catch rates was the “Increased effort” strategy. Under this management strategy the biomass, and associated catch rates, were depleted to below 2007 levels. The “No inshore fishing in sanctuaries” management strategy was more likely to achieve the catch rate objective under the low compliance level (high infringement) assumption, as this implies that some of the catch can be taken from the sanctuary zones.

The simulated average 2025 CPUE relative to 2007 in Figure 15, shows that under the “Increased effort” strategy catch rates would be reduced in the long run as compared to the initial period, whereas they would be significantly increased under the “Catch Limit” management strategy. The simulations involving all the other strategies produced slightly higher CPUE than in 2007 (i.e. >1.0). As expected, the CPUE under these management strategies is indicative of the corresponding biomass levels in the areas open to fishing (Figure 8, top).

As indicated in Figure 14, the proportion of catch greater than 50cm was higher than 25% for all management strategies. The lowest proportion occurred under the “Catch Limit” management strategy (Figure 16), because simulated fishers in this management strategy allocated their fishing effort more frequently at the beginning of the year when the average fish size was smaller (because year classes of cohorts (1 Oct – 30 Sep) are not offset from each calendar year (1 Jan – 31 Dec)) than what it was later in the year. By the time the fish would be larger at the end of the year, the Catch Limit had often been met, and so no fishing activity occurred. There was also almost always a higher percentage of 50cm fish in the catch under higher infringement simulations (compliance lower, 0.50) than lower infringement simulations (higher compliance, 0.95) because fishing tended to occur in the closed sanctuaries.

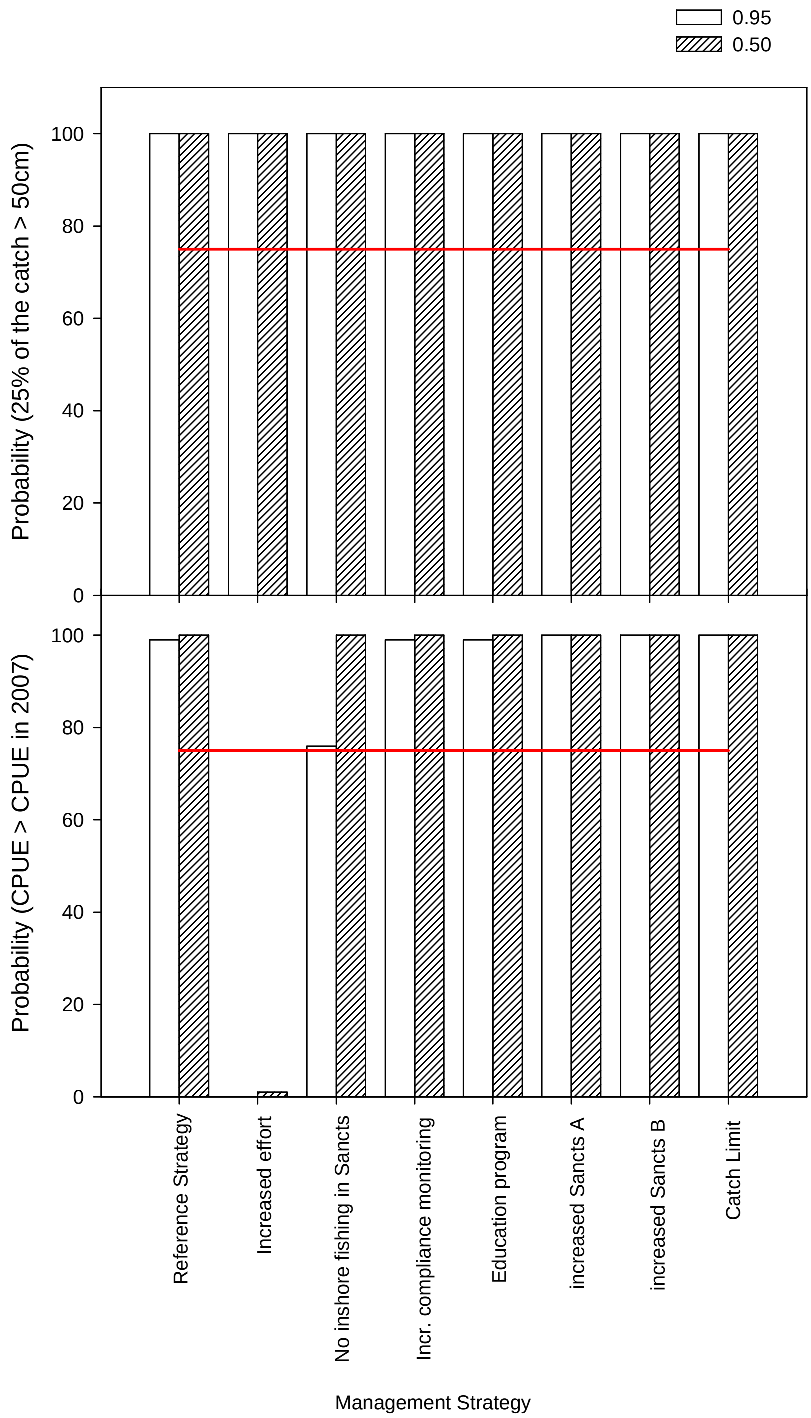


Figure 14 The probability that different management strategies lead to greater CPUE in 2025 (objective 8) and lengths (objective 9) of spangled emperor in relation to reference levels on Ningaloo Reef, with management objective indicated by the red line, and under two levels of compliance (0.5 and 0.95).

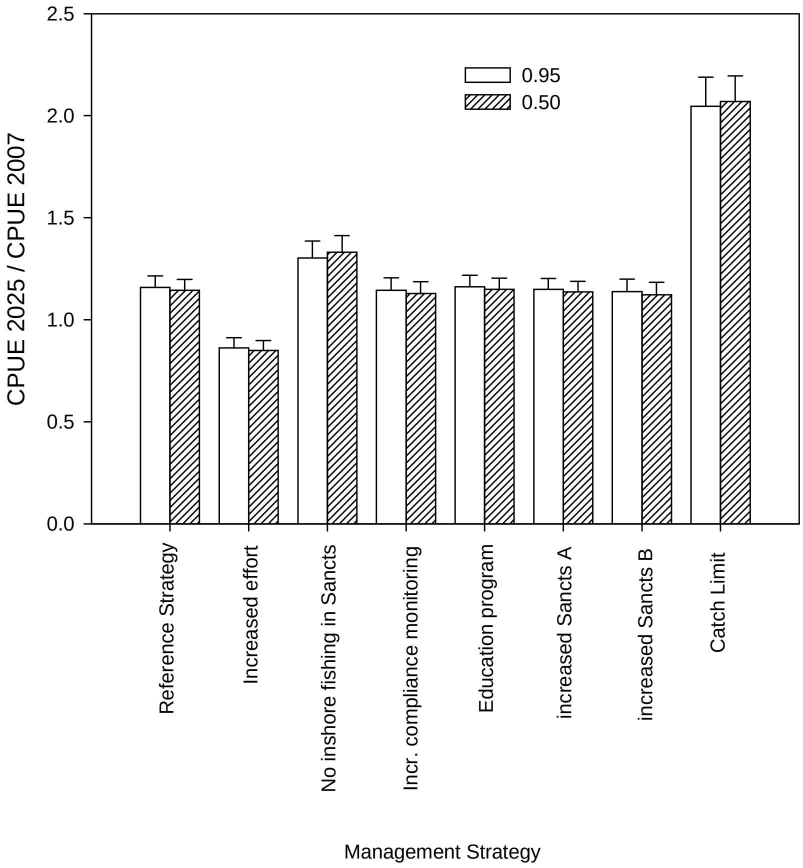


Figure 15 Average CPUE (± SE) in 2025 relative to simulated 2007 level of spangled emperor for different management strategies, with two levels of compliance (0.50 and 0.95).

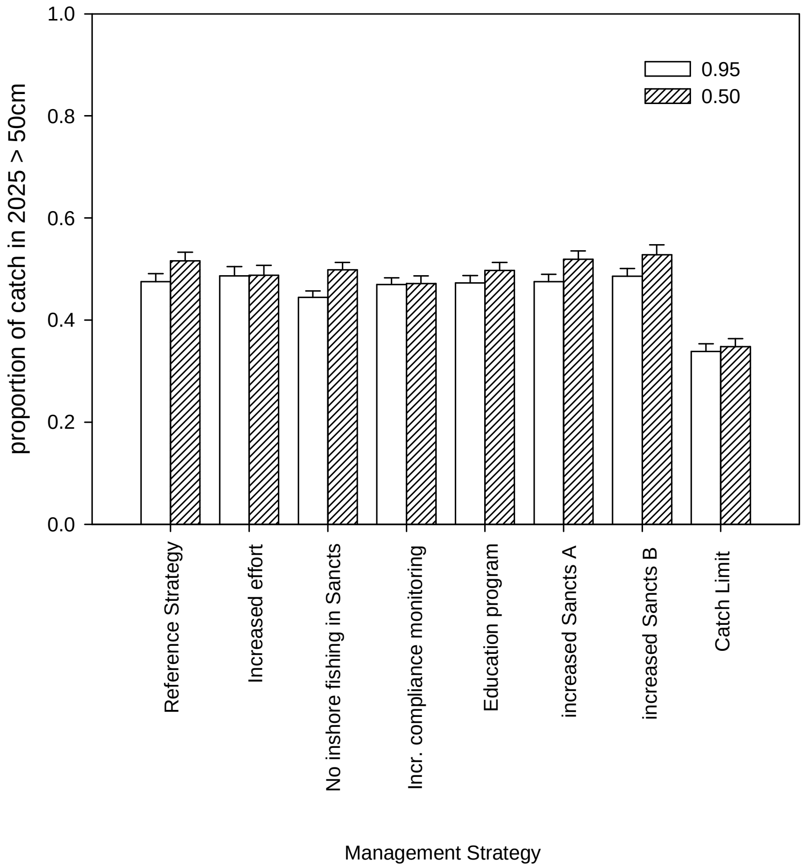


Figure 16 Simulated average proportion of spangled emperor (± SE) caught in 2025 that were > 50cm for different management strategies, with two levels of compliance (0.50 and 0.95).

Measuring other indicators under current conditions

Other indicators raised by the stakeholders that were of interest to monitor, but without explicit targets to be met, included the level of recreational catch, the discards of undersized fish, and the catch variation (average deviation in catch from vessel trip to trip), which included the probability of not catching a fish in a fishing trip. The purpose of catch variation as such was to capture the variability of fish that would be expected to be caught from trip to trip, and was determined as the average difference in the number of fish caught from one trip to the next. Calculating a measure of not catching a fish on a fishing trip, however, was more difficult because, given modelling assumptions, a non-zero fishing effort will always generate a non-zero catch in the model. Such catches are usually calculated in terms of biomass; we used this information and the expected average size of fish to calculate an indicator describing fishing trips with catches of less than one fish of average size.

The long-term results achieved by management strategies with respect to these indicators are shown in Figure 17 through to Figure 20. Across all strategies, catches were higher when infringement was highest (i.e. compliance level was 0.5). The “Increased effort” management strategy led to the highest catches (Figure 17). Simulated effort in this management strategy was twice that of the “Reference Strategy” strategy, but lower catch rates (Figure 15) led to a less than proportional increase in catch given the increase in effort. The lowest catch levels occurred when shore-based fishing effort was banned from the sanctuaries (“No inshore fishing in sancts”) and under the “Catch Limit” management strategy. All other strategies led to catches of comparable levels to those of the “Reference Strategy”.

Discards from the simulations were more variable than other indicators (Figure 18), and tended to be higher, sometimes significantly, when compliance levels were higher (0.95 compared to 0.50, Figure 18). This is due to the way in which discarding behaviour is represented in the model, whereby the simulated behaviour of fishers after reaching their daily bag limits, continue to fish releasing the remainder of what is caught according to the assumed level of compliance (see model description). Under the conditions of high compliance, bag limits are more constraining and so more fish are discarded. This result suggests that the promotion of practices to reduce the incidence of post-release mortality is a potentially important issue, given the high rates of discarding that are possible when bag limits are enforced.

Catch variation from trip to trip was relatively low and comparable across all strategies except the Catch Limit strategy (Figure 19). The latter had the highest catch variation (Figure 19) because in the model vessels may fish in one session, but then be prevented from fishing or retaining caught fish, in the next because the Catch Limit had been reached.

The indicator describing poor fishing in terms of zero catches (Figure 20) was lowest for the “Catch Limit” management strategy, and was relatively comparable across most strategies. The strategies that improved this indicator over the “Reference Strategy” tended to have either higher levels of fishing effort, causing stock depletion (Figure 17), or lower levels leading to improved catch rates from recovery of the simulated stock (Figure 15).

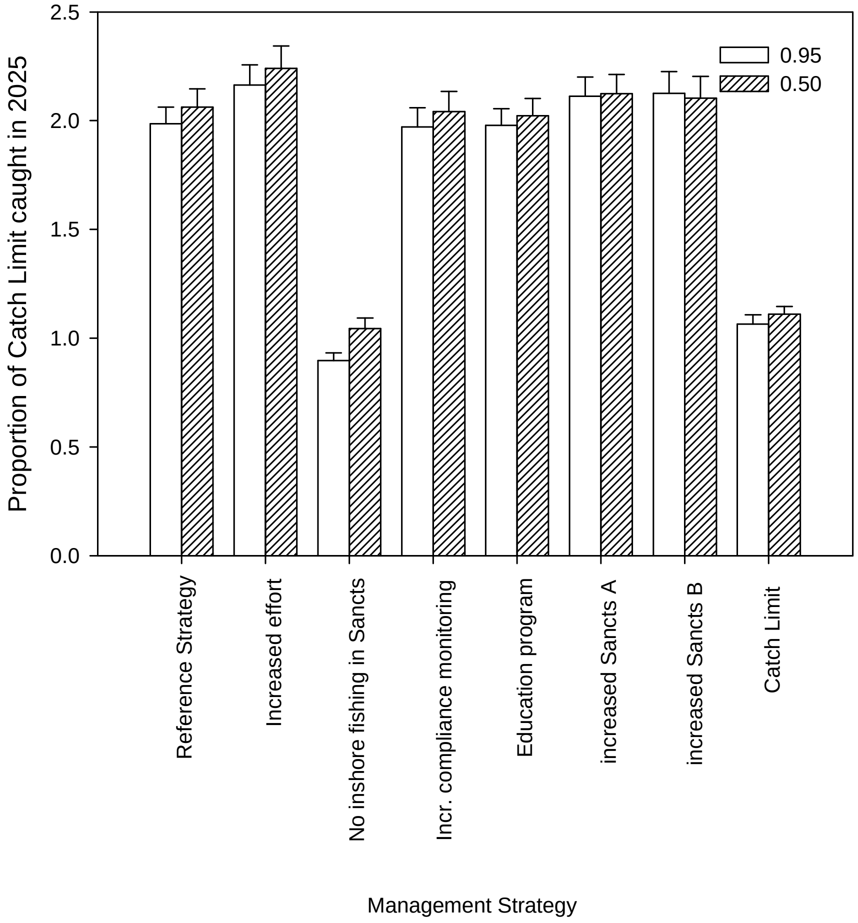


Figure 17 Simulated average catch (% of the simulated catch limit) of spangled emperor (± SE) in 2025 for different management strategies, with two levels of compliance (0.50 and 0.95).

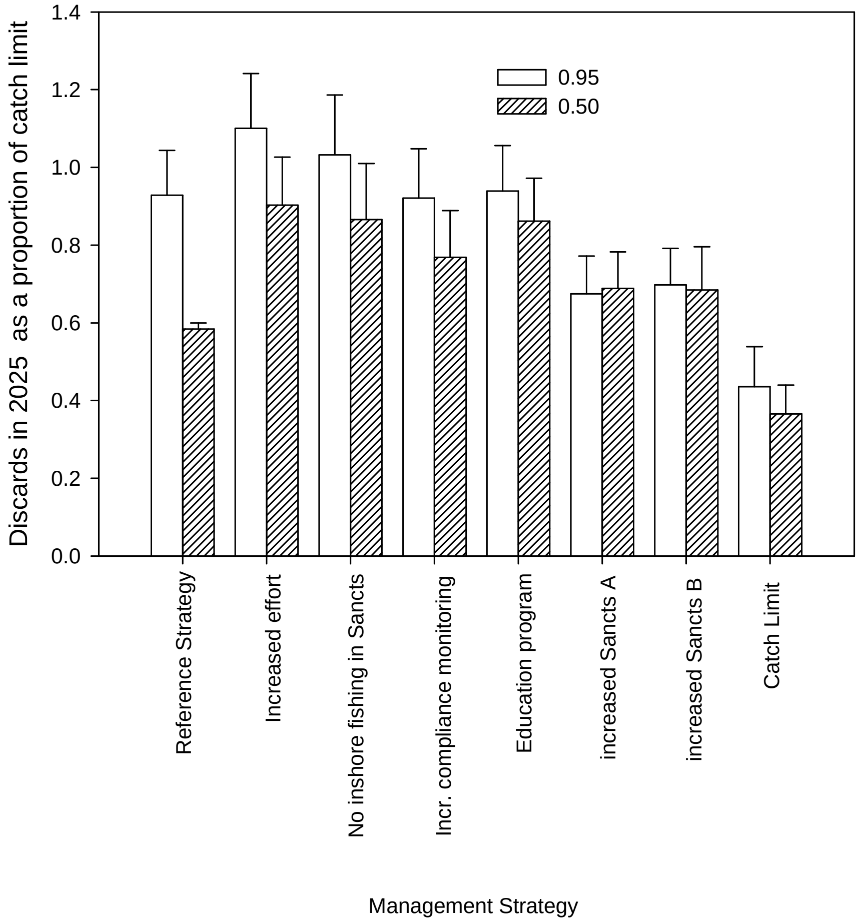


Figure 18 Simulated average discards (% of the simulated catch limit) of spangled emperor (± SE) in 2025 for different management strategies, with two levels of compliance (0.50 and 0.95).

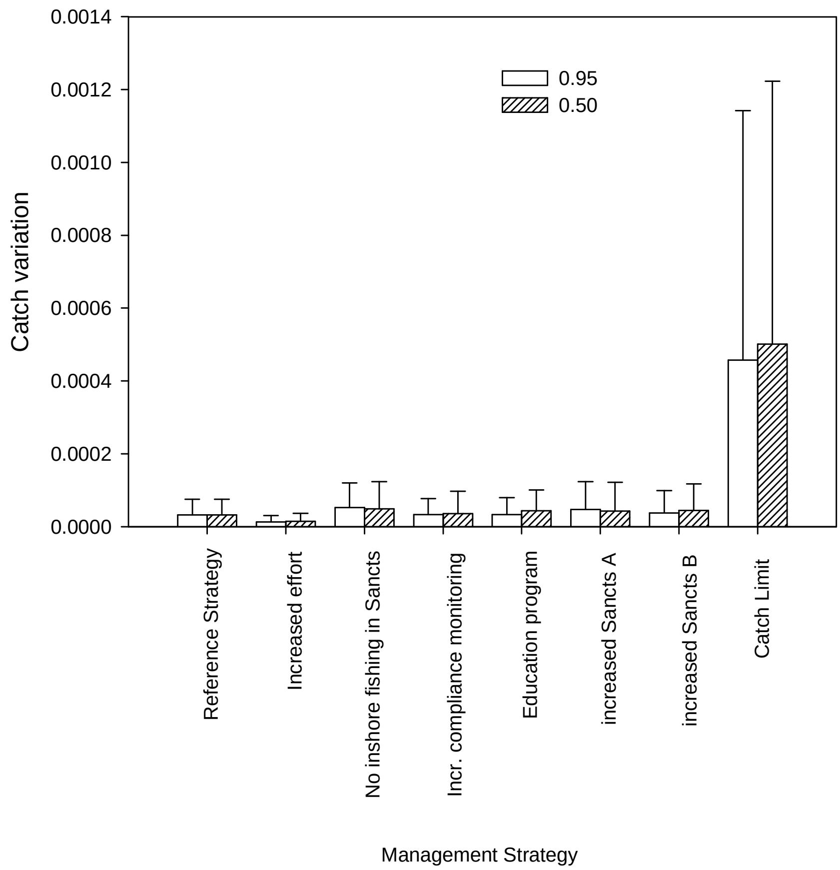


Figure 19 Simulated average catch variation of spangled emperor (± SE) in 2025 for different management strategies, with two levels of compliance (0.50 and 0.95).

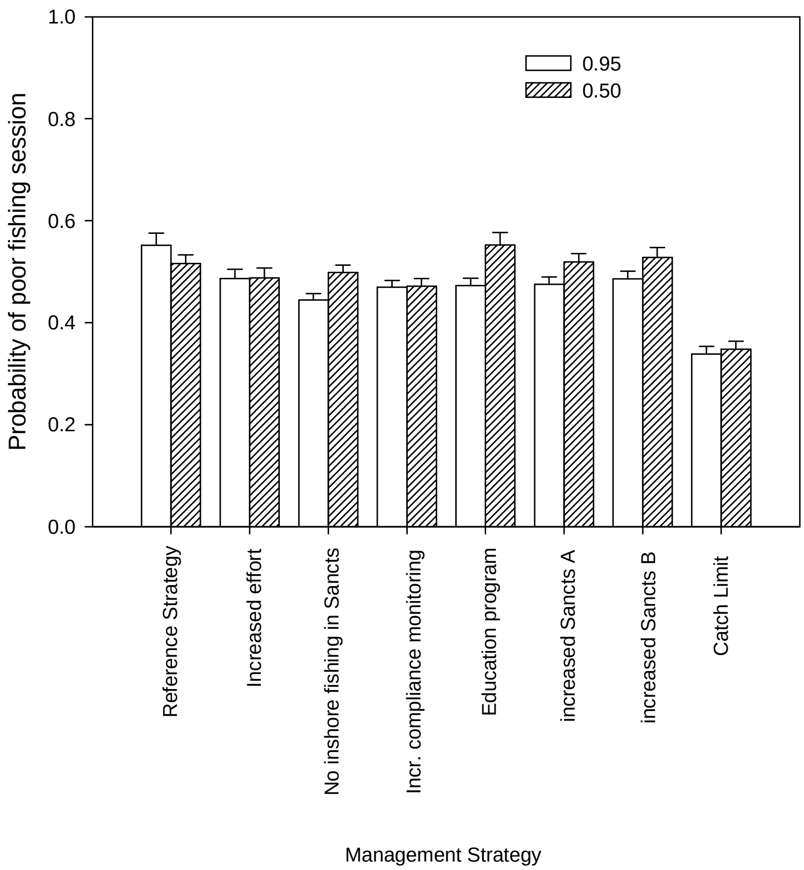


Figure 20 Average probability (± SE) that a fishing session in 2025 will not catch any spangled emperor for different management strategies, with two levels of compliance (0.50 and 0.95).

Management Performance summary

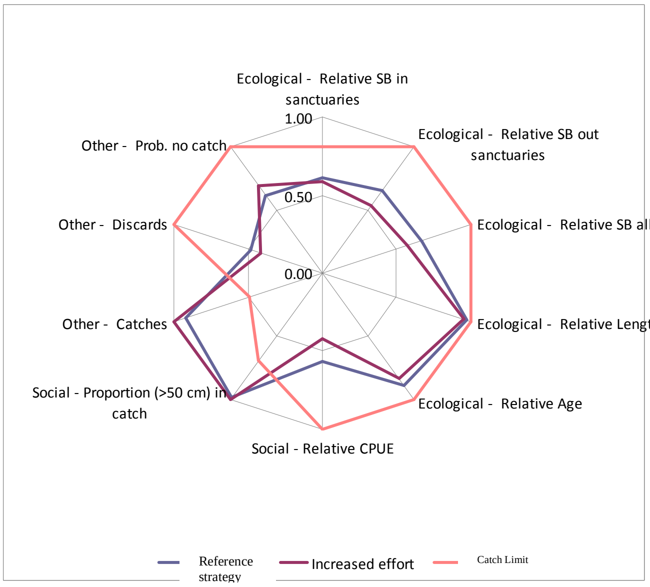
The summary of performance indicator values for the major management objectives and management strategies are shown for Current conditions in this section (3.3.1; Table 8, Figure 21). Under current conditions, the management strategy that best achieved the ecological objectives were the preclusion of shore-based fishing in sanctuaries ("No inshore fishing in sancts"), and having a strategy that limits catch to some constant level over time ("Catch Limit"; Table 8). Extending sanctuary size ("Increased sancts A", "Increased sancts B") increased protected biomass, but in the absence of reduced fishing pressure, reduces biomass outside of the sanctuaries, and as a consequence, across the entire region. Because CPUE is related to biomass outside of the sanctuaries, the "Catch Limit" management strategy also performed well for this indicator. The "No fishing inshore in sancts" strategy performed somewhat less well in this respect, as it involves restricting fishable areas where higher biomass recovery may occur. The "Catch Limit" strategy however did not perform well for the other social objective, which was to have a high proportion of the catch as big, so-called trophy-sized, fish, whereas the "No inshore fishing in sancts" strategy performed slightly better with regards to this indicator. The "Catch Limit" and "No inshore fishing in sancts" strategies also performed poorly with respect to average fisher catch in 2025. Not surprisingly these also delivered the highest catches of large fish. The "Increased effort" strategy however also tended to have high discards, as compared to the other strategies, particularly the "Catch Limit" strategy. The indicator that was proposed to measure fisher enjoyment in the probability of not catching anything, "Prob. of no catch" (Table 8), suggested that the "Reference Strategy" was the poorest performer, and that you could improve on this performance either by reducing catches (through a Catch Limit) and thus increasing catch rates, or fishing harder ("Increased effort"). Some of the other management strategies, "Increased compliance monitoring", and "Education program" perform moderately well across all objectives (Table 8, Figure 21).

Table 8 Summary of performance indicators from the last year of projection, 2025, under different management strategies and current conditions. Colours: **blue** the best result for a column (indicator), **green** the second best result, **red** poorest result, **orange** the second worse result.

Objective:	Ecological					Social		Other		
Strategy	**Relative SB in sanctuaries**	**Relative SB out sanctuaries**	**Relative SB all**	**Relative Length**	**Relative Age**	**Relative CPUE**	**Proportion catch (>50 cm)**	**Catches (Catch Limit%)**	**Discards (Catch Limit%)**	**Prob. no catch**
Reference Strategy	0.55	0.46	**0.48**	**0.95**	0.82	1.16	**0.48**	197%	92%	**0.55**
Increased effort	**0.53**	**0.38**	**0.41**	**0.93**	**0.77**	**0.86**	**0.49**	**215%**	**107%**	**0.49**
No inshore fishing in sancts	**0.90**	**0.67**	**0.72**	**0.95**	**0.84**	**1.30**	**0.44**	**89%**	**102%**	**0.44**
Incr. Compl. Monitoring	0.55	0.46	**0.48**	**0.95**	0.83	**1.14**	0.47	197%	92%	0.47
Education program	0.55	0.47	**0.48**	**0.95**	0.83	1.16	0.47	197%	94%	0.47
Increased sancts A	0.72	**0.44**	**0.46**	**0.94**	**0.81**	1.15	0.47	210%	**68%**	0.47
Increased sancts B	**0.50**	0.45	0.47	**0.94**	**0.81**	**1.14**	**0.49**	**213%**	71%	**0.49**
Catch Limit	**0.73**	**0.71**	**0.72**	**0.98**	**0.92**	**2.04**	**0.34**	**105%**	**44%**	**0.34**

Figure 21 Performance summary showing radar plots of how different management strategies (coloured lines) achieve the objectives under current conditions: objectives are on the axes. a. Reference Strategy, Increased effort and Catch Limit management strategies. b. Increased sancts A, Increased sancts B and No inshore fishing in sancts management strategies, c. Increased sancts A, Increased sancts B and Catch Limit management strategies compared.

a.



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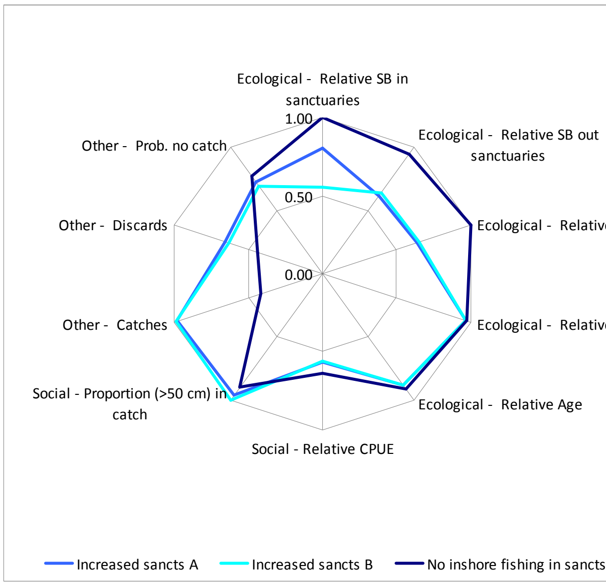

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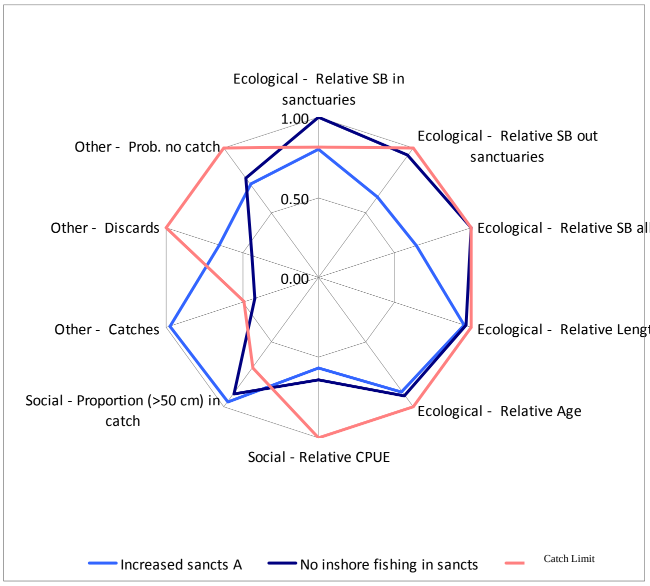


3.3.2 An evaluation of management strategies under alternative future projected scenarios

The previous section examined the performance of alternative management strategies with respect to the ecological and social objectives that were identified for recreational fishing on Ningaloo Reef. Simulation results allow the assessment of pre-defined management strategies across a wide range of objectives, and illustrate that alternative approaches are likely to perform variably across these different objectives. For example, two contrasted strategies, producing similar levels of catches in the long-term, are: (i) the implementation of a catch limit, which produces a marked recovery of spangled emperor population biomass, improved catch rates and higher catch variability in response to the simulated depletions from fishing, versus (ii) allowing fishing effort to increase, which results in reductions in the population biomass and catch rates of spangled emperor, and lower variability in catches.

In this section, we examine the effects of including the alternative scenarios about the future conditions within which management will operate, in order to see the effectiveness to these two contrasting management strategies. We also include the simulated “Reference Strategy” management strategy for comparison. The nuances between these and the other strategies considered in the current conditions of the previous section will not be developed again in this section, but instead will focus on the interactions with the alternative scenarios.

The time series shown in Figure 22 shows the effect of the different projected scenarios on the spawning biomass of spangled emperor on Ningaloo reef, under the “Reference Strategy” management strategy. To keep the presentation of the results manageable we have illustrated these only under the management compliance of 0.95. The results under greater infringement of 0.5 are qualitatively similar.

The “Current conditions” scenario reflects the conditions simulated and reported in the previous section 3.3.1. All other future scenarios led to lower spawning biomass than under the “Current conditions”, but some scenarios led to greater declines than others. The greatest decline from a single scenario came from the “Environmental Pressure” scenario, which involved the doubling natural mortality of the species by 2025. Under this scenario, the long-term declining trend in simulated biomass in the past resumes, after a short interruption in the first years of the projection. The “Environmental catastrophe” scenario had the second strongest effect, but was substantially lower than “Environmental pressure” mainly because the effects were spatial, allowing a chance of recovery before another disturbance affected the area. The variability associated with this scenario was larger than the other scenarios because of the uncertainty associated with disturbance events. “Technology creep” had a moderate influence on the spawning biomass as fishers were able to catch more with the same amount of effort. Under this and the “Environmental catastrophe” scenario, the restoration of spawning biomass on Ningaloo reefs under current management arrangements is only transitional as biomass declines back to its simulated 2007 level by 2025. The “Decreased costs” and “Coral Bay upgrade” scenarios had a more limited effect on the spawning biomass, slowing down the recovery under “Reference Strategy” management arrangements. Not surprisingly combining the two most effective scenarios of “Environmental Pressure” and “Technology creep”, led to the most negative outcome for spawning biomass. This scenario also illustrates the fact that effects were not additive across different scenarios, in that the effect of the combined scenario was not equal to the simple sum of the effects of both scenarios alone. Some of these scenarios resulted in more of a localized depletion effect outside of sanctuary zones, and others resulted in more of a stock-wide depletion effect (i.e. depletions evident both inside and outside of sanctuary zones) relative to Current conditions, as discussed below with reference to results presented in Figure 25 below. Figure 23 shows the simulation results of the different projected scenarios on the catch of the spangled emperor on Ningaloo reef, under the “Reference Strategy” management strategy. The “Technology creep” scenario led to the highest catches, which increased to 2016 (as specified by the scenario), but then declined in response to the reduction in biomass. Two other scenarios that led to greater catches than the “Current conditions” were the scenarios in which cost of fishing decreased (“Decreased costs”), and the “Coral Bay upgrade” scenario. Scenarios that involved changes to the environment of the species (e.g. “Env. Pressure” and “Env. Catastrophe”) led to lower catches than would be taken under the “Current conditions” scenario.

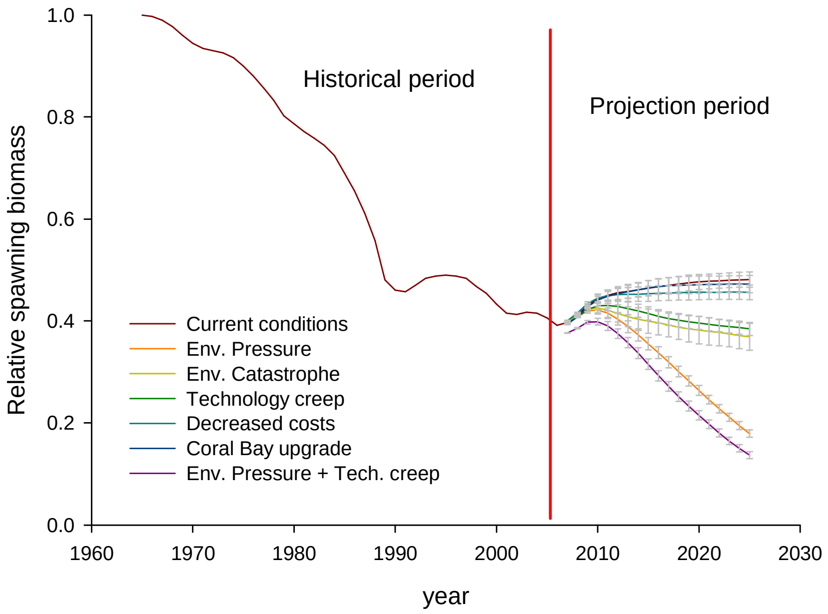


Figure 22 Simulated average spawning biomass (± SE) relative to the total unexploited spawning biomass projected under the Reference Strategy management strategy for different scenarios.

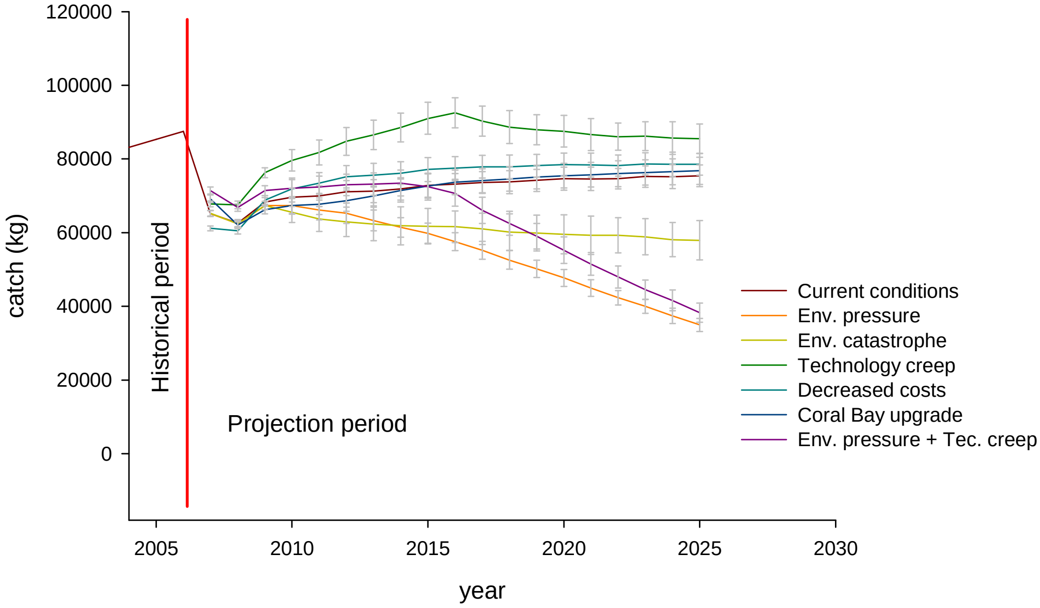


Figure 23 Average landed catches across 100 simulations (± SE) relative to the total unexploited spawning biomass projected under the Reference Strategy management strategy for different scenarios.

Achieving ecological objectives under alternative future scenarios

Evaluation of the three management strategies (“Reference Strategy”, “Increased effort” and “Catch Limit”) with respect to the ecological objectives, under the range of potential future scenarios, shows that none of these management strategies achieved the ecological objective for spawning biomass in sanctuary zones (Figure 24, bottom panels). This is not surprising given the results of the previous section 3.3.1 under “Current conditions”, which showed that the only management strategy to achieve the objectives for spawning biomass in sanctuary zones involved the preclusion of fishing in these (“No inshore fishing in sancts”), an option that was not considered here (Figure 7). Under the projected scenarios, none of the strategies simulated resulted in greater spawning biomass in 2025 than in 2007 (Figure 25, bottom panels), as no management strategy involved precluding fishing in the sanctuary zones.

Both the “Reference Strategy” and “Catch Limit” management strategies achieved the ecological objectives pertaining to the spawning biomass outside of the sanctuaries, but only under certain scenarios (Figure 24, top panels). The “Catch Limit” management strategy achieved the ecological objectives under all scenarios except “Env. Pressure”, and “Env. Pressure + Tech. creep” (Figure 24, top panels). Unlike the “Catch Limit”, the “Reference Strategy” management strategy did not achieve the objectives under the “Env. Catastrophe” and either of the scenarios involving technological creep (“Tech. creep” and “Env. Pressure + Tech creep”; Figure 24, top panels). The “Reference Strategy” did achieve the objectives under “Decreased costs” and “Coral Bay upgrade” scenarios, however, similar to the “Catch Limit” management strategy.

The “Increased Effort” management strategy did not achieve the ecological objectives under any scenario. This is similar to the previous section (3.3.1), in which the “Increased effort” was the only management strategy from a wide range of strategies considered, not to have achieved the ecological objective for spawning biomass outside of sanctuaries (Figure 7).

Comparing and contrasting observed spawning biomasses inside and outside the sanctuaries for the three management strategies and under the seven projection scenarios reveals further details about the nature of depletion effects (Figure 25). As seen in the time series plots (Figure 22) biomass is lowest under the “Env. Pressure”. This scenario, in particular, affected the simulated spangled emperor population both inside and outside of the sanctuaries. Other scenarios capture different conditions in the fishery (“Technology creep”, “Decreased costs”, “Coral Bay upgrade”) and result in relatively greater differences in spawning biomasses between sanctuaries and non-sanctuaries than the scenarios that capture different environments for the species (“Env Pressure” and “Env catastrophe”). Therefore, in context of the frequently-made assertion that a greater fish biomass within than outside of sanctuary zones is indicative of their effectiveness, these results indicate that sanctuary zones are likely to be effective in instances of increased fishing pressures except when environmental change(s) affect the whole system. However, it is also important to note that although a greater fish biomass within the sanctuaries compared to outside of sanctuary zones may indicate sanctuary zone effectiveness in one respect, this may not be a desired outcome in terms of ecological or social objectives for a fishery when the cause of that difference is the consequence of localised overfishing outside of the sanctuary zones.

The nature of simulated depletion effects is seen as greater declines outside the sanctuaries compared to inside, indicated greater localized depletions for the Technology creep, Decreased costs and Coral Bay upgrade scenarios. Declines were greater by a similar magnitude for spangled emperor inside and outside of sanctuary zones, indicating more general stock-wide depletions for the Env. Pressure and Env. Catastrophe scenarios. For the Env. Pressure + Tech. Creep scenario the depletion was much higher than under Current conditions inside and outside of sanctuary zones, but depletions were slightly higher outside of sanctuary zones, indicating a combination of localized and stock-wide depletion effects under that scenario. (Figure 25)

The simulated available biomass outside of the sanctuaries for the three management strategies and under the seven projection scenarios, is shown in Figure 26. The results are similar to those for spawning biomass (Figure 25, upper panel). “Increased effort” results in reduced biomass compared to the “Reference Strategy” and “Catch Limit” management strategy under all future projection scenarios. One of the most important results seen in Figure 26 is that under all other alternative projection scenarios presented, the Reference Strategy results in lower biomasses than the Catch Limit strategy (Figure 26), indicating that restricted catches, and a larger population biomass, are likely to provide greater hedges against the possible impacts of changes in the conditions characterizing both the fishery and the environment. On the other hand, allowing effort to increase in the region is likely to lead to a degradation of the available biomass in the long run, which would also negatively impact the effectiveness of management for achieving the specified social objectives.

Evaluation of the ecological objective across all of Ningaloo reef (inside and outside of sanctuaries) that spawning biomass be above 0.4 the simulated pre-exploitation level (a DoFWA target level for sustainable harvest) 75% of the time shows that the “Catch Limit” management strategy was the best at achieving this objective across the various projections scenarios (Figure 27). No management strategy was able to achieve the objective under the “Env Pressure” scenario, or the composite “Env Pressure + Tech creep” scenario. The “Increased effort” scenario did not achieve the objective under any of the projected scenarios, other than “Current conditions”, and the “Reference Strategy” only achieved the objective under the “Decreased costs” and the “Coral Bay upgrade” scenarios. Figure 28 shows the spawning biomass relative to pre-exploitation levels in the simulations, which resulted from the scenario and strategy combinations, reflecting the nature of differences in results shown in Figure 27. Similar to what was observed under current conditions, the evaluation of the length and age objectives shows that all management strategies achieved the length objective, but not the age objective (Figure 29). The only management strategy that achieved the age objective was the “Catch Limit” strategy. The observed average length relative to pre-exploitation average length, and the average age relative to the pre-exploitation average age is shown in Figure 30. Average lengths were in general more then 0.9 that of the equilibrium average length, while average ages in relation to equilibrium ages varied more (Figure 30). However, across all scenarios, the “Catch Limit” strategy allowed the age structure to stay closer to the estimated equilibrium one. It should be noted that the comparison to the equilibrium ages and lengths in these figures are assumed under current conditions. Under the “Env Pressure” and the composite scenario “Env Pressure + Tech creep”, the equilibrium conditions actually change because the natural mortality changes, and so even in the absence of fishing it is possible that the population will not return to the pre-exploitation equilibrium conditions.

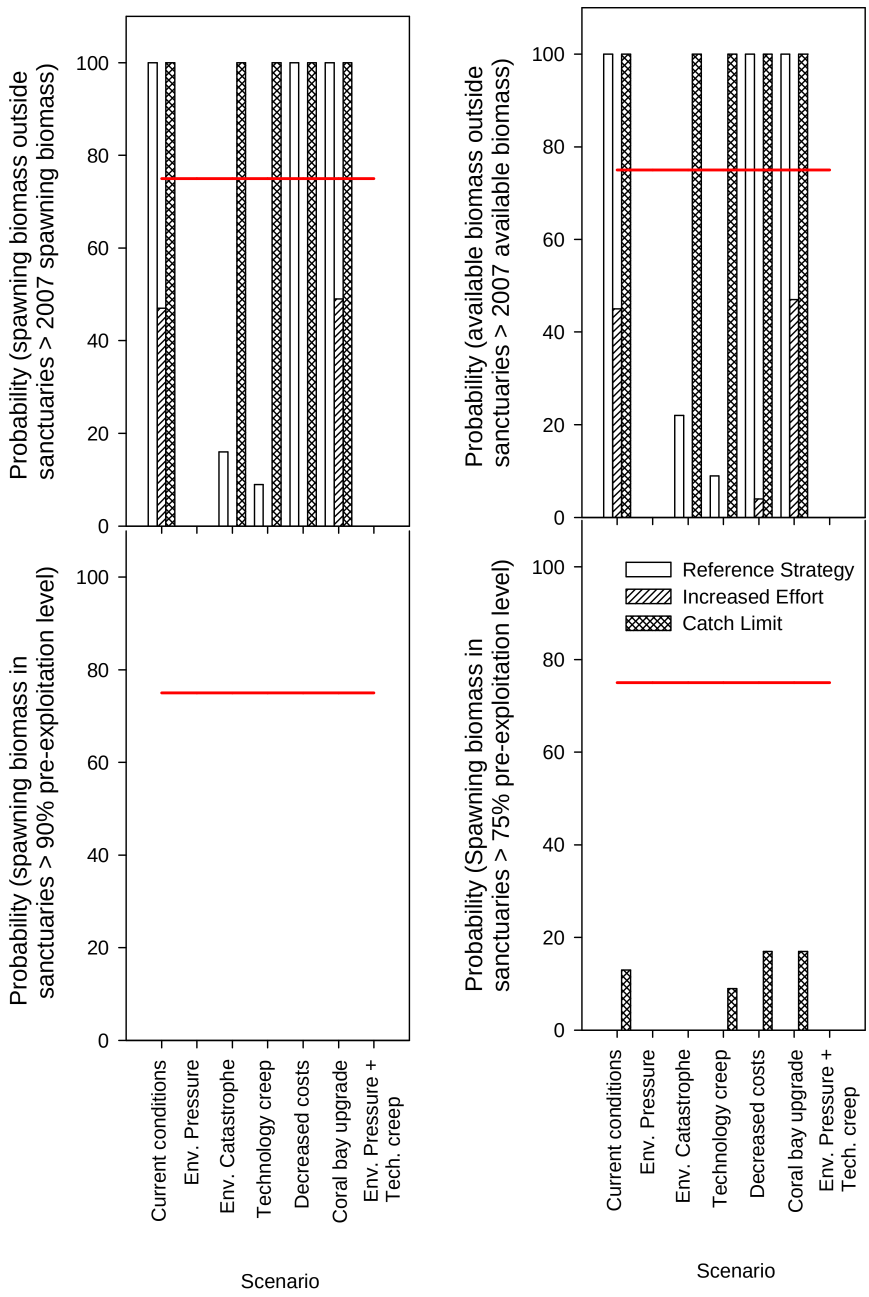


Figure 24 The probability that management strategies, the Reference Strategy, Increased Effort and Catch Limit are above the associated reference point (management objective indicated by the red line) under a range of scenarios for different performance indicators for spangled emperor (upper left: objective 6 spawning biomass outside sanctuaries, upper right: objective 5 available biomass outside sanctuaries, lower left: objective 1 spawning biomass in sanctuaries, lower right: objective 2 spawning biomass in sanctuaries).

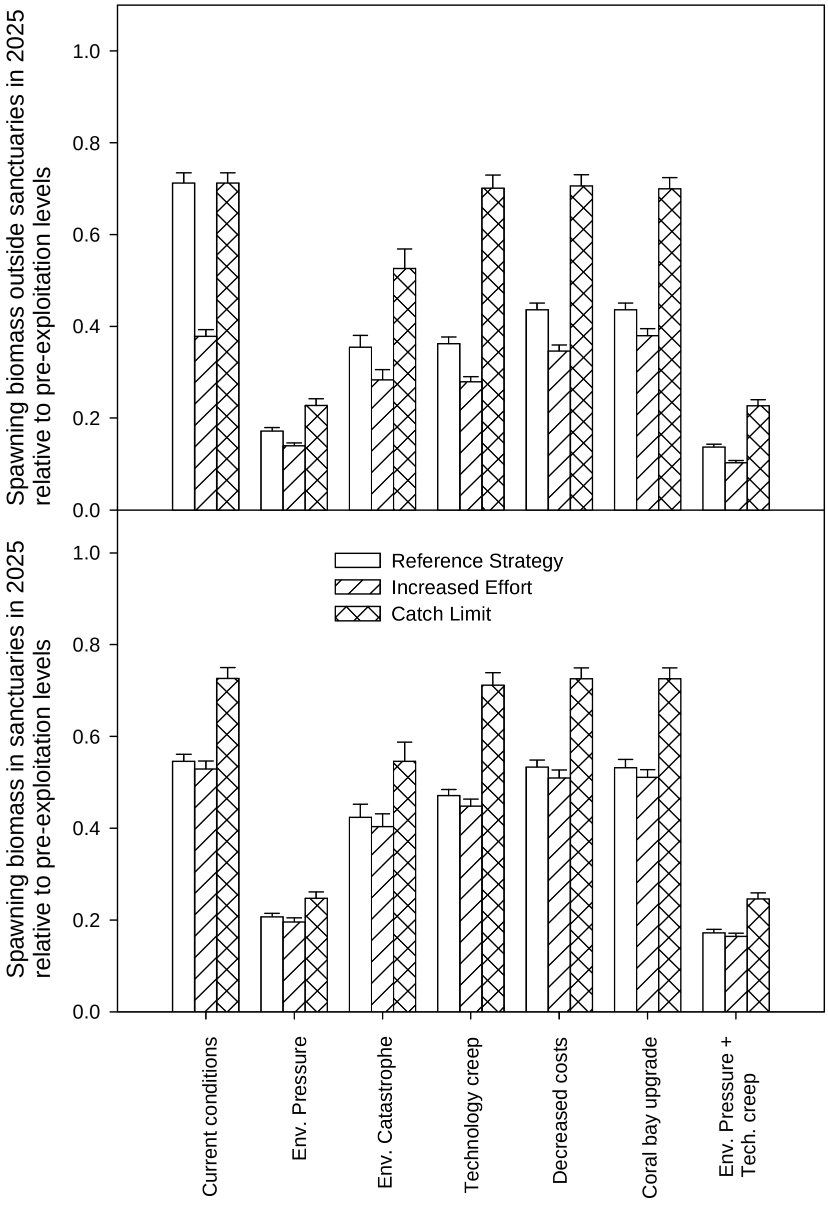


Figure 25 Average (± SE) spawning biomass relative to pre-exploitation of spangled emperor inside and outside the sanctuaries in 2025 for the Reference Strategy, Increased Effort and Catch Limit management strategies, under a range of scenarios.

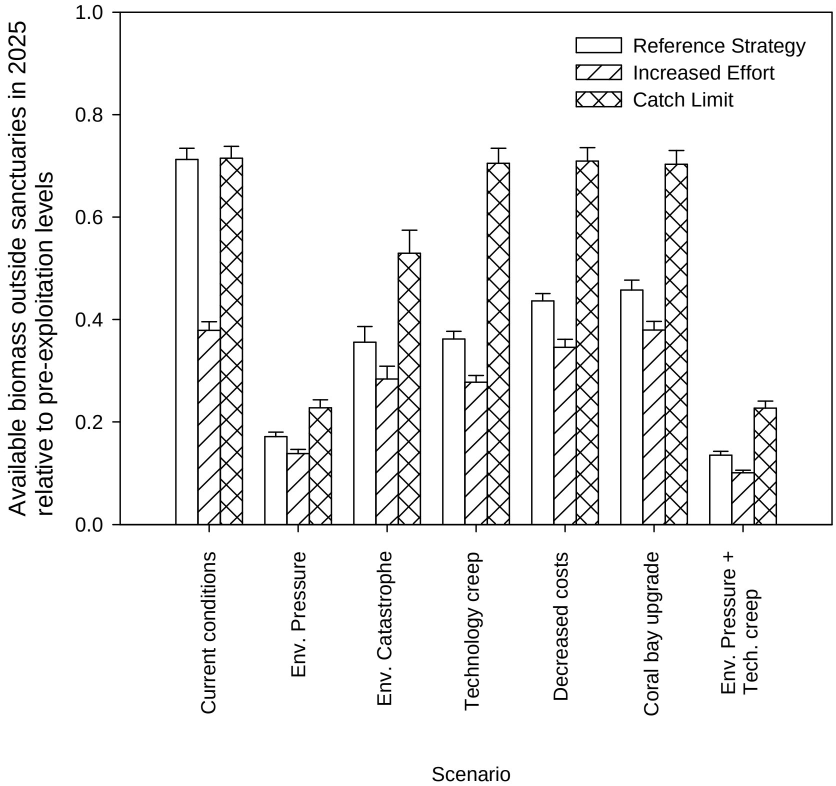


Figure 26 Average (± SE) available biomass relative to pre-exploitation of spangled emperor outside the sanctuaries in 2025 for the Reference Strategy, Increased Effort and Catch Limit management strategies, under a range of scenarios.

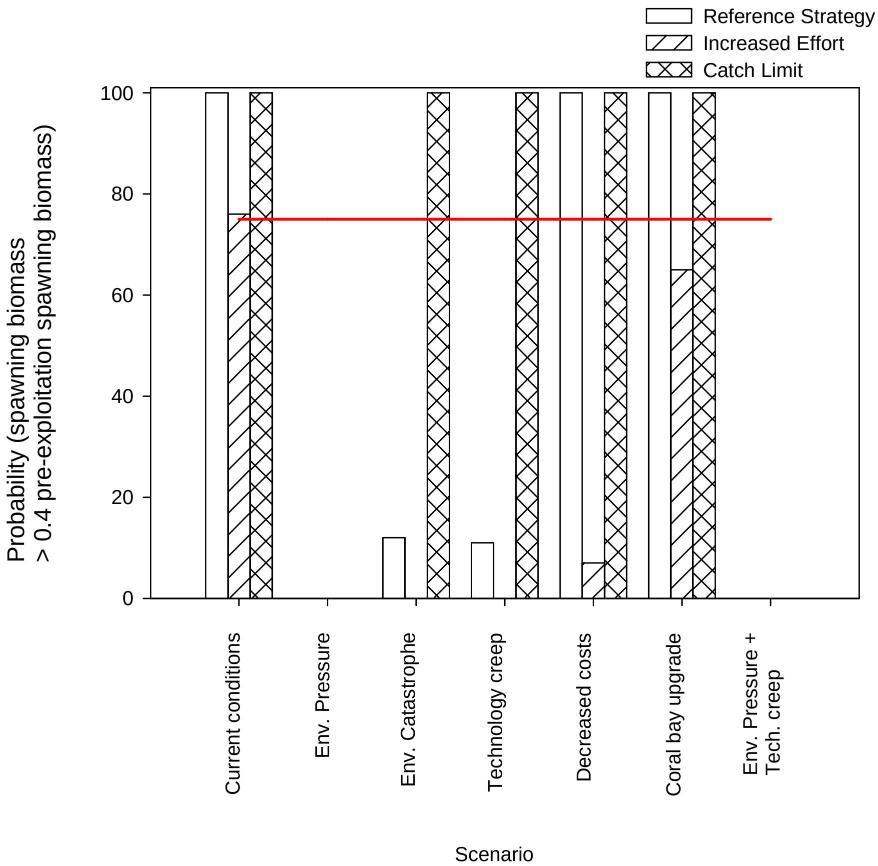


Figure 27 The probability that the Reference Strategy, Increased Effort and Catch Limit management strategies lead to spawning biomass of spangled emperor across all of Ningaloo Reef greater than 40% of pre-exploitation levels (objective 7), with management objective indicated by the red line, under a range of scenarios.

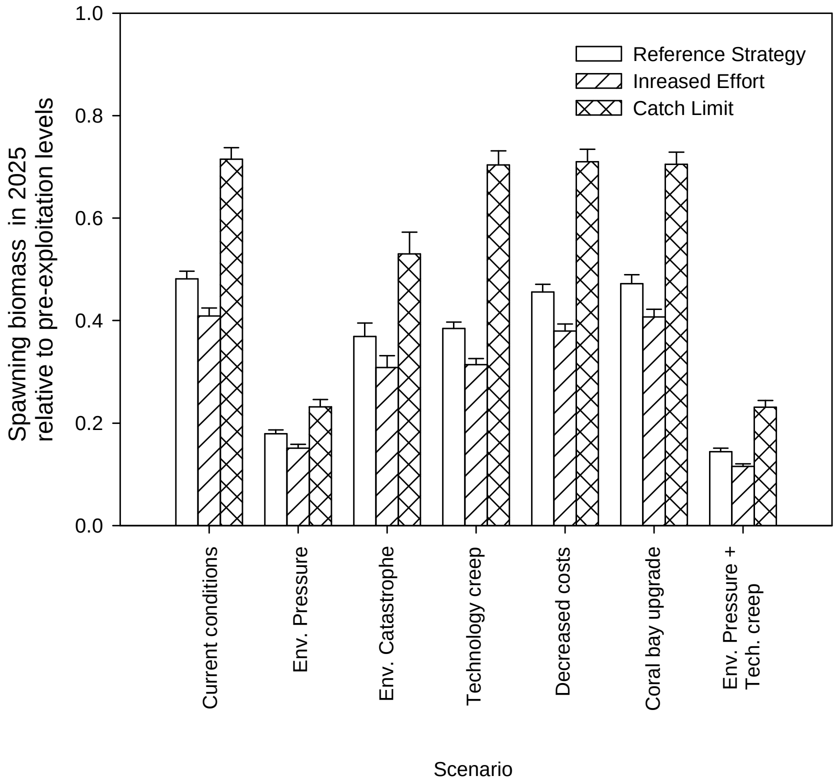


Figure 28 Simulated average (± SE) spawning biomass relative to pre-exploitation of spangled emperor across Ningaloo Reef in 2025 for the Reference Strategy, Increased Effort and Catch Limit management strategies, under a range of scenarios.

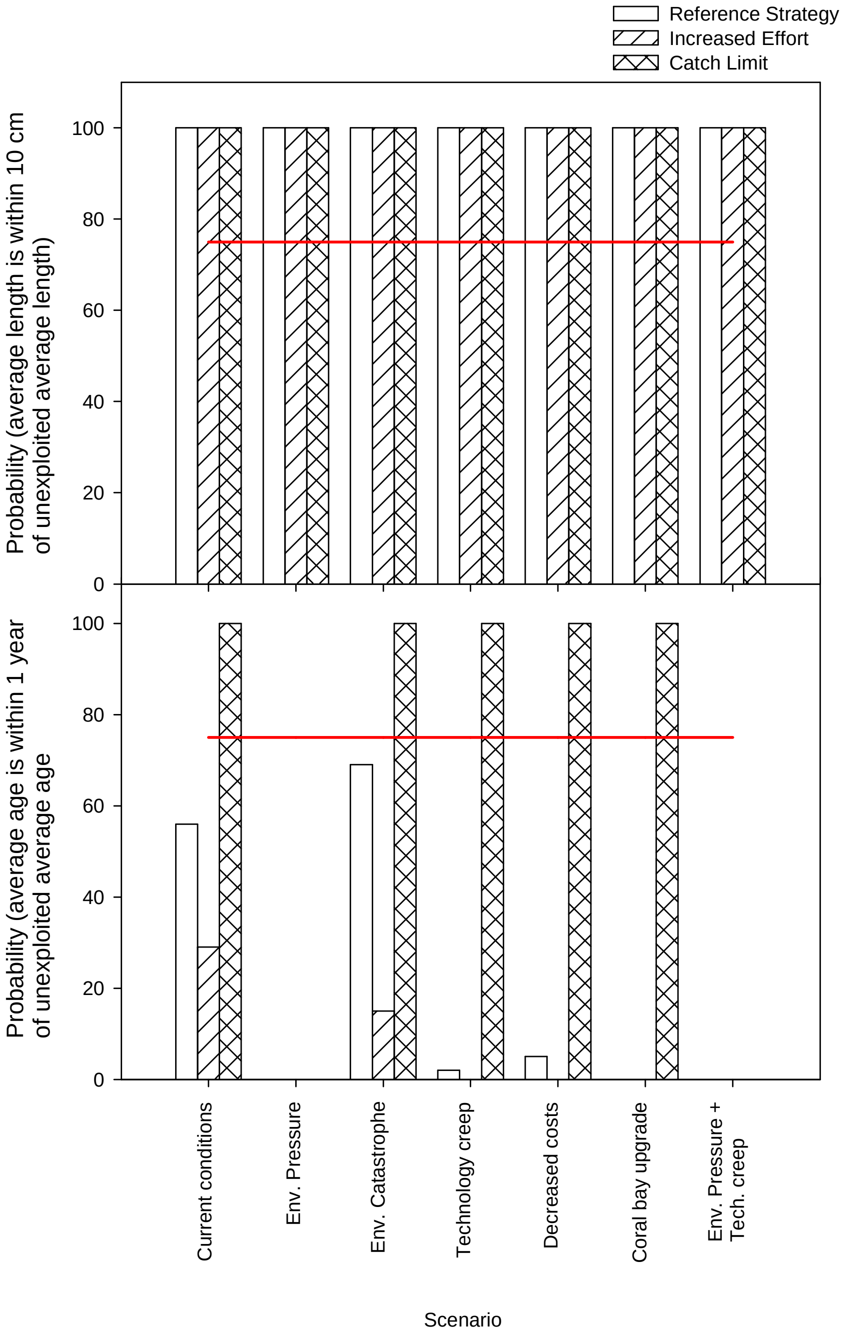


Figure 29 The probability that the Reference Strategy, Increased Effort and Catch Limit management strategies lead to average ages (objective 3) and lengths (objective 4) in the spangled emperor on Ningaloo Reef greater in relation to pre-exploitation levels, with management objective indicated by the red line, and under a range of scenarios.

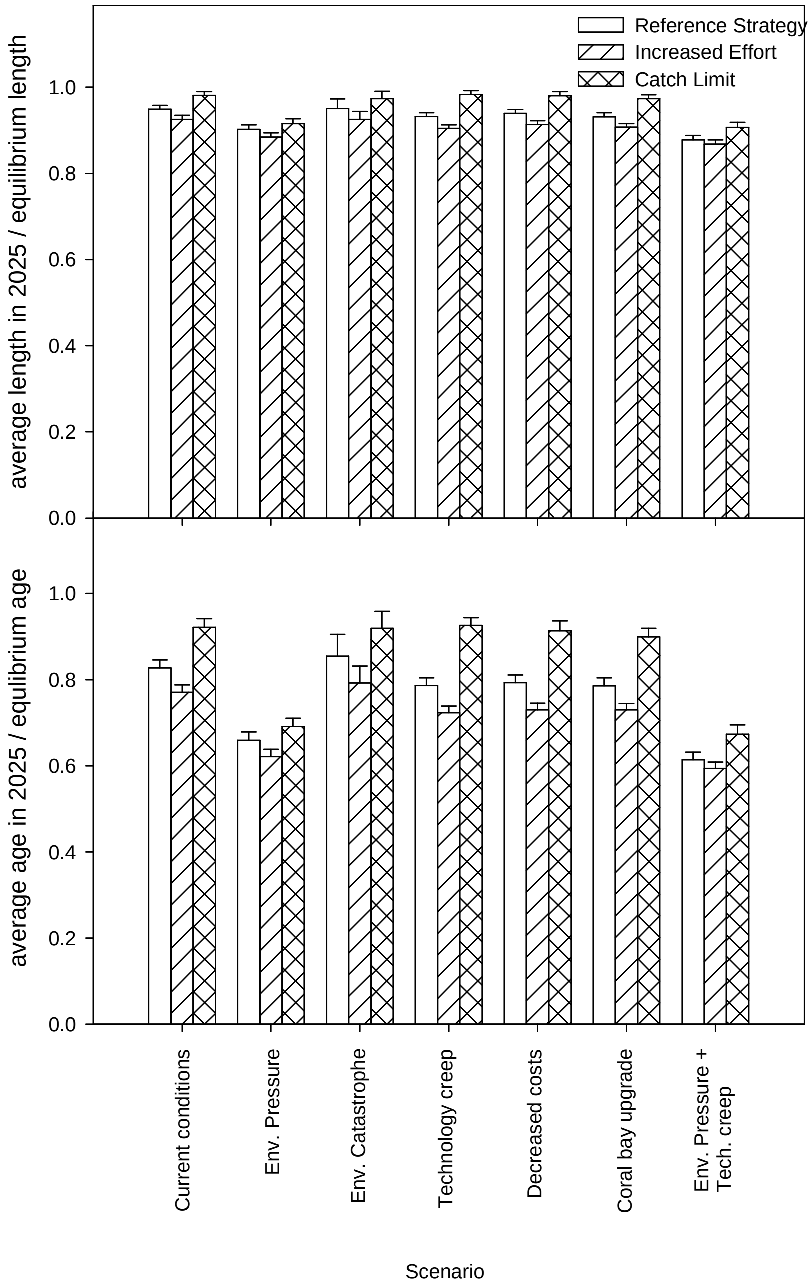


Figure 30 Average length and age of spangled emperor (± SE) relative to simulated pre-exploitation equilibrium levels in 2025 for the Reference Strategy, Increased Effort and Catch Limit management strategies, under a range of scenarios.

Achieving social objectives under alternative future scenarios

The evaluation of the proposed management strategies under future projected scenarios as they relate to the social objectives indicated that the objective of having more than 25% of the catch made of large (>50 cm) fish, at least 75% of the time, was always achieved in these simulations (Figure 31 upper panel). The second social objective, that catch rates should be above the simulated 2007 levels more than 75% of the time, was less often met (Figure 31 lower panel). Whereas this objective was not met under any scenario for the “Increased Effort” management strategy, the “Catch Limit” management strategy was able to achieve it under all scenarios except the “Env Pressure”. That is, the strategy was able to achieve the objective even under the “Env Pressure + Tech creep” scenario, mainly because the technological creep allowed catches, and thus catch rates, to be maintained at relatively high levels (and potentially increase) despite a declining population (e.g., Marriott et al. 2011). The sustainability of such a result beyond the time horizon adopted in this analysis would of course be questionable.

The simulated average 2025 CPUE relative to 2007, in Figure 32, shows that “Technology creep” tended to lead to higher catch rates. The other scenarios of “Decreased costs” and “Coral Bay upgrade” also led to high CPUE because these scenarios allowed increased fishing in areas that were not traditionally fished.

The proportion of catch greater than 50cm was greater than 25% in 2025 for all management strategies (Figure 33). The lowest proportion occurred under the “Catch Limit” management strategy and “Technology creep” scenario. In general the management strategies that permitted higher levels of fishing and catches than the “Catch Limit” strategy resulted in more large fish in the catch, although they also resulted in much less population biomass (Figure 28). Overall, the conclusion that can be derived from these results is that management strategies that keep effort under control, in the face of specific changes in the fishery (e.g. “Coral Bay upgrade”), could achieve the social objectives. However, when broader environmental changes occurred (e.g. “Env. Pressure”), the social objectives were less likely to be met, except where management was explicitly targeted at restricting fishing mortality. In the case studied in this section, this involved setting a “Catch Limit”, which proved an effective strategy from a social perspective (as defined here) except in the face of extreme environmental change, but is no simple task to implement in a recreational fishery. So although the simulations pick this management strategy as an effective strategy, in practice a combination of strategies limiting effort, or something else quite novel and resource intensive (like pink snapper tags in Freycinet Estuary in Shark Bay, WA for implementing a recreational Catch Limit), may need to be used for indirectly limiting the overall level of catch of spangled emperor from this sector. Of course such a strategy is also species specific and does not limit potential sustainability risks for other species, despite the use of spangled emperor as an indicator species for the suite of demersal scalefish species in the Gascoyne Bioregion.

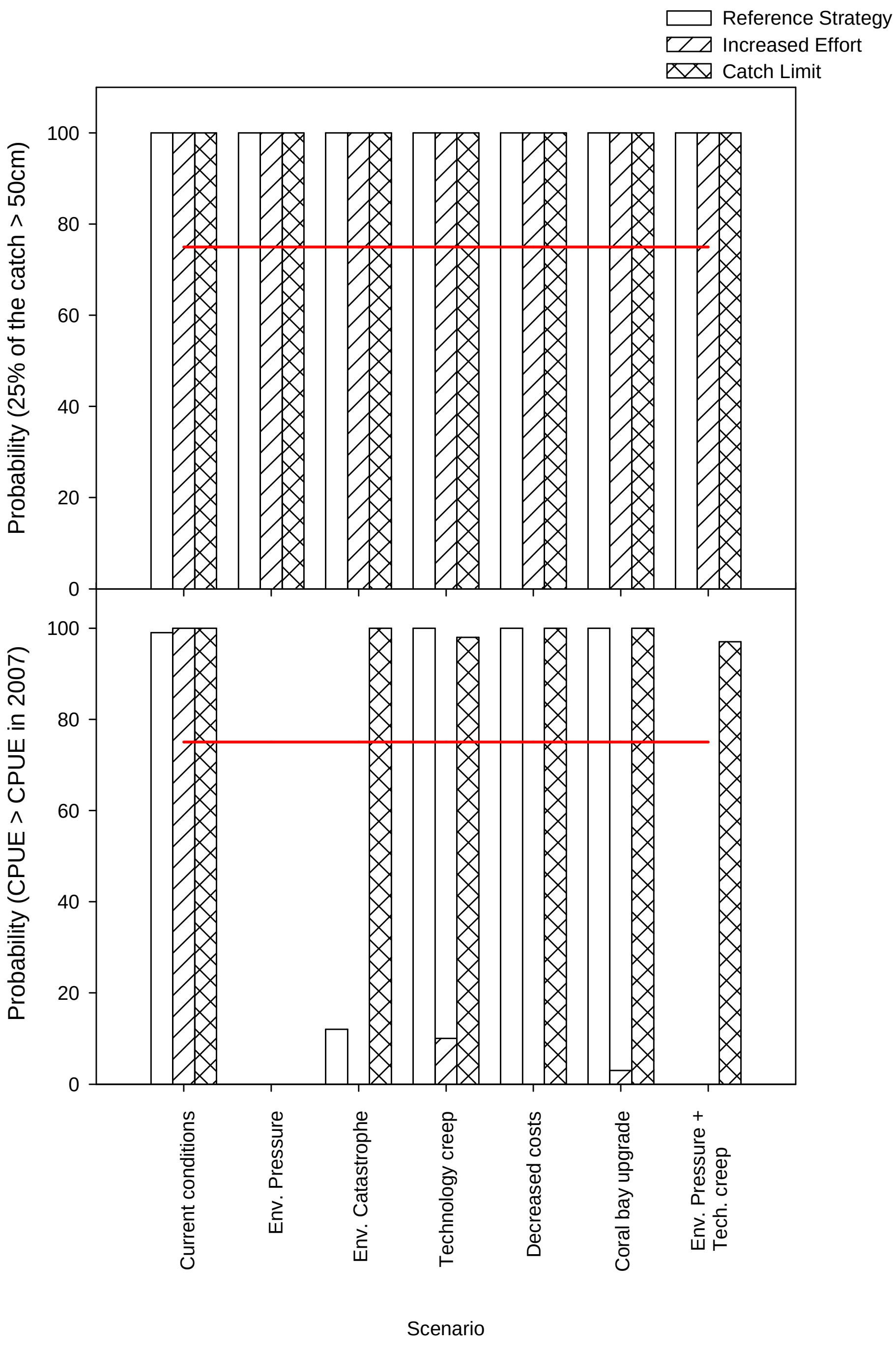


Figure 31 The probability that the Reference Strategy, Increased Effort and Catch Limit management strategies lead to greater CPUE (objective 8) and lengths (objective 9) of spangled emperor in relation to reference levels on Ningaloo Reef, with management objective indicated by the red line, and under a range of future projection scenarios.

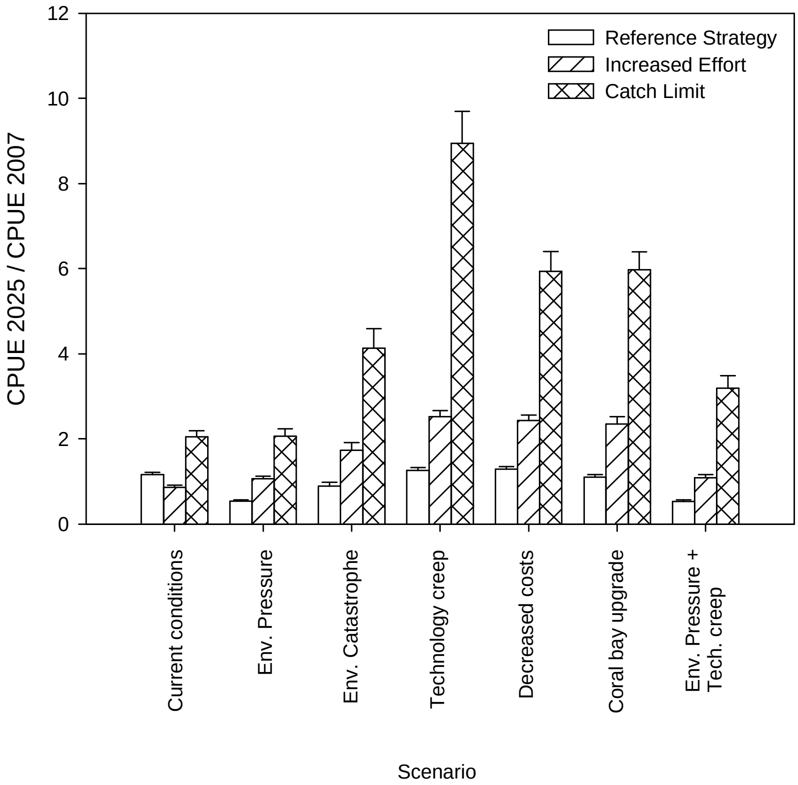


Figure 32 Simulated average CPUE of spangled emperor (± SE) relative in 2025 relative to CPUE in 2007 for the Reference Strategy, Increased Effort and Catch Limit management strategies, under a range of future projection scenarios.

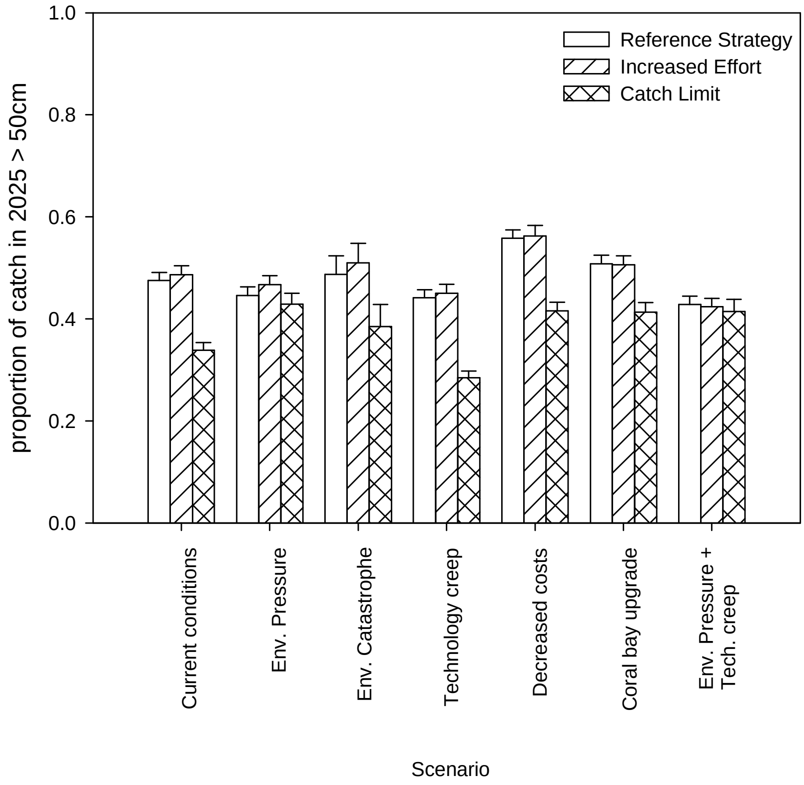


Figure 33 Simulated average proportion of spangled emperor caught in 2025 (± SE) that were > 50cm for the Reference Strategy, Increased Effort and Catch Limit management strategies, under a range of future projection scenarios.

Measuring other indicators under alternative future scenarios

The other indicators of interest suggested by the stakeholders (3.7 Appendix), but without explicit targets or threshold values, included: the total recreational catch taken, the discards of undersized fish, and indicators of the catch variability, including the chances of not catching a fish at all during a fishing trip. The simulation results obtained for these indicators in 2025, for the three management strategies ("Reference Strategy", "Increased Effort", "Catch Limit") under the range of projected scenarios are shown in Figure 34 through to Figure 37.

Catches were lowest under the "Catch Limit" management strategy (Figure 34), at relatively constant level across different future projection scenarios, because the upper limit of total catch was fixed. The "Increased effort" management strategy tended to have the highest catches. However, these were based on relatively large effort increases, and also led to reduced catch rates due to reduced fish availability. However, while effort by 2025 was double that of the "Reference Strategy" under the "Increased effort" strategy, the increase in catch by 2025 was less than doubled. The scenarios with "Environmental pressure" led to the lowest catches across all management strategies, while those scenarios that resulted in increasing the fishing power of the fleet, either through technological means ("Tech. creep"), or reduced costs ("Decreased costs") or increased accessibility ("Coral Bay upgrade"), resulted in relatively higher catches.

The discard results were similar to the landed catches (Figure 35). As previously noticed, the management strategy that had the highest catch variation (average deviation in catch from vessel trip to trip) was the "Catch Limit" (Figure 36) because in the model vessels may fish in one trip, but then be prevented from fishing in the next because the Catch Limit had been reached. Thus the variation for discards was also high for this simulated management strategy. The indicator describing poor fishing trips (Figure 37) tended to be lowest for the "Catch Limit" management strategy, and highest under the "Increased effort" management strategy. Further, the highest probability for a poor fishing trip (as defined) experienced was found for "Environmental Pressure + Tech Creep" and "Technology Creep" scenarios.

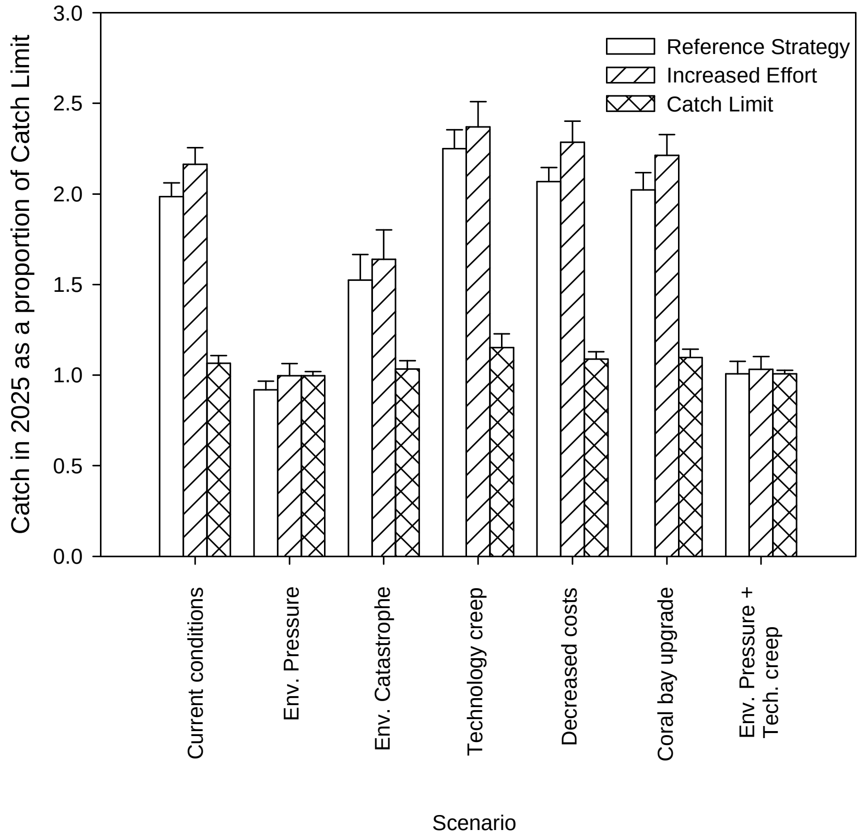


Figure 34 Average catch (kg) of spangled emperor in 2025 (± SE) as a proportion of the catch limit for the Reference Strategy, Increased Effort and Catch Limit management strategies, under a range of scenarios.

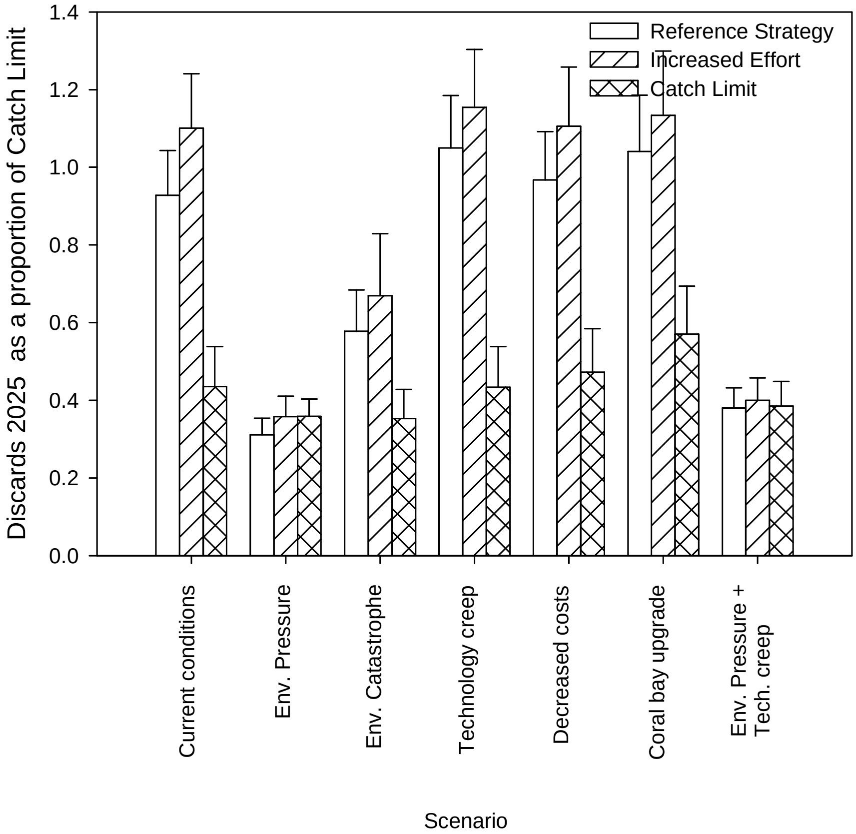


Figure 35 Simulated average discarded catch (kg) of spangled emperor in 2025 (± SE) for the Reference Strategy, Increased Effort and Catch Limit management strategies, under a range of future projection scenarios.

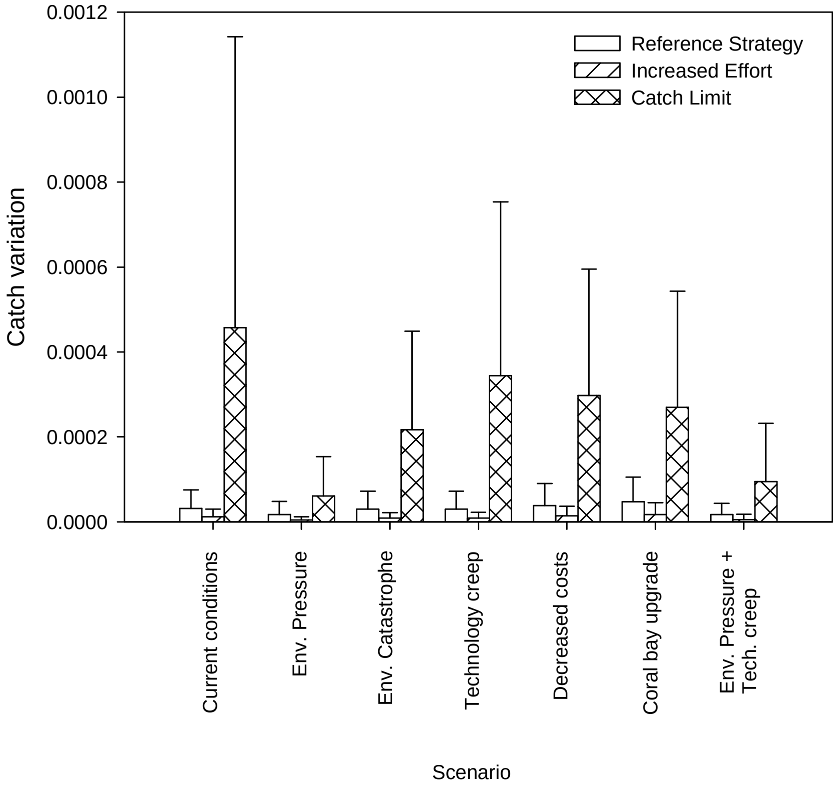


Figure 36 Average simulated catch variation of spangled emperor in 2025 (± SE) for the Reference Strategy, Increased Effort and Catch Limit management strategies, under a range of future projection scenarios.

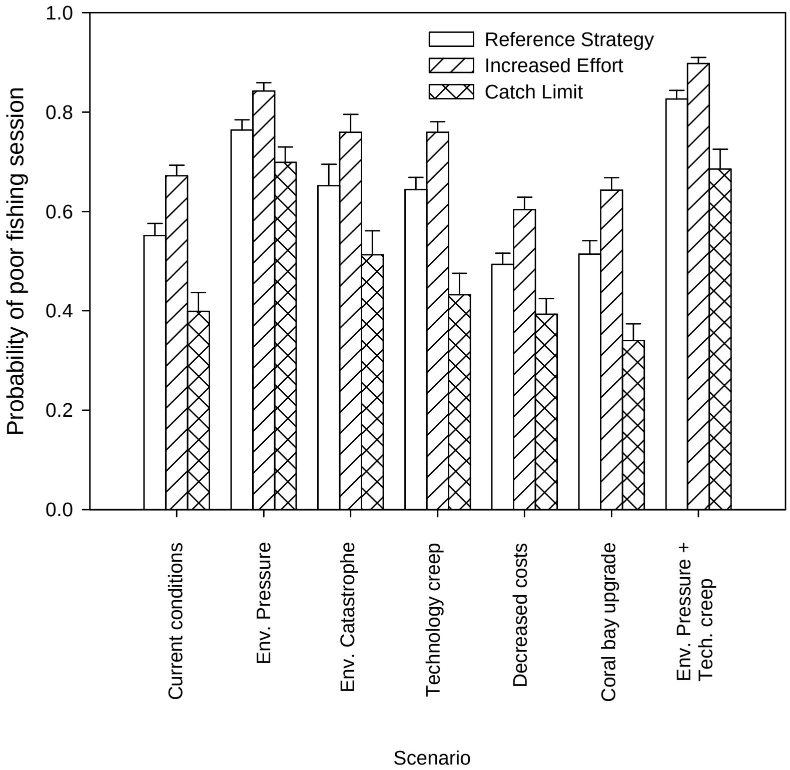


Figure 37 Average probability (± SE) that a fishing session in 2025 will not catch any spangled emperor for the Reference Strategy, Increased Effort and Catch Limit management strategies, under a range of scenarios.

Management performance summary

The performance summary under the future projections (Table 9, Figure 38) tended to indicate that the reduced catches resulting from the "Catch Limit" management strategy did significantly better for the ecological objectives, including reduced discards, under the "Current conditions" and across all the fishery related scenarios, as well as in the "Environmental catastrophe" scenario. It also did well with respect to reducing the probability of not catching any fish on a fishing trip. However it performed systematically less well with respect to the Big Fish catch objective and total catch indicator for meeting social objectives. The results thus illustrate the existence of a trade-off between the different objectives that are being pursued in managing the recreational line fishery on Ningaloo reef, between catch levels and catches of larger fish, and the other objectives that have been stated as important to consider in regulating the activity (i.e., the Ecological objectives listed in Table 5). In the simulation runs that were carried out, the "Catch Limit" strategy clearly out-performs the other two strategies (i.e., "Reference Level", "Increased Effort"). However, it is also clearly out-performed by the "Reference Strategy" and "Increased effort" strategy with respect to the former two objectives. This trade-off is not apparent, however, under the "Environmental pressure" scenario. In this case, all three strategies achieved comparable levels of performance across all objectives.

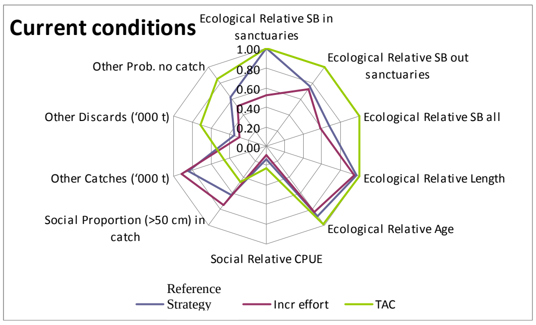
Table 9 Summary of performance indicators from the last year of projection, 2025, under different management strategies and future projection scenarios. Colours: **blue** the best result for a column (indicator) and scenario, **red** poorest result.

	Objective:	Ecological					Social		Other		
Scenario	Strategy	**Relative SB in sanctuaries**	**Relative SB out sanctuaries**	**Relative SB all**	**Relative Length**	**Relative Age**	**Relative CPUE**	**Proportion catch (>50 cm)**	**Catches (Catch Limit%)**	**Discards (Catch Limit%)**	**Prob. no catch**
Current conditions	Reference Strategy	**0.71**	0.55	0.48	0.95	0.83	1.16	0.55	197%	92%	0.55
	Incr effort	**0.37**	**0.53**	**0.41**	**0.93**	**0.77**	**0.86**	**0.67**	**215%**	**110%**	**0.67**
	Catch Limit	**0.71**	**0.73**	**0.71**	**0.98**	**0.92**	**2.04**	**0.40**	**105%**	**44%**	**0.40**
Env. Pressure	Reference Strategy	0.17	0.21	0.18	0.90	0.66	**0.54**	0.76	**92%**	**31%**	0.76
	Incr effort	**0.14**	**0.20**	**0.15**	**0.88**	**0.62**	1.06	**0.84**	**100%**	**36%**	**0.84**
	Catch Limit	**0.23**	**0.25**	**0.23**	**0.92**	**0.69**	**2.07**	**0.70**	**100%**	**36%**	**0.70**
Env. Catastrophe	Reference Strategy	0.35	0.42	0.37	0.95	0.85	0.89	0.65	152%	57%	0.65
	Incr effort	**0.28**	**0.40**	**0.31**	**0.93**	**0.79**	**1.73**	**0.76**	**163%**	**65%**	**0.76**
	Catch Limit	**0.53**	**0.55**	**0.53**	**0.97**	**0.92**	**0.46**	**0.51**	**102%**	**34%**	**0.51**
Tech. creep	Reference Strategy	0.36	0.47	0.38	0.93	0.79	**1.26**	0.64	226%	105%	0.64
	Incr effort	**0.28**	**0.45**	**0.31**	**0.90**	**0.72**	2.52	**0.76**	**236%**	**115%**	**0.76**
	Catch Limit	**0.70**	**0.71**	**0.70**	**0.98**	**0.93**	**8.94**	**0.43**	**115%**	**42%**	**0.43**

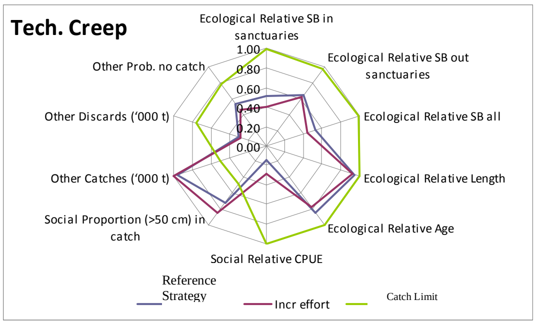
	Objective:	Ecological					Social		Other		
Scenario	Strategy	**Relative SB in sanctuaries**	**Relative SB out sanctuaries**	**Relative SB all**	**Relative Length**	**Relative Age**	**Relative CPUE**	**Proportion catch (>50 cm)**	**Catches (Catch Limit%)**	**Discards (Catch Limit%)**	**Prob. no catch**
Decreased costs	Reference Strategy	0.44	0.53	0.46	0.94	0.79	**1.28**	0.49	207%	97%	0.49
	Incr effort	**0.35**	**0.51**	**0.38**	**0.91**	**0.73**	2.43	**0.60**	**228%**	**110%**	**0.60**
	Catch Limit	**0.71**	**0.73**	**0.71**	**0.98**	**0.91**	**5.93**	**0.39**	**107%**	**47%**	**0.39**
Coral bay upgrade	Reference Strategy	0.44	0.53	0.47	0.93	0.79	**1.10**	0.51	202%	105%	0.51
	Incr effort	**0.38**	**0.51**	**0.41**	**0.91**	**0.73**	2.34	**0.64**	**221%**	**113%**	**0.64**
	Catch Limit	**0.70**	**0.73**	**0.70**	**0.97**	**0.90**	**5.67**	**0.34**	**110%**	**57%**	**0.34**
Env pressure+	Reference Strategy	0.14	0.17	0.14	0.88	0.61	**0.53**	0.83	**100%**	**36%**	0.83
	Incr effort	**0.10**	**0.16**	**0.11**	**0.87**	**0.59**	1.08	**0.90**	**102%**	**39%**	**0.90**
	Catch Limit	**0.23**	**0.24**	**0.23**	**0.91**	**0.67**	**3.19**	**0.69**	**100%**	**39%**	**0.69**

Figure 38 Performance summary showing radar plots of how different management strategies (coloured lines) achieve the objectives under different future scenarios. Objectives are on the axes, management strategies are coloured lines

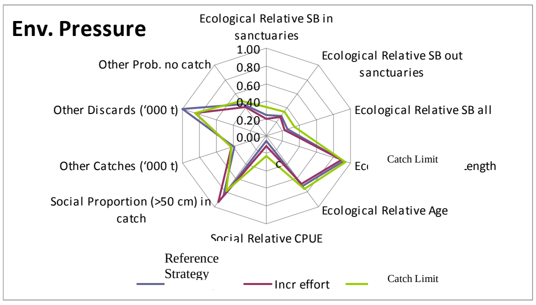
a. Current conditions



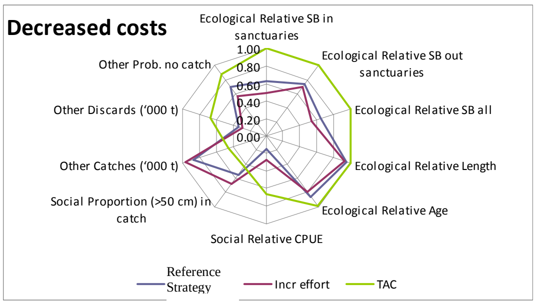
b. Tech. Creep



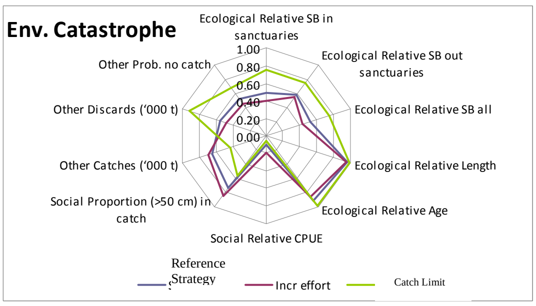
c. Env. Pressure



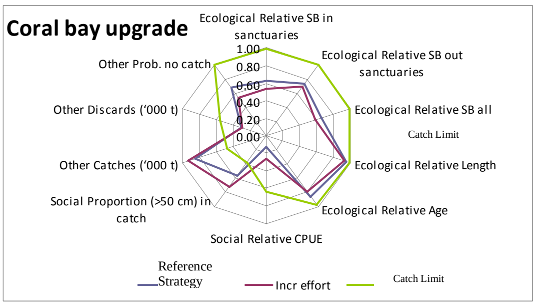
d. Decreased costs.



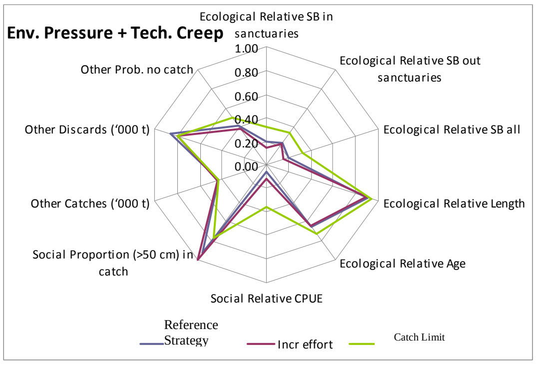
e. Env. catastrophe



f. Coral Bay upgrade



g. Env. Pressure and Tech creep



3.4 Discussion

This research has concentrated on the use of the ELFSim modelling platform for the evaluation of alternative approaches to the management of recreational fisheries in the Ningaloo Marine Park. Although the original objectives of the NRP were much broader than this, the analysis presented in this report illustrates the way in which simulation modelling tools can be used for Management Strategy Evaluation (MSE). Other NRP results will provide a more encompassing broad MSE framework for integrated management of the Ningaloo Marine Park.

The results reported above demonstrate both the variability and trends in a range of potential candidate indicators for the Ningaloo recreational fishery that targets spangled emperor, which is an indicator species that is monitored by the DoFWA to represent all demersal scalefish species occurring in waters up to 250m deep in the Gascoyne Coast Bioregion (which includes Ningaloo Marine Park) and is thought to be a critical component of the Ningaloo marine ecosystem. We calibrated a model which fully accounts for the spatial and temporal evolution of both biomass of the species and of fishing effort distribution, and used this model to explore different management strategies aimed at regulating fishing of this species, under a range of bio-physical and human-usage scenarios. The results were examined in terms of the capacity for alternative management strategies to achieve target values for a range of indicators, with a given probability. The indicators and target values were selected in consultation with management bodies and stakeholder representatives (Appendix), to reflect the key objectives that are being pursued in regulating fishing activities within the boundaries of the marine park. These model-based results can help to pinpoint the most important features of the biological and human components of the simulation model, in terms of the management strategy evaluations, and how management agencies might best set their strategies in order to achieve their stated objectives.

Whether the objectives were achieved for the sanctuaries depended on how the sanctuaries were defined. Under current conditions, controlling shore fishing into the sanctuary zones would seem to be the strategy that best achieved the ecological objectives, in particular Ecological objectives 1 and 2. However, there is a great deal of uncertainty with this result because there are very few reliable estimates of how many fish are being removed by this category of fishing. We assumed that the shore-based effort was equal to the most recent boat-based off-shore effort of 12 000 boat days (Figure 2). The accuracy of this assumption may become clearer as other work in the marine park emerges. Although we identified that unregulated shore fishing might prevent the achievement of these management objectives, discussions during the workshops with stakeholders also showed that there would be great difficulty in determining methods of controlling shore fishing into the sanctuary zones, to achieve effective compliance levels.

The results also showed that sanctuary zones can be useful in controlling a possible increase in fishing pressure on those sub-populations of spangled emperor that reside within them but that they are not particularly effective in dealing with potentially impending environmental change. Only control of catch, or effort was capable of doing this. Indeed under the “Env Press” and the composite scenario “Env Pressure + Tech creep”, the model equilibrium conditions actually change because the natural mortality changes, and so even in the absence of fishing it is likely that the simulated population would not return to the initial equilibrium conditions.

The results illustrated the existence of a trade-off between catch levels and catches of larger fish, and the other ecological objectives. In the simulation runs that were carried out, the “Catch Limit” strategy clearly out-performed the “Reference Strategy” and the “Increased Effort” strategy with respect to the ecological objectives. However, the “Catch Limit” strategy was also clearly out-performed by the “Reference Strategy” and “Increased effort” strategy with respect to the social objectives. The effectiveness of the “Catch Limit” strategy depended mainly on the catch limit level used in the model. Since the actual status of the stock biomass is not known, the effect of a catch limit as simulated can not be reported with confidence without knowing how this catch limit relates to stock biomass in relative terms. It is important to note that setting a catch limit, as simulated, would likely not be a simple task for a recreational fishery. So although the simulations pick this management strategy as an effective strategy, in practice a combination of strategies limiting effort, or something else quite novel and resource intensive (like pink snapper tags in Freycinet Estuary in Shark Bay, WA for implementing a recreational Catch Limit), may need to be used for indirectly limiting the overall level of catch of spangled emperor from this sector. Of course such a strategy is also species specific and does not limit potential sustainability risks for other species, despite the use of spangled emperor as an indicator species for the suite of demersal scalefish species in the Gascoyne Bioregion.

We did not examine the possibilities of maintaining a constant level of fishing (effort) and/or having a catch-and-release only fishery. Such a fishery could prevent compounded pressure on the stock from fishing and environmental changes. It would however require a high amount of compliance from the community.

One development that was not included in this report but has helped with the development of management strategies with stakeholders is the cross-project exploratory tool ScenarioLab (Boschetti et al. 2010). This tool was used to provide rapid assessment of alternative management strategies under a range of bio-physical and social scenarios appropriate to the Ningaloo Marine Park stakeholders.

The power of management strategy evaluation is that it can capture and simulate the full actions of the management cycle (Smith et al. 1999) including monitoring and measurement through to assessment and the ultimate decisions that are made by management. Monitoring and assessment methods are becoming increasingly important in this fishery (Wise et al. 2007, Marriott et al. 2010a), and a next step could be to simulate monitoring strategies in order to determine their effectiveness at detecting important changes in the ecosystem and associated fishing activities. Another potential development would be to implement a realistic decision rule and harvest strategy that can be applied to a recreational fishery. This offers management a powerful tool to be able to test their management practice(s) in the simulation setting before they implement them in reality.

3.5 Acknowledgements

We would like to thank Beth Fulton and Miriana Sporcic of CSIRO for collaborative efforts. Dan Gaughan (DoFWA) for his input at the start of the project, and all of the stakeholders including Kelly Waples and Chris Simpson, who attended our workshops. Russ Babcock and Bill de la Mare (CSIRO) provide much needed advice throughout the project. We also thank Norm Hall, Lyndsay Joll and Brett Molony for their helpful comments on earlier drafts. Wendy Steele (CSIRO) is thanked for her efficient project management.

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3.7 Appendix

Through a consultative process in a workshop in March 2010 with stakeholders in the management the recreational fishery, a range of management objectives were identified in a quantifiable form. We also identified a range of potential management strategies with which to assess their performance against the objectives. The participants in this workshop were:

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	Dan Gaughan	Dan.Gaughan@fish.wa.gov.au

4. COMMUNICATION AND OUTPUTS

4.1 Communication Achievements

4.1.1 Publications

Boschetti, F., de la Tour, A., Fulton, E.A., and Little L.R. 2010. Interactive modelling for natural resource management. Environmental Modelling & Software 25, 1075-1085.

Little, R., Thebaud, O., Fulton, B. 2010. Evaluation of management strategies in Ningaloo Marine Park, Western Australia. IIFET 2010 Proceedings, Montpellier, France. 13-16 July 2010.

4.1.2 Planned Publications

Little, R., Thebaud, O., Fulton, B. 2010. Evaluation of management strategies in Ningaloo Marine Park, Western Australia. Submitted to: International Journal of Sustainable Society..

4.1.3 Presentations

Little, R., Thebaud, O., and Fulton B. 2010. Evalaution of management strategies in Ningaloo Marine Park, Western Australia. 2010 IIFET Proceedings. 13-16 July 2010, Montpellier France.

R. Little. Evaluating Management Strategies for Line fishing in the Ningaloo Marine Park. 3rd Annual Research Symposium. 26-27 May 2009, Exmouth, WA.

4.2 Project outputs

Little, L.R., A. David McDonald, Fabio Boschetti, Ross Marriott, Brent Wise, Rod Lenanton 2009. An Evaluation of Management Strategies for Line Fishing in the Ningaloo Marine Park, Mid-term Report for WAMSI Ningaloo Reef Project 3.2.3 Biodiversity Assessment, Ecosystem Impacts of Human Usage and Management Strategy Evaluation, March 2009.

Little, L.R., McDonald, A.D., and Boschetti, F. 2008. A calibrated model for Evaluation of Line Fishing Management Strategies on the Ningaloo Reef. Report for WAMSI Ningaloo Reef Project 3.2.3 Biodiversity Assessment, Ecosystem Impacts of Human Usage and Management Strategy Evaluation, June 2008.

4.3 Data management

Please answer the following questions about your WAMSI research datasets. If you have other documentation that describes the data you collected please also attach with this spreadsheet or just attach that if it answers all these questions.	Project
What	
What is the title of the study? (e.g. what would like to be the title of the metadata record)	Ningaloo Reef Project 3.2.3 Biodiversity Assessment, Ecosystem Impacts of Human Usage and Management Strategy Evaluation
What would be some key words for searching for this data?	Management Strategy Evaluation, MSE, simulation, fisheries, spangled emperor
What constraints would you place on the data (e.g. legal, usage - purposes that shouldn't use the data)	Subject to Deed of Confidentiality and Non-Disclosure signed by CSIRO for DoFWA's data, which stipulates that written approval is required before DoFWA's data [data and data derived from the data collected by DoFWA] is published. Geodatabase technology will be used to satisfy WAMSI's cross-nodal information management requirements by ensuring compatibility with government agencies and other research providers.
what kind of data will/has been collected (e.g. sp richness, inventory, abundance, density etc)	No data have been collected from this study. Simulation data have been generated by it.
Who	
Who did the research? Please list names and the contact details.	Rich Little (Rich.LittleAcsiro.au) Olivier Thébaud (Olivier.Thebaud@csiro.au) Fabio Boschetti (Fabio.Boschetti@csiro.au) A. David McDonald (David.McDondald@csiro.au) Ross Marriott (Ross.Marriott@fish.wa.gov.au) Brent Wise (Brent.Wise@fish.wa.gov.au) Rod Lenanton (Rod.Lenanton@fish.wa.gov.au)
Who is point of contact in case of questions? Please list their contact details - is there a generic contact that could be used to ensure longivity?	Rich Little CSIRO Marine and Atmospheric Research GPO Box 1538 Hobart, 7001
Who else should be acknowledged? Any links to journal articles?	

Why	
Why was the research done? This is the abstract - a brief summary of the content of the research is required including the research intentions include summary of aims and objectives and use	This project was developed for the Ningaloo Research Program (NRP) to explore the effects of managing recreational fishing, which is perhaps the most important extractive activities in the Ningaloo Marine Park. The project used simulation techniques known as Management Strategy Evaluation (MSE) to explore the consequences of a range of management actions, under a series of alternative future scenarios on the management of a major target species on Ningaloo Reef, spangled emperor (Lethrinus nebulosus). The results of the scenarios are examined against the objectives set out by management and other stakeholders in the park. A simulation model, known as ELFSim, was used. ELFSim is a decision support software system designed to evaluate options for conservation and harvest management, and includes a number of key components: a population dynamics model of target species that captures the full life history (including larval dispersal, reproduction, development, and habits) of the target species, a model of fishing dynamics that captures the exploitation pattern due to fishing behaviour, a management model that simulates the implementation of management actions. ELFSim was developed for other coral reef fisheries where commercial fishing was the primary fishing activity, and in this sought to develop a simulation model of recreational fishing dynamics. This model was agent-based, meaning that individual recreational fishing boats were represented in the model, and a range of management measures were tested on the ability to manage these virtual recreational fishers. These management measures, derived from stakeholder workshops include the effect of increasing the no-take sanctuary zones, and restricting the fishing in sanctuary zones that occurs from shore. The effectiveness of these management actions in the simulation model was measured against the management objectives of the stakeholders. Management objectives were classified according to ecological (conservation) objectives, or social and economic objectives. The results showed that the current management arrangement perform adequately against the range of ecological and social objectives. However, for other management actions, the results showed the inherent trade-off that exists between the ecological objective and the social objectives. For

	example, restricting fishing in sanctuaries from shore did well to achieve the conservation objectives, but did not achieve the social objectives as well as other management strategies. Imposing catch restrictions, increasing compliance monitoring and implementing an education program to reduce infringement also performed well against both social and ecological objectives, but consideration of effectiveness, and cost are uncertainties that our analysis did not consider. Such factors are likely to be extremely important and weighed in any realistic implementation of these management actions. Under the alternative scenarios the management strategy that was most likely to achieve the objectives was the hypothetical "Catch Limit". The management strategy that allowed effort to increase was best at achieving the social objective of maximizing catches, including the catch of large fish. Although the simulations indicated that the "Catch Limit" strategy as an effective strategy for future alternative scenarios, in practice a combination of strategies limiting effort, or something else quite novel and resource intensive (like pink snapper tags in Freycinet Estuary in Shark Bay, WA for implementing a recreational Catch Limit), may need to be used for indirectly limiting the overall level of catch of spangled emperor from this sector. Of course such a strategy is also species specific and does not limit potential sustainability risks for other species. It is for this reason that DoFWA uses spangled emperor as an indicator species for the suite of demersal scalefish species in the Gascoyne Bioregion. The power of management strategy evaluation is that it can capture and simulate the full actions that are made by management. This offers management a powerful tool to be able to test their management practice(s) in the simulation setting before they implement them in reality.
How	
How was the research done? (e.g. instrumentation, brief description of procedure)?	Desktop, e-research project.
How often were measurements taken? Were they aggregated into a specific unit of time (e.g. day, multi-day, week, month, multi-month, year, multi-year)? Change to an overview of sampling design with more detail - spatial and temporal parameters	N/A

How is the data currently stored, that is what format is the data? (e.g. GIS shapefiles, compressed AVI etc.) Please provide as much information as possible.	MS Access database
When	
When was the research carried out? When were the start and end dates?	May 2007 – December 2010
Where	
Where was the research done? As a minimum please indicate the 'bounding box' in latitude/longitude (decimal degrees) (e.g. North bound latitude -22.00; West bound longitude 113.00; East bound longitude 114.00; South bound latitude -23.00)	Ningaloo Reef ()
Where are any other related publications/information about the research published - if any? (e.g. url)	Boschetti, F., de la Tour, A., Fulton, E.A., and Little L.R. 2010. Interactive modelling for natural resource management. Environmental Modelling & Software 25, 1075-1085.
Where in the vertical column of the ocean was the research undertaken? (e.g. minimum and maximum depth)	2 dimensional model
site names and GPS coordinates	
ACCESS	
where is raw data stored (full name, file and location	Elfsim.exe; ELFSim source code; elf_input.mdb; elf_CatchandEffort.mdb
where are derived/processed data products stored (full name, file andlocation)	elf_results.mdb; (Rich Little; CMAR, Hobart, Tasmania)
where are any other related publications/info	N/A
what constraints/restrictions would you place on the data…	Subject to Deed of Confidentiality and Non-Disclosure signed by CSIRO for DoFWA's data, which stipulates that written approval is required before DoFWA's data [data and data derived from the data collected by DoFWA] is published.
Supplementary information - Please attach any further information you think would be useful for future researchers	

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