A multi-model approach to engaging stakeholder and modellers in complex environmental problems

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Abstract

Models are increasingly used to support decision-making in the management of natural resources. They can provide system understanding, learning, a platform for stakeholder engagement, projections of system behaviour and an environment for virtual testing of alternative management strategies. However, rarely is a single numerical model suitable for all these purposes. Our experience is that a suite of models of different size, complexity and scope can be more effective and can better address the needs of environmental management projects. Models of different complexity can address different needs, but can also be combined as a flexibly sculpted tool kit - as they require very different development effort they can be deployed at different stages during a project. Using rapidly deployed qualitative, or simple quantitative, models stakeholders can be exposed to models very early in the project, eliciting feedback on appropriate model content and familiarity with the modelling process without affecting the development of more complex, resource intensive, models aimed at answering core management questions. This early and continuous stakeholder exposure to models provides flexibility in addressing specific novel questions as they arise during project development, as well as an opportunity for developing skills and changing both modellers and stakeholders' attitudes, as is often needed when facing complex problems.

Using an example where we used five different model types in an effort to inform policy-making around regional multiple use management in north-western Australia, we describe (i) how each model type can be used, (ii) the different roles the models cover, and (iii) how they fit into a full decision making process and stakeholder engagement. We conclude by summarising the lessons we learnt.

Keywords: ecological modelling, stakeholder engagement, system dynamics, adaptive management, participatory modelling.

1 Introduction

This paper describes the use of several model types within a large research project aimed at integrating scientific information to support decision-making with the view of ensuring a sustainable future for the Ningaloo-Exmouth region in Western Australia (Figure 1). The area has immense natural beauty (listed as a World Heritage Area in 2011), but is also currently the focus of rapid industrial development (e.g. around oil and gas extraction) with a highly diversified economy – including tourism, oil and gas, pastoralist and fisheries. There are many groups, with clashing objectives, interested in the region and the future development over the area will necessarily occur in a contested stakeholder environment.

The political tension surrounding the location saw a large research programme carried out in 2007-2011 to provide the information required for evidence based decision making about future management and development for the region. Within this programme, our team was tasked with developing both targeted industry specific models and a fully integrated whole-of-system model of environmental, social and economic processes in the region. The goal of these models was to: (i) provide a means of integrating information collected by several other research activities within the larger project; (ii) explore the potential impact and effectiveness of various management options; and (iii) encourage stakeholder engagement. Our previous experience and much other research has shown the many benefits (e.g. utilitarian, social, ethical, political and uptake) of participatory co-management approaches when trying to find long lasting sustainable outcomes for common property resources, such as the marine and coastal estate (Bramwell and Sharman 1999, Glasson and Marshall 2007, Syme et al., 2012).

The original proposal for the modelling work was to use the Management Strategy Evaluation framework – which explicitly represents the resource, users and management feedbacks (de la Mare 1998, Sainsbury et al., 2000) to model individual sectors as well as the overall system; with the intent of using industry specific models to address pressing industry specific questions for tourism and fisheries while field programs and the development of the whole-of-system model was underway. However, once the project began, it quickly became apparent that the different model types had complimentary science and engagement roles too and that more models were needed – simpler ones that could be used rapidly and in a highly interactive way.

An initial round of workshops eliciting questions for the modelling efforts and discussing key model content indicated that the models would need to address multiple processes and feedbacks across a range of spatial and temporal scales. It was evident that the complexity required to achieve this would lead to tools too unwieldy and slow running for use in interactive workshops. The models would be equally unsuited as tools for introducing and training potential users to modelling. Furthermore, we knew from previous experience that long development times for such complex models almost inevitably leads to a loss of interest and engagement, potentially leading to little subsequent uptake. This is because the modellers reticence to interact with busy people can lead to patchy or infrequent communication, which combines with rapidly shifting topics of interest and a fast turnover in the identity of representatives of local stakeholders and regulatory bodies, ultimately results in a loss of the key sense of participatory investment in the modelling process.

Sequentially defining, implementing and delivering a model may be the standard vision of modelling held by scientists and some managers (Figure 2a), but a more iterative and adaptive approach (Figure 2b) has been found to lead to greater engagement and uptake (Daniell 2008;

Fulton et al., 2011). This form of model development and stakeholder engagement leads to changes in model complexity and focus, as the problem becomes more defined and stakeholders appreciate what modelling can (and cannot) provide. Such an adaptive modelling process also more effectively accommodates different types (Joshi et al. 2007) and dimensions (Cross et al. 2001) of knowledge.

We addressed these modelling and engagement challenges by developing a suite of models each covering different roles within the project. Some of these models were the initially intended quantitative models of industries and the system, but others were used to keep the communication channels open and maximise the value of the activities for all involved. Most the modelling team had extensive experience in fisheries, where there was long experience, and thus ease, with the use of models to inform management, the same familiarity is not common in other marine and coastal sectors (Jennings et al 2014). Consequently, we developed simpler, more rapidly deployed models that could be used interactively to introduce stakeholders and decision makers to the philosophy of modelling; to showcase the value of modelling and train potential users in system dynamics; and to engage with the community over model developments and facilitate the exploration of management options. In total we developed five types of models: (i) conceptual, (ii) toy, (iii) industry specific, (iv) shuttle and (v) whole-of-system.

Conceptual models highlight the main drivers of a system and summarise our understanding of how the system works. Toy models are used to simplify the problem so that only a handful of components are included. In our project, these models were used to help stakeholders understand how different model components can address specific concerns. Industry specific models include a fairly detailed representation of a single component of the system. They address and provide an early analysis of a single sector or activity, which subsequently feed into the development of the whole-of-system model. Shuttle models incorporate the minimum number of core processes, considered crucial for a basic understanding of the overall problem. These models provide sufficient understanding to conceive and develop a full problem description. Finally, a whole-of-system model includes all information collected through the project and addresses a comprehensive set of stakeholders concerns, whose definition has been greatly eased by the use of 'simpler' models. As found from other ecosystem assessments (e.g. Fulton et al 2014), the simpler models can highlight key issues rapidly, facilitating fast action, with the whole-of-system model only called upon for the more complex and interlinked management questions, or when verification of conclusions drawn from the other classes of models was required.

2 Models Toolkit and Results

In this section we will provide an overview of each of the model types (see supplementary materials for additional details).

Conceptual models

In conceptual models the main drivers of a system are highlighted and captured in a diagram summarising the collective understanding of how the system of interest works. For the Ningaloo-Exmouth region these models were drawn up using qualitative models for individual parts of the system (e.g. Figure 3a which captures a minimal representation of tourism drivers and connections). These could be used as a basis for discussion around the connections and concepts captured, but could also be examined to see how shifts in one property may propagate through the sub-system (Dambacher et al 2009). In combination with sociograms (Syme et al., 2012), which highlighted connections amongst the human actors, the qualitative models painted a picture of the basic structure of the sub-systems and were pieced together to form the structural basis for the more complex quantitative approaches (e.g. the industry specific, shuttle and whole-of-system models).

An important role for the conceptual models was as a means of capturing alternative understandings of elements of the system. For instance, a series of meetings with key stakeholders (beginning with local Department of Environment staff and then moving on to tourism operators, local land owners and tourists) produced a qualitative model of the key determinants of coastal camping impacts and their links with the form of regulations used (Figure 3b). This proved important for clarifying the relative roles of regulation (including access, infrastructure and the identity of the regulator, whether landowner or government), and environmental state in determining the kind of visitors to a site. This not only improved the accuracy of the quantitative model dynamics, but also (more importantly) assisted in developing institutional knowledge around how management actions shaped the use of the coastline.

Toy (simple) models

Toy models are educational, helping stakeholders understand how (i) the modelling process works, (ii) different model components can address specific concerns, (iii) their interaction generates complexity and (iv) models can provide information that may not otherwise be clear. In this study toy models were used to introduce a broad audience to the concepts of stocks, flows, accumulation, and positive and negative feedbacks. These models were of a general form, rather that representing a specific component of the Ningaloo-Exmouth system.

A descriptive CO_2 accumulation question (Sterman, 2008), a “stock and flow” model, was used in a questionnaire (Boschetti et al., 2011) to provide an explicit, practical demonstration of how intuition can lead to mistaken judgements (even with simple problems) and how models could be used as useful checks by people of all backgrounds. A feedback loop model was also used as the core of a large interactive workshop. The mode was a version of the tourism impact model of (Casagrandi and Rinaldi 2002). It includes environmental status, tourism numbers and infrastructure development and the interaction between these variables (Figure 4). The workshop attendees were invited to pose tourism management and development questions and predict the model behaviour. Model responses were then analysed by following model dynamics incrementally in an open discussion session, highlighting where the participants’ intuitions were correct or misplaced. These exercises attracted considerable attention and while several model sceptics remained unconvinced, a few key stakeholders were persuaded, making subsequent interaction with them much easier.

Industry specific models

These are detailed representations of the direct influences on, and impacts of, the activity of a single component of the system, ignoring most other parts of the system. If parts of the broader system are considered they are either included as external forcing factors (drivers) or by simple closure terms or random parameter draws. We used such models to simulate tourism and recreational fishing on Ningaloo reef.

The Ningaloo Tourism Destination Model (NTDM) was a “stocks and flow” model (built in the Vensim software) of the relationships between tourism management and larger scale planning (Jones et al., 2011) which was built on data drawn from tourist and resident surveys and secondary sources. The model was a sophisticated set of interlinked sub-models covering visitor types, transport, accommodation, available activities, utility consumption, labour force demands, economic turnover related to tourism, environmental impacts and social pressures such as crowding (Table 1). The model provided an arena for group learning and scenario building by a range of interest groups. It also provided a lens through which to view the economic, social and environmental outcomes of different development and planning scenarios, proposed tourism events, targeted trajectories of change in tourism numbers and types and specific system shocks such as cyclones, pandemics and loss of a significant natural assets (e.g. coral bleaching and changing patterns of iconic wildlife visitation). The model was spatially explicit (representing tourism and planning nodes in the region) so that scenarios could be tailored to the specific locations and the outcomes used to address opportunities and concerns identified through stakeholder forums and workshops (Jones et al., 2011). The value of the model is highlighted by its subsequent use in regional planning exercises.

The NTDM included a simple environmental impact model, but was further extended by linking it with the Ecopath with Ecosim (EwE) model (described below). This coupling was one way, with NTDM usage patterns represented as pressure drivers in EwE to allow for assessments of the ecosystem implications of the development scenarios. The outcomes of these analyses were used to identify scenario to include in the analysis undertaken with the whole-of-system model.

Table 2 summarises the outcomes of three of the most requested scenarios – the planning scheme (Regional Strategy) current in 2006, which saw modest development spread across all tourism locations in the region; a single large resort; and a variation on the Regional Strategy, with additional fishing regulations (a two fish bag limit). The last was defined by locals concerned over the negative environmental outcomes of many of the other scenarios trialled. Positive outcomes, in terms of stocks and catch rates, under this scenario encouraged the community to seek change to fishing regulations. This was achieved via interaction with the ELFSim modelling team (see below), who were working with the Western Australian Department of Fisheries to test different recreational fishing regulations.

ELFSim is a spatially resolved fishing simulation model (Little et al. 2007), which includes reef habitat, a reef dependent fish stocks (typically 1-2 species), the fishery and its management (Figure 5a). The Ningaloo implementation focused on the recreational fishery and its primary target spangled emperor (*Lethrinus nebulosus*). The model was used to evaluate the effects of the current fishery management arrangements operating in Ningaloo Marine Park. This initially included evaluation of the current and previous arrangements of marine reserves, the then current bag limit and effort levels on biomass, inside and outside the reserves, as well as catches and catch rates (Thébaud et al. in 2014). The results showed that although more biomass was protected under the current reserve plan than under previous one, in areas open to fishing, effort was more concentrated resulting in localised depletion. This was only compounded if bag limits were removed or population and tourism driven effort increases continued. When these outcomes were presented at a workshop, stakeholders worked together to propose a number of alternative potential future management actions, including increasing the no-take sanctuary zones, restricting the fishing in sanctuary zones, introducing an educational program (aimed at reducing infringement and shifting more to catch and release fishing), and increasing the compliance monitoring on the fishery.

All of the alternative management actions were assessed against the stakeholders' objectives (classified as either ecological, social or economic). For example, the stakeholder workshop proposed a conservation objective that the spawning biomass in the sanctuaries should be above 75% of pre-exploitation level with a > 75% probability. The simulation results indicated that restricting inshore fishing in sanctuaries was best able to achieve this objective (Figure 5b) while imposing catch limits (initially more palatable to the public and regulatory officers) did not.

Shuttle models

Shuttle models include the minimum number of processes required for a basic understanding of broader issues the project needs to address. Rather than going into deep detail on one aspect (e.g. fishing) it is a light touch across entire sub-systems. Such models help to 'shuttle' information from a simple to a fuller description of a problem. This is a journey necessary both for developers, during model definition and parameterisation, and for stakeholders in the interpretation of the final whole-of-system model results.

ScenarioLab was designed to fulfil the role of a system level toy model. While based on the major features of the Ningaloo-Exmouth region (Figure 6) it was not intended to contribute directly to the assessment of management options, but to provide a fully interactive modelling experience to non-expert modellers. It was designed to allow for an exploration of model behaviour and played a role very early in the project, by demonstrating to key stakeholders that understandable model approaches were possible and that modellers were serious in addressing the needs of non-specialists. During interactive workshops, stakeholders were asked to choose parameter values, run the model and to identify input parameters they wished to manipulate and output data they wished to visualise. Discussions resulting from these questions were important both for clarifying the essential model features and for allowing stakeholders to understand what type of questions could be asked of the models. This joint understanding then informed the development of the other industry specific models as well as the whole-of-system models.

Ecosim with Ecopath (EwE) is a food web model that was used to collate the information made available by various research activities and models, while the development of fully integrated whole-of-system model was underway. Its role was important in (i) extending the environmental impact analysis of the NTDM model, (ii) testing some of the management strategies initially developed during stakeholder workshops and (iii) producing some initial food web level results, which consequently helped develop scenarios for used with the whole-of-system model.

The EwE model included 13 human activities (split across seven geographic locations) and 53 functional groups (Table A3), mostly marine (from plankton and habitats through to top predators) but also including buffell and native grasses, foxes, marsupial grazers, goats, sheep and birds of prey so that the interactions of coastal and marine sub-systems could be considered. While the focus of the overall Ningaloo research program focused on the reef and its users, a broader consideration of system drivers was required to really understand the region's dynamics - where much of the tourism is hosted on pastoral properties and there is concern over the management of the coastal strip. The model could not address the pressure on utilities (water and electricity) and social and economic concerns around housing and employment, but it could consider the environmental implications of increasing levels of various marine and coastal industries, especially recreational activities (e.g. fishing and snorkelling).

The EwE model complimented the NTDM by providing insight into the environmental implications of the Regional Strategy, but also alternative futures such as: the slower growth in the resource sector; adoption of modified recreational fish bag limits; a change in the type of visitors and tourists; a land release allowing the construction of 2000 more houses in Exmouth; and construction of additional infrastructure (roads and ramps). Results showed that even under the Regional Strategy, pressure on the system could treble, if all the planned and proposed developments were completed. Using the model, local planners and councillors soon realised that their actions had consequences for the reef and that they needed to acknowledge the tradeoffs and discriminate between different types of growth and regulation. Meanwhile government regulators, faced with budgetary constraints, struggled to find easily implementable and enforceable management actions that saw good conservation outcomes across the entire modelled food web. Decisions around fishing can have a large impact on that one activity, and modelled fish stocks, but had little influence on the habitat or iconic species, which were much more strongly impacted by large-scale climate drivers and ocean acidification (Figure 7).

Whole-of-system model

Whole-of-system models aim at a comprehensive representation of the system from biophysical to socioeconomic processes (land and sea in this case), accounting for all available information. In this project, an agent based socioecological system model (**InVitro**, Gray et al. 2006) was used to address the broad scenarios of stakeholder concern. The extensive and iterative interactions with key stakeholders, facilitated by the use of simpler models through the course of the entire project, produced a set of over 100 combinations of management strategies and contextual scenarios that could describe alternative futures for the region.

The Ningaloo-Exmouth InVitro (Ningaloo-InVitro) was implemented on a 30x30m resolved grid and included the dynamic representation of the marine food web and main terrestrial species of interest (as originally defined in the EwE model), as well as all major anthropogenic activities, both land and sea (Table A4).

A series of workshops indicated that the majority of the local population felt they were recipients of pressures originating outside the region. These included trends in population growth, growth in resource (oil and gas) exploration and extraction across north-western Australia, increase in tourism and consequent infrastructure development (and the resulting potential change in usage patterns). This meant that the questions most often asked of the model related to the impact of alternative development paths on locally scarce resources (like water and electricity), on environment status (currently the core driver for tourism) and on standards of living, in terms of employment opportunities and housing availability and affordability.

A full discussion of the results is presented in (Fulton et al., 2011). Multivariate cluster analysis and Principle Components Analysis performed on the simulation results showed that there were eight major classes of outcomes (Table 3). Each class had its distinguishing features, but there were also some significant common features that held across all classes. For instance, the proportion of the local elderly population (50+) consistently increases relative to today, while large and potentially vulnerable megafauna like whale sharks and turtles decrease (to differing extents depending on the management strategy in place).

These simulations confirmed the complex relationships between development and environmental status in the region hinted at by some of the simpler models. The picture portrayed by the InVitro simulations is one of a typical "complex" system: controlled by large-scale external pressures as much as by local processes, which could only be understood via across-scale perspectives. The region's future is affected by global drivers, like climate change and external industrial development, but also by local points of intervention (e.g., the availability of housing), sanctuary zone boundaries, infrastructure (e.g., boat ramps or utilities) and road access. While stakeholders familiar with regional issues had already identified some of these, the full extent of the potential interactions could only be assessed via a whole-of-system model. Some of the simpler models discussed above had highlighted some aspects of these potential futures, but the interconnection between the industrial developments and larger marine state (even though not physically co-located) was only evident once the system information was integrated in InVitro.

The degree of detail in InVitro and the volume of results generated could be daunting for many people, so the outcomes were presented in several ways. Radial plots were used to highlight tradeoffs; tabulated results allowed readers to explore the numerical details and to compare the outcome of different runs. An interactive visualization of the model results was also made available (www.csiro.au/seaview/index.html) and computer-generated images were used to try to capture how different possible futures may impact the appearance of the region (Figure 8). This last approach proved the most effective means of allowing stakeholders to associate model results with tangible personal experiences.

2.1 How the models informed the overall project

Each of the models types had benefits beyond their immediate outputs produced. These included i) the models as tangible tools with on-going use after project completion, ii) stakeholder engagement, iii) stakeholder learning around model use and system function and iv) education of the modellers. The later was most useful in model development. For example prior to visiting the region and holding the first round of workshops, the high biomass of whales in the region was neglected as it was not highlighted in scientific reports or tourism brochures for the region (both of which focused on the reef and the visiting whale sharks). The addition of the whales was important however, because it presented a good alternative tourism venture (one that has since become important in the region). The modellers also benefited from being able to observe how real users and managers of the system responded in model based role-play sessions (responding to changing model states and attempting to rectify the situations). This was exceptionally useful for effectively parameterising human behaviour in the final fully dynamic models.

In our experience, the use of a multi-model approach had a considerably positive impact on research in the Ningaloo-Exmouth region. Firstly, the range of models developed in the toolbox changed the perception of what models are: from purely academic abstractions, to tools that can help address actual, local problems (Chapman 2011). Secondly, it shaped the definition of scenarios to be explored with the models in a way that was useful to the intended audience. If the scenario definition had been left to scientists and resource managers only, then meaningful insights into some of the most pressing questions affecting the region's future would have been missed.

Using several models in the engagement process improved the general system understanding (and hopefully an improved capacity for handling complex systems more broadly) and facilitated on-going use of at least some of the tools developed during the project. For instance, InVitro, NTDM and ELFSim have fed decision-making and consultative processes around new management options and development plans.

This level of uptake required a significant investment of resources, both in terms of funding and time. This investment wasn't just in the standard model development and calibration steps, but was particularly needed to build trust in the models and the modelling process: involving stakeholders in conceptual model building, regularly communicating model development, and new results and running training courses. All of this was essential for building trust, understand and ownership among the many operators and residents who were unfamiliar with modelling and because there was frequent turnover in departmental representatives. This approach also proved an effective means of improving communication among people with different backgrounds, assumptions and knowledge.

The modellers also learned many lessons, particularly the distinction between a job academically well done and one having meaningful impact. A significant insight gained by modellers relates to the role of modelling in asking and answering complex questions. In its purest analytical sense, a model is developed to provide results, thus answering rather than formulating questions. However, helping both the asking as well as the answering of questions is crucial from an engagement perspective, particularly if we accept that modelling which is to have any useful longevity is not what expert outsiders do, but is a process which includes experts, stakeholders and the local community. A model built to cover both asking and answering roles may lead to a living product that is used and appreciated, rather than merely receiving academic praise and sitting unused on dusty shelves in the region itself. Single models are unlikely to meet this dual role across all backgrounds and for all question types - that is where the multi model approach can be particularly beneficial. Table 4 summarises the role of the different types of models used for Ningaloo within the different engagement phases.

3 Discussion

Modelling is not always a well-understood tool, with many quailing at the thought of implementing one model let alone seven different platforms. However, experience in the Ningaloo-Exmouth region demonstrates the potential benefits of integrating different types of models at different stages of the project for different purposes. Tackling the process as an adaptive exercise, where new tools are brought to bear as the modeller gets a better understanding of local needs. A frequent admonition of experience modellers is that you need to "know your critters" (Walters, UBC, pers com) – understanding the focus of your modelling is not only important from an ecological perspective, but in terms of appreciating the hurdles that stakeholders face in engaging with the tool.

Van den Belt (2004) divides the process of using models to engage with stakeholders into three stages: an extensive preparation phase, workshops (including qualitative and quantitative model building), and follow-up. The preparation stage is required to introduce the main players, to identify and assess key stakeholders ("champions") and social and information networks that may facilitate (or stifle) the effort. The later are key, as experienced socioecological modellers have found that champions and information networks are ultimately key for positive outcomes (Walters 2007). Van den Belt's approach assumes the same stakeholders will be involved from the beginning to the end of a project, but this is not typically the case in adaptive management projects, which are often characterised by a high turnover rate among management personnel and so having a champion to see it through is important. Similarly, having a locally trusted champion in isolated geographic locations, like the Ningaloo-Exmouth region, is beneficial for continuity and trust as such locations feature a complex mix of long and short term and even transient residents. This does not invalidate Van den Belt's or similar approaches (D'Aquino et al., 2003), but does mean that a "two steps forward, one back" progress often occurs. Formulating and carrying out the modelling project may thus require evoking and strengthening emergent behaviours, which may also help in dealing with any attitudinal inertia, high turnover rates, communication barriers and mismatches between the scales of industry operation and the speed of response of management bodies (such mismatches typify the average coastal adaptive management environment (Chapman et al., 2011)).

Not all stakeholders wish to become model users, though many of them may want to be familiar with model development to better understand what it can offer to the final decision making process. When dealing with issues of sustainable multiple use management of natural resources and coastal systems, this is not easy to deliver because of the diversity of issues, system complexity and the wide variety of stakeholder backgrounds. The complexity of the topics and jurisdictions means that it can be easy for regulators to feel they have little time to add another task to their overflowing schedules (engaging with the modellers) and equally for modellers to retreat into the modelling and spend little time communicating more broadly. However experience (e.g. in the Pilbara directly adjacent to the Ningaloo-Exmouth region) has shown that models developed in such a climate are not used and if anything act to increase scepticism around the value of modelling. Regardless of the scientific excellence a model won't be used if potential users do not understand its contents or role and so feel overwhelmed, distrustful or dissatisfied. Gaining the requisite trust for on-going model use requires hard work on the part of the modellers (and the stakeholders if they are really to participate and learn), a diversity of approaches, and a flexible (but anchored) research approach. Using multiple complimenting models is one such approach.

It cannot be denied however that the level of interaction required to develop and share the modelling platforms was a costly exercise. The magnitude of the problem would only grow with the size of the population involved. The high level of interactive engagement associated with this approach may start to break down on large scales (Walters 2007), where it can be hard to find sufficiently inclusive representatives. While the Ningaloo-Exmouth region is large geographically (spanning over 300km of coastline) it has a small standing population (<6000) – meaning that industry, NGO and other representatives were fairly closely woven into the local communities.

4 Conclusion

In our experience, a multi-model approach strengthens modelling outcomes by (i) providing a common interpretation of available information; (ii) developing the skills and attitudes needed when facing complex problems; and (iii) offering an avenue for communication, negotiation and collaboration.

A multi-model approach facilitates the first two outcomes by providing continuous engagement and thus allowing for a much greater intensity of model exposure and use. At the same time, it de-couples the engagement process from the development of complex whole-of-system models, which may require the full length of the project to complete. Furthermore, the parameterisation of the whole-of-system model is also subject to interdependencies with other projects and fieldwork, and may experience rescheduling for reasons beyond the researchers control. Adopting different model types can overcome this problem, providing for continuous engagement, while programmers, software engineers and other researchers focus on coding and parameterisation of the whole-of-system model. This, in turn, enhances the adaptive aspect of the engagement process by providing repetition in engagement activities and variety in presenting and discussing information (all characteristics of a positive learning experience). It also provides flexibility by including novel ideas and available data (occasionally in real time during meetings and workshops) in a manner that is relevant and topical for stakeholders. This may result in suggestions for alternative and novel ways to carry out a project which could otherwise be missed. While this is in principle possible with whole-of-system models, it may (i) be delayed unless the model is already available, (ii) be made less intuitive if the model is particularly complex or (iii) prevent real-time use if the full-scale model is slow to run.

Industry specific models and shuttle models in particular were useful in the Ningaloo-Exmouth project because they were powerful enough to address topical issues of local concern and allowed modellers to communicate model outputs throughout the project, rather than only at project completion. This is particularly important in situations where a diverse and divided stakeholder community may be sensitive to specific issues and even specific wording, since this sensitivity can be detected and addressed before the whole-of-system model is released.

Finally, a further benefit of a multi-model approach is to facilitate the modellers' understanding of local priorities and histories. In the Ningaloo-Exmouth project, this led to proposals for further environmental monitoring and tourism research. Whether or not this is an extension of the role of the modeller, or an entirely different role is debatable. However, in our experience the multi-model approach strengthened the capacity of modellers to act as 'change-agents'. If the purpose of modelling more broadly is to support changes in attitudes, practices and management systems, then the effect of a multi-model approach on stakeholder engagement should be welcomed and further developed.

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Figure Captions

Figure 1: Ningaloo-Exmouth region of Western Australia, showing the major tourism nodes identified in the region – including the major settlements (yellow), pastoral stations (red), national parks (green) and other features (blue and purple).

Figure 2: Model development steps (a) the traditional, sequential model development stages (with stakeholder interaction only in the first and final stages); (b) iterative model development (with stakeholder interaction throughout).

Figure 3: Example conceptual models for (a) tourism drivers and (b) coastal camping and its regulation. Links ending in an arrow head indicate positive direct effects, those ending in a filled circle indicate negative direct effects and the dashed line links indicate potentially opposite ways that campers may react to regulation (some like it, others do not).

Figure 4: Tourism feedback model, showing the interaction between environmental status, tourism numbers and infrastructure development. Arrows indicate positive interactions and circles indicate negative interactions.

Figure 5: Schematic of the components of the ELFSim model (a) and a summary of the main ELFSim model trajectories (b).

Figure 6: Schematic of the components of ScenarioLab. Solid lines indicate within software steps, dashed lines are the ways in which users can interact with the model.

Figure 7: Example Ningaloo EwE output.

Figure 8: Examples of the computer-generated images used to help visualise the results of the Ningaloo-InVitro model: (a) an undeveloped tourism node if tourism operations and management regulations of 2010 remained in place (i.e. beach camping dominates) and little industrial resource development in the region; (b) an undeveloped tourism node if 2010 tourism operations and management regulations remain in place and all planned resource sector development occurs in full by 2035 (i.e. high level of camping and recreational fishing by industry workers); (c) coastal tourism location developed with ecolodge accommodation; and (d) resort and retail development on a coastal node.

Figures

Figure 1

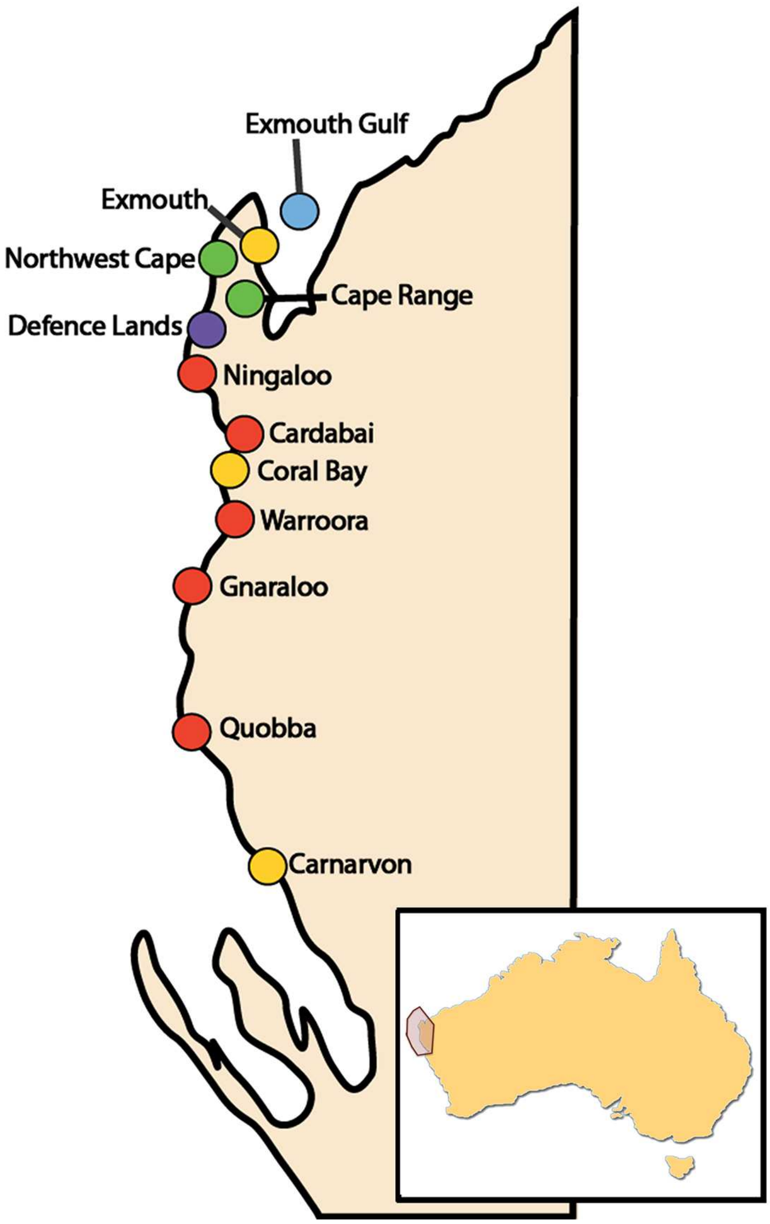
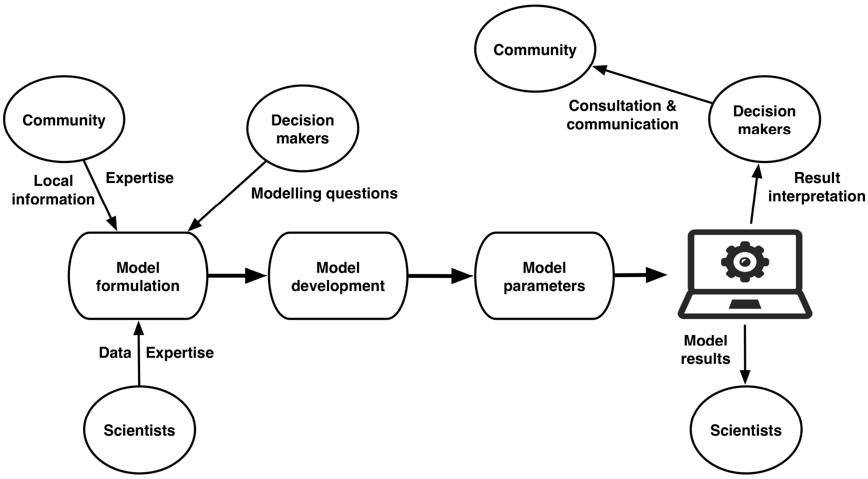


Figure 2

(a)


Community
Decision makers
Community
Consultation & communication
Decision makers
Local information
Expertise
Modelling questions
Result interpretation
Model formulation
Model development
Model parameters
Data
Expertise
Model results
Scientists
Scientists

(b)

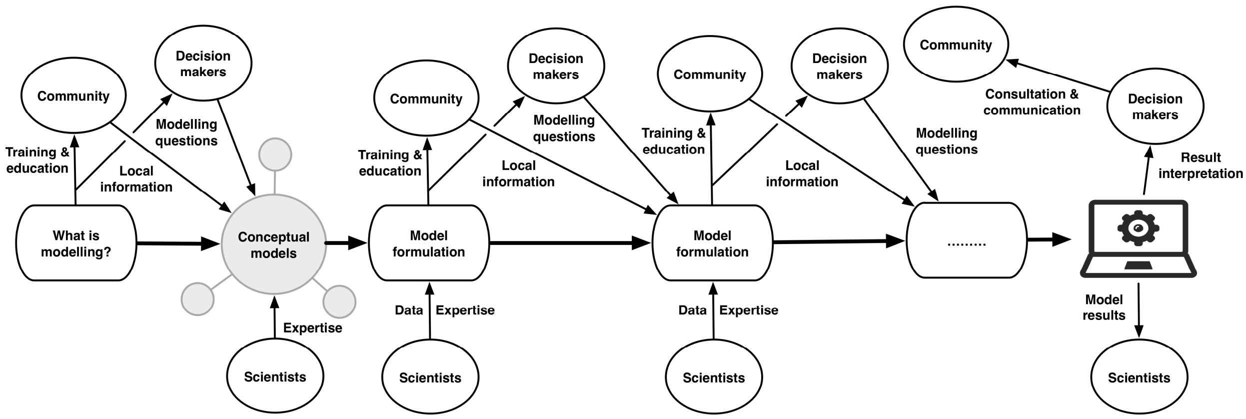
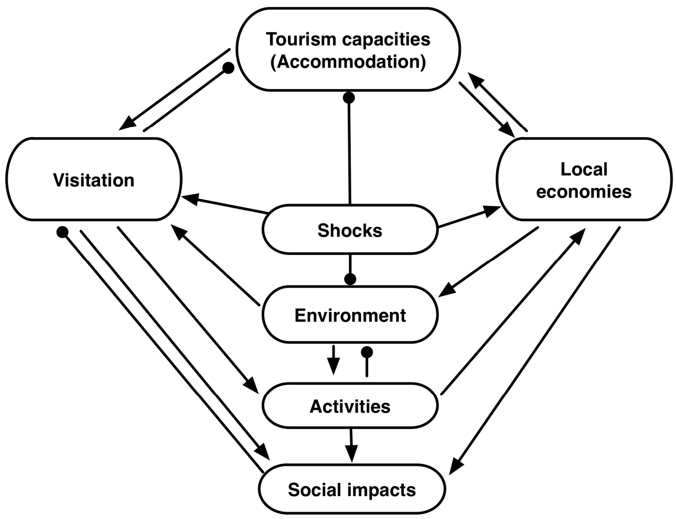

Decision makers
Community
Decision makers
Community
Decision makers
Community
Community
Decision makers
Training & education
Modelling questions
Local information
Training & education
Modelling questions
Local information
Training & education
Local information
Modelling questions
Consultation & communication
Result interpretation
What is modelling?
Conceptual models
Model formulation
Model formulation
....
Data
Expertise
Data
Expertise
Expertise
Model results
Scientists
Scientists
Scientists
Scientists

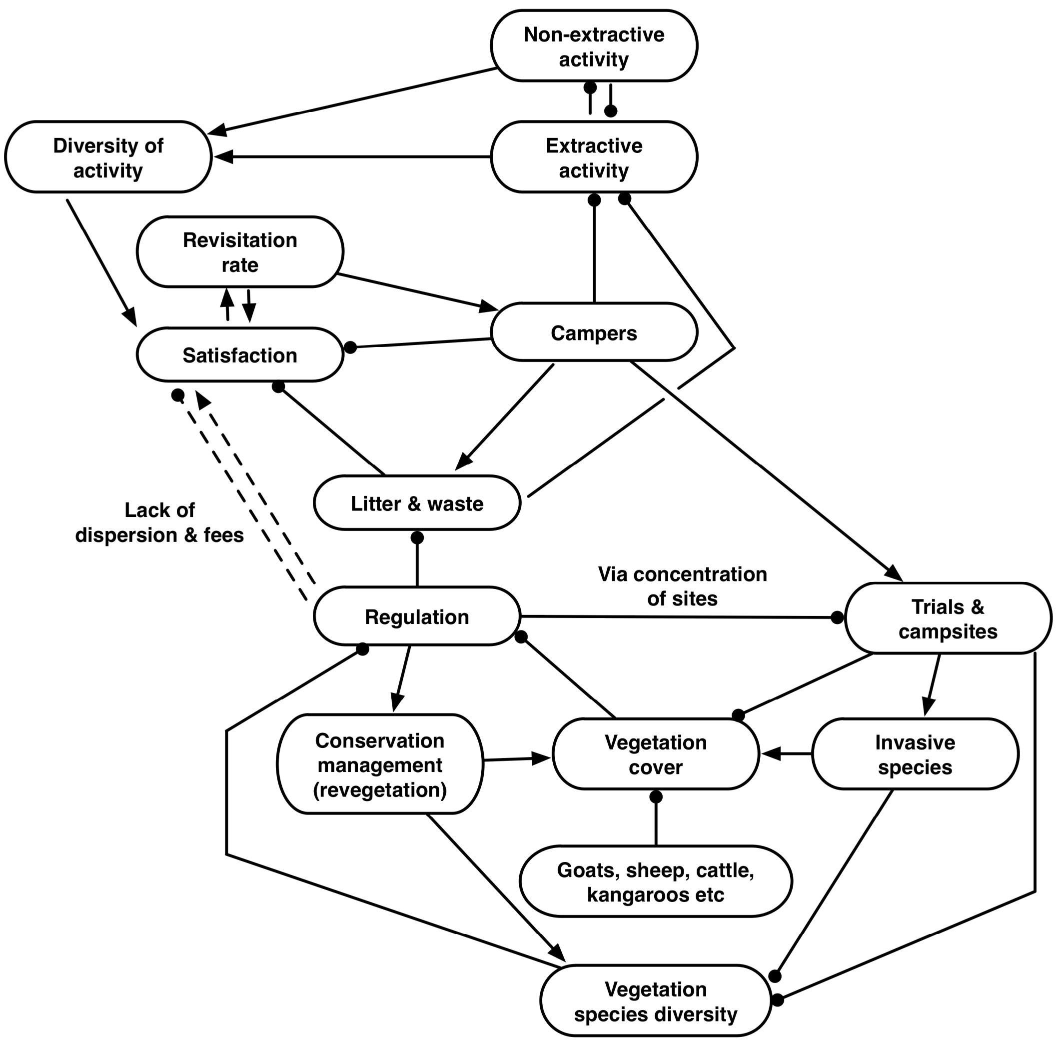
Figure 3

(a)



Tourism capacities (Accommodation)
Visitation
Local economies
Shocks
Environment
Activities
Social impacts

(b)



Non-extractive activity
Diversity of activity
Extractive activity
Revisitation rate
Satisfaction
Campers
Litter & waste
Lack of dispersion & fees
Via concentration of sites
Regulation
Trials & campsites
Conservation management (revegetation)
Vegetation cover
Invasive species
Goats, sheep, cattle, kangaroos etc
Vegetation species diversity

Figure 4

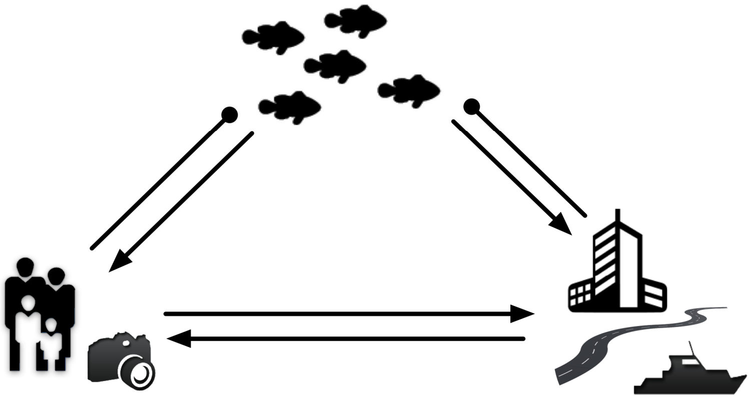
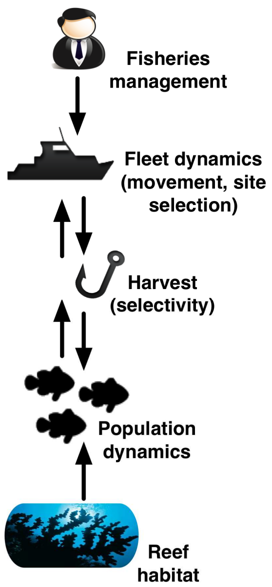


Figure 5

(a)


Fisheries management
Fleet dynamics (movement, site selection)
Harvest (selectivity)
Population dynamics
Reef habitat

(b)

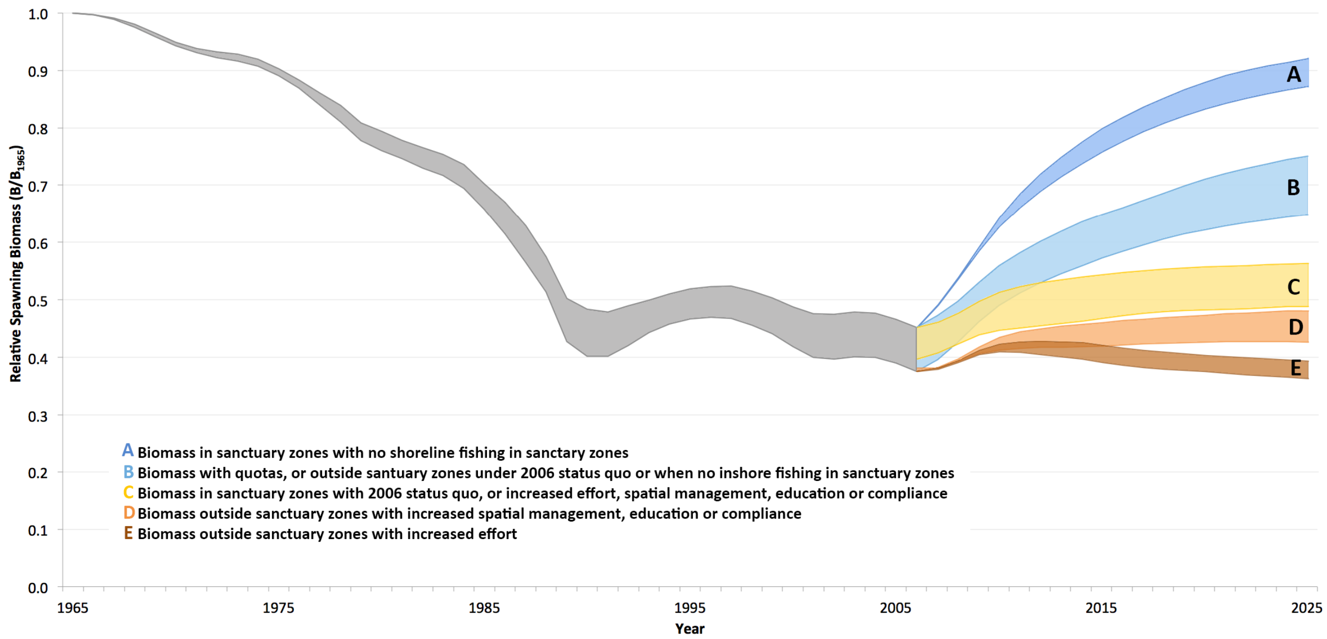

1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Relative Spawning Biomass (B/B1965)
1965
1975
1985
1995
2005
2015
2025
Year
A
B
C
D
E
A Biomass in sanctuary zones with no shoreline fishing in sanctary zones
B Biomass with quotas, or outside santuary zones under 2006 status quo or when no inshore fishing in sanctuary zones
C Biomass in sanctuary zones with 2006 status quo, or increased effort, spatial management, education or compliance
D Biomass outside sanctuary zones with increased spatial management, education or compliance
E Biomass outside sanctuary zones with increased effort

Figure 6

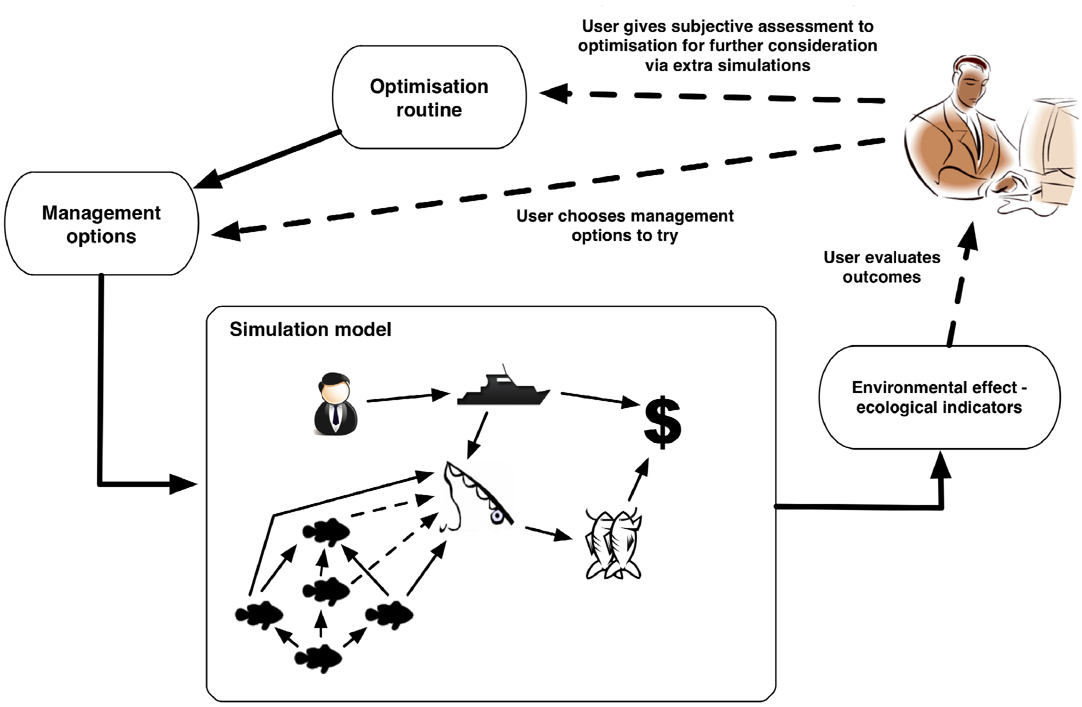


Figure 7

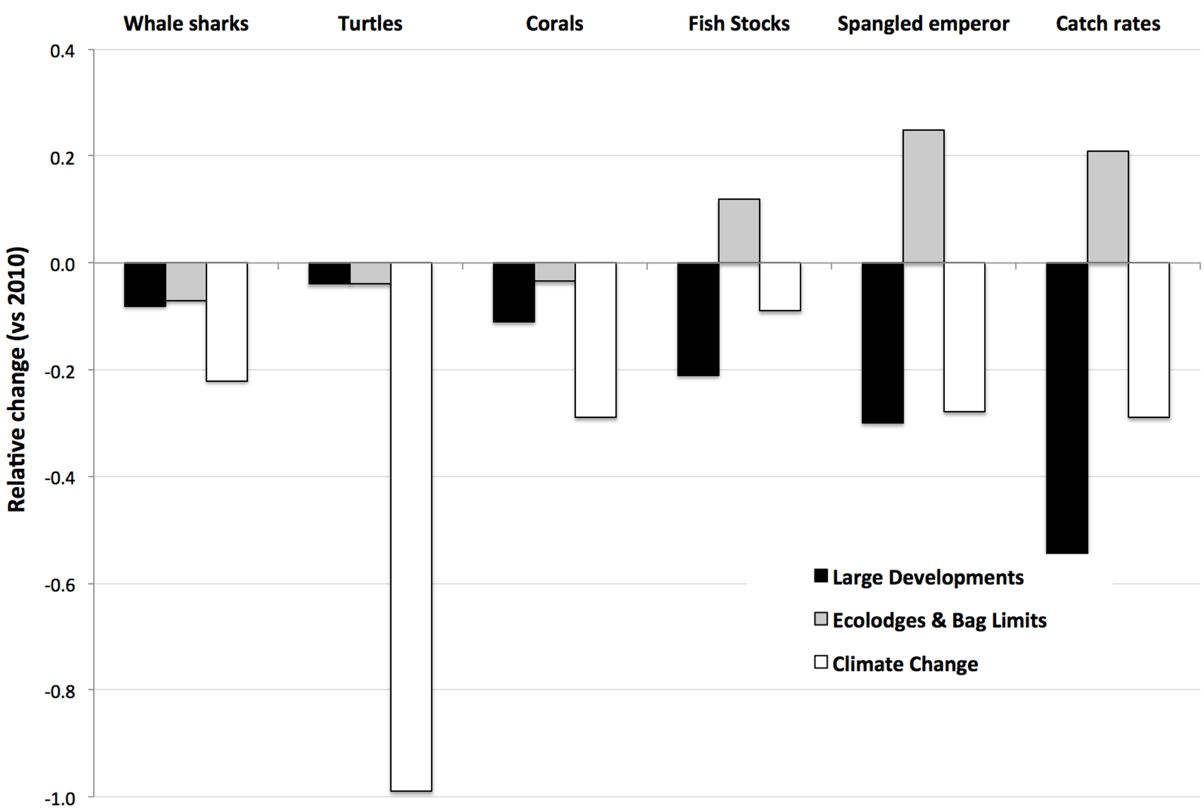
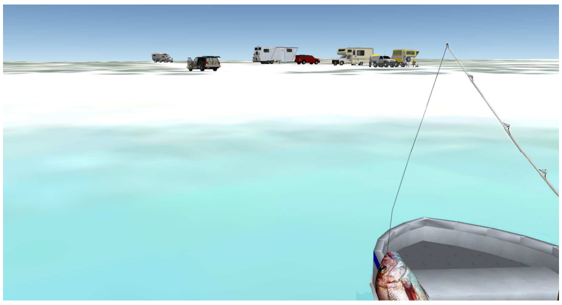
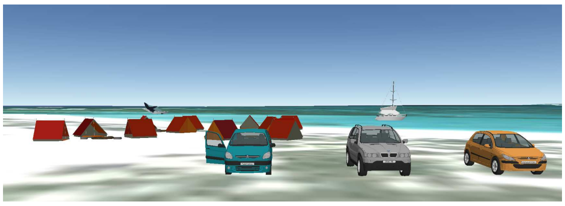


Figure 8

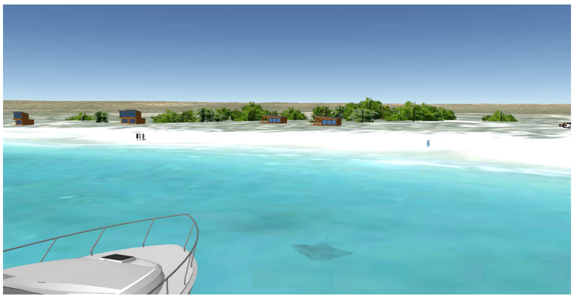
(a)



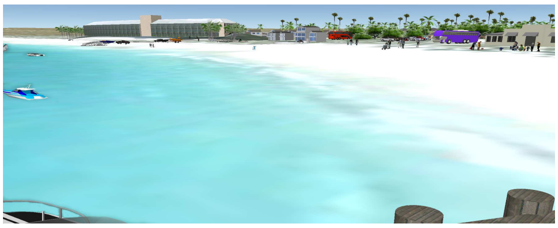
(b)



(c)



(d)



Tables

Table 1: The nine sub-models included in the Ningaloo Tourism Destination Model (NTDM).

Sub-model	**Summary content**
Visitor numbers and mix	Links the visitor cycle (numbers, mix and seasonality) to other cycles in the region (weather, cyclones, marine, European visitation, holidays).
Residents and industry	Addresses growth in regional industries and housing availability as determinants of population numbers and the activities undertaken by the resident population.
Visitor activities	Links visitor activities and experiences to tourism infrastructure, environmental quality and the characteristics of the tourism industry.
Accommodation sector	Addresses accommodation supply and demand in the context of land availability, investment returns, demand from other sectors and staffing.
Visitor spending	Uses visitor spending and economic data to calculate employment, income, value added and gross regional product.
Environmental loads	Addresses water availability in the context of climate change and water consumption, waste water generation, treatment and implications for the region’s ecology, electricity demand and supply, and the potential impacts of sustainable technologies for reducing water and electricity use.
Environmental impacts	Links activities of visitors and residents to a range of environmental impacts, including marine and terrestrial impacts such as coral damage, fish stocks and vegetation loss, and the monitoring of these impacts.
Transport linkages/options	Addresses transport to (and within) the region, including transport constraints and shocks that could disrupt travel, and links to national trends.
Social impacts of tourism	Identifies positive affects (extra facilities, regional pride) and negative impacts (crowding, incidents, dislocation) to residents’ quality of life.

Table 2: Example outputs of the coupled Ningaloo Tourism Destination Model and the Ningaloo EwE Model (catch rates and biomasses) – given as percentage change per indicator from 2007 to 2037. The Regional Strategy and large resort scenarios assume 2006 management rules continue throughout.

Indicator		% Change (2007-37)		
		Regional Strategy	**Large resort**	**Additional bag limit**
Visitors		66	420	67
Visitor nights		64	380	62
Visitor activities	Going to beach	41	305	42
	Fishing	60	220	54
	Snorkelling	48	310	50
	Eating out	59	80	64
	Surfing	97	120	100
Jobs		95	670	96
Expenditure		63	510	60
Water use		20	730	18
Electricity demand		71	570	72
Landfill generated		57	75	49
Community pride		60	95	61
Housing availability		- 9	-12	- 8
Catch rates		-55	-75	22
Fish stocks		-20	-31	13
Lethrinus nebulosus		-30	-38	18
Coral		- 6	-12	- 4

Table 3: Major classes of outcomes from the Ningaloo-InVitro whole-of-system model.

Class of InVitro Outcome	**Description**
Base case	Little if any population growth, stagnation of the regional economy, rising unemployment and an aging population; the visitor mix moves toward recreational fishing, with a further decline in stocks, but some reduction in demand for services and infrastructure
Reduced growth	Similar in trend to the base case, but more extreme so that there is a contraction in the system state away from nearly all objectives (environmental, social or economic)
Changed management, but no developments	Irrespective of the form of alternative management used (increased spatial zoning, education or enforcement), the changes typically mitigate some of the environmental impacts (e.g. protecting habitats), but have little overall effect on the system
Ecolodges and reduced growth	Reduced growth in the broader regional economy, significant per capita increase in expenditure, positive environmental outcomes (due to the visitor profile attracted); strong competition for local housing continues (as there is insufficient development for land release, but sufficient tourism labour market to generate in-migration and competition for dwellings).
Modified bag limits	Significant fish stock increase, probability of catching trophy fish per trip significantly increases; the recreational fishers attracted to the region help maintain the local economy, but compete with residents for dwellings
Large developments (resorts or resource sector)	Major expansion of a sector (oil and gas, tourism or other industry) increases regional economy, road transport, resident population and demand on services and infrastructure; environment declines.
Large developments and the introduction of modified bag limits	Trends as for the large development case, but with little impact on fish stocks (which remain at the 2006-2010 levels or increase).
Changed climate	Contraction of the local economy (e.g. agriculture and tourism), tourism season constrained to the cooler months, or tourism segments willing to pay for air conditioned accommodation; slower population growth, decline in available services; strong ecological impacts, turtle nesting beaches often washed out (by storm surges and sea level rise), increased habitat vulnerability (due to storms and acidification).

Table 4. Relation between modelling purpose, model type and engagement phase

Engagement Phase	**Modelling Purpose**							**Model Type**				
	Understand casual relationships	Understand system functioning	Build tools for others to use	Training & develop useful learning attitudes	Perdict, retrodict	Foster effective communication & collaboration	Explore system behaviour	Conceptual models	Industry specific models	Toy models	Shuttle models	Whole-of-system models
What is modelling?												
Problem or model definition												
Skills and attitude training												
Showcase progress and further model definition												
Scenario testing												
Model calibration												
Final model runs												

Supplementary Materials – Model details

Conceptual models:

The qualitative modelling approach of Dambacher et al (2009) was used to capture conceptual understanding of drivers and connections for sub-systems, particularly those that had not previously been modelled. These conceptual models define system variables and links between them. The models are constructed in stakeholder workshops, focusing on relevant sub-systems, the main ecological and anthropogenic processes and feedbacks that sustain or regulate it, and the potential system stressors.

The most formal work on the conceptual models was undertaken for the tourism sector (see Jones et al., 2011 for full details). Workshops were held in the region to define qualitative models for:

i. Visitor numbers and mix: defining links between the visitor cycle (numbers, mix and seasonality) to other cycles in the region (weather, cyclones, marine, European visitation, holidays).
ii. Residents and industry: addressing the drivers of growth in regional industries and housing availability, which are determinants of population numbers and the activities undertaken by the resident population.
iii. Visitor activities: linking visitor activities and experiences to tourism infrastructure, environmental quality and the characteristics of the tourism industry.
iv. Accommodation sector: addressing accommodation supply and demand in the context of land availability, investment returns, demand from other sectors and staffing.
v. Visitor spending: identifying the links between visitor spending and economic data to calculate employment, income, value added and gross regional product.
vi. Environmental loads: the connections between water availability in the context of climate change and water consumption, waste water generation, treatment and the implications for the region’s ecology, electricity demand and supply, and the potential impacts of sustainable technologies for reducing water and electricity use.
vii. Environmental impacts: linking the activities of visitors and residents to a range of environmental impacts (and the monitoring of the impacts), including marine and terrestrial impacts such as coral damage, fish stocks and vegetation loss.
viii. Transport linkages/options: identifying the links between transport to the region and within the region, including transport constraints and shocks that could disrupt travel, and links to national trends.
ix. Social impacts of tourism: identifies the positive impacts (extra facilities, regional pride) and negative impacts (crowding, incidents, dislocation) of the tourism industry on residents’ quality of life.

Conceptual models (taking the form of signed diagraphs) were also used in an informal way in project meetings, workshops and stakeholder interviews as a touch point for sharing information around key concepts or contentious, uncertain or new topic areas – for example see the issue of coastal camping highlighted in the main text of this paper.

Toy models:

While academia (from physics to ecology and economics) has used models to increase understanding and make projections or forecasts, there is an increasing awareness of the usefulness of models as evidence-based “flight-simulators”, training users to fly in the space of management challenges and to guide them in their choice of appropriate strategies (Boschetti et al 2011). Toy models are simple models built in this context to address dynamic (but often poorly understood) processes characterizing complex systems – like phase transitions, tipping points, hysteresis, and oscillations. Both of the toy models used in this work can be found at http://www.per.marine.csiro.au/staff/Fabio.Boschetti/ToyModels/ToyModels.htm.

The first toy model used by the study was inspired by Sweeney and Sterman (2000) and allows users to interactively control the in and out flows into a bathtub (Boschetti et al. 2011). The user is asked to predict the amount of water in the bathtub (the stock at time *t*) as a function of how much water enters and exits at different times (the flows):

$$\text{Stock}(t+1) = \text{Stock}(t) + \text{Inflow}(t) - \text{Outflow}(t) \qquad (1)$$

This proves a surprisingly challenging task even for the well educated (Sweeney and Sterman 2000). All managed systems depend on a careful balance of resource usage (water, energy, people, CO2, biological species) so understanding stocks and flows are crucial to effective management.

The model (in the form of a questionnaire) was presented to biologists and ecologists working in the Ningaloo-Exmouth region as well as managers of the region's resources and local stakeholders active in tourism development or ecological sustainability. As observed by Sterman (2008) well over two thirds of the mathematically proficient experts (scientists and managers) failed the tests and the figures were higher still amongst the operators and general public. Sterman (2008) and Cronin et al. (2009) suggests that this failure is due to a human tendency to match patterns and assume the stock dynamics matches that of flow. While the broader stakeholder audiences found this a sobering exercise, it was particularly useful for demonstrating to skeptical professional audiences that their knowledge of the system was not a sufficient guide alone and that models could be a useful decision support tool for them.

The second toy model used was a tourism feedback loop model (Casagrandi and Rinaldi 2002, Boschetti et al. 2011), which allows for an exploration of the interaction between three abstract variables: (i) the size of a population exploiting a resource, (ii) the way exploitation is carried out and (iii) the dynamics of the environment which provides the resource. By specifying the nature of the population and type of resource, this abstract representation can be applied to a range of different problems, including fishery management, water conservation, tourism development and climate change; in this case the modelled resource was a tropical ecosystem and the users were tourists. The management levers that could be pulled included technological fixes (infrastructure to mitigate impacts such as pollution), advertisements, reclamation, bed capacity and tourism type being serviced (e.g. ecotourism versus mass tourism).

While a simple three-variable model cannot capture the complexity of a real system, it can help understanding of the medium and long-term effects of positive and negative feedback loops. It can also help users develop an intuition for the role and impact of specific links on system behaviour and where points of intervention may lie. This type of model can thus be seen as a learning tool and a reality check to verify the soundness of assumptions about system behaviour. While some of the stakeholders were initially suspicious of the model, assuming the difficulty of constraining environmental impacts under mass tourism was the result of an agenda rather than model dynamics, in the main when confronted with the difficulties of managing and predicting outcomes in even such a simple system many stakeholders who had previously had little explicit contact with models (and so were skeptical, untrusting or even nervous of them) began to appreciate that models had a potential role in helping find sustainable outcomes for the Ningaloo-Exmouth region.

Industry specific – Ningaloo Tourism Destination Model (NTDM)

The NTDM was developed to allow for the exploration of alternative futures related to infrastructure development, tourism growth, external economic impacts, resource use, service delivery, energy consumption, waste generation and system shocks (such as cyclones or changed usage patterns as the result of transport restructures). It was constructed through a consultative process. In addition, an extensive survey of 1574 visitors and 287 locals (regional population of about 7800) was undertaken to provide parameters for behavioural and attitudinal components of the model that could not be readily obtained for large-scale tourism, census and economic databases. Government and industry data bases were used to supply tourism data (from Tourism Research Australia's national and international visitor surveys); water, electricity and waste data (from the Australian Bureau of Statistics (ABS), local government strategic waste management plans and service providers); and employment and accommodation capacity data (from the ABS, supplemented by information from local visitor centres, real estate agents and planners).

Conceptual diagrams drawn during a series of stakeholder workshops were refined in Vensim, focusing on key feedback loops so as to capture important system dynamics while remaining as simple as possible. Inputs were assessed against planning documents for the region, to help address uncertainties around future development. A regional scale model (including the entire Ningaloo Marine Park, plus 300km of adjacent coastline stretching across two local government areas and a variety of land tenures) was developed as past research indicates that the regional level is a particularly appropriate scale for territorial integration of natural and socio-economic systems (Jenkins et al. 2003, Roberts 2006, Yorque et al. 2002).

While standard sensitivity analysis, hindcasting and model validation were performed on the NTDM, final model validation and the communication of model outcomes was done via 15 forums held across the Ningaloo-Exmouth region, building regional knowledge and understanding of the potential consequences of current plans and decisions, and overlaps in areas of institutional responsibility. This then acted as a springboard for workshops, with attendees from a broad range of backgrounds (e.g. tourism industry, pastoralists, the shires, government agencies, researchers and interest groups such as NGOs) defining archetype scenarios for further consideration (Table A1). This process linked groups through the modelling process, building relationships and shared understanding, resulting in support for use of the model in future planning exercises. This uptake was only successful however, because of the degree of interaction between modellers and stakeholders (with requests for information and experimentation coming from a wide range of collaborators) and because of the flexibility of NTDM to morph as planning priorities shifted through time, but also between locations (with interest in the different tourism nodes reflecting locally important issues; destinations in Carnarvon, resorts and accommodation in Coral Bay and cumulative impacts of tourism development and resource sector growth in Exmouth).

Industry specific – ELFSim

ELFSim is a simulation model intended for use in fisheries management strategy evaluation (Little et al., 2011), incorporating the various steps of an adaptive management cycle; specifically:

- a (meta) population dynamics model of the target species, which captures its full life history (including larval dispersal, reproduction, development, and habitat use);
- a spatial fisheries effort allocation model that accounts for behavioural patterns of fishers, but also harvesting by multiple sectors (each with its own idiosyncrasies); and

- a management model that simulates the implementation of management strategies (such as bag limits, spatial zoning and quotas).

The biological model at the heart of ELFSim is implemented on a 1 minute spatial grid and operates at a monthly time step, representing the target population as a set of several age-, sex- and size-structure sub-populations, each associated with a single reef or spatial location. It incorporates a stock-recruitment relationship, and allows for larval movement (in this case based on distance between habitat patches as no larval advection model existed), sequential hermaphroditism, variable larval survival, natural mortality and growth curves. An adult movement module also exists for the model, but was not used in this case.

Fishing mortality experienced by the sub-populations is dictated by the harvest sub-model, which includes catchability, size based selectivity and a representation of daily effort allocation that allows for multiple vessel-classes. Several effort allocation models exist for ELFSim (Little et al. 2004, Little et al. 2008), but the one used for Ningaloo was an individual based model, which simulated the spatial fishing behaviour of individual recreational and charter fishing vessels. This model simulates the movement, reef selection processes, and fishing activities of individual vessels – each of which has its own preferences, efficiencies, perspective, accumulated knowledge (with a degrading memory if a site is not visited for a length of time), learning and history (port/ramp of origin); responding to their situation using a rule based model of the decision-making processes. Decisions are based on fishing conditions (e.g. catch rates on individual reefs) and management arrangements (e.g. area and seasonal closures). Progressively discounting historical catches, the effort allocation model looks to maximise expected catch per unit effort and responds to the more recent experiences and personal information (which out weighs historical information or fleet-wide experience). A small level of exploratory fishing is allowed, but vessels are largely constrained to fish at locations they have fished in the past. If bag limits are in place any fish caught in excess of that limit are released after capture. Shore based fishing was done in a similar way but was only allowed from a list of shoreline fishing locations (e.g. camp sites).

The model was parameterised with biological and catch data from the Department of Fisheries Western Australia, with little to no fishing assumed to have occurred before 1965.

As the model is based on the adaptive management cycle, fundamental to the approach is the identification and representation of stakeholder objectives. This makes stakeholder engagement essential for the definition and acceptance of credible management objectives and strategies that represent the divergent interests of the different user groups. Stakeholder workshops are used to elicit specific operational management objectives, associated performance measures and management strategies. As this was a recreational fishery only ecological and social objectives were identified for the Ningaloo ELFSim modelling exercise (Table A2), each with a performance target and a measure of tolerance or acceptance that the indicator must achieve (specified as a probability).

Management strategies evaluated included:

1. spatial management: whether to use then current or an increased network of marine sanctuaries;
2. fishing access: allowing (or not) fishing to occur from shore in sanctuaries;
3. effort levels: maintaining then current recreational effort, (presumably through a licensing platform), or allowing it to increase in connection with projected increases in visitor numbers in the region;
4. quotas: whether to implement an annual total allowable catch (TAC) of 38 t, or to simply focus on input controls;

5. education: implementing an educational program, aimed at reducing infringement into closed areas and informally reducing the bag limit by encouraging a catch and release style of fishing;
6. enforcement: whether to rely solely on ramp and roadside checks or to have a monitoring vessel patrol the coast;

General bag limits and minimum legal sizes were used in all simulations, as the fisheries department had ruled out changes to these regulations.

To capture variation in external drivers and system context the simulations were repeated under "stable" conditions and in cases where there were environmental pressures as a result of climate change, an environmental catastrophe (e.g. large cyclone), infrastructure (ramp and road) upgrades allowing for greater fisher access and significant technology creep increasing catchability or leading to a wider footprint of effort (e.g. if fishers moved to bigger and more powerful boats).

The results of the simulations pinpointed the important features of the biology and human exploitation that were driving change in the Ningaloo system. The results also indicated that under current environmental and use conditions, the management strategy that best achieved the ecological objectives was the preclusion of inshore fishing in sanctuaries in combination with the introduction of a TAC. Increasing sanctuary size did increase the biomass conserved, but in the absence of reduced fishing pressure still saw reductions in biomass outside of the sanctuaries. Stopping fishing in sanctuaries and introducing a TAC also saw the best performance in terms of CPUE, but failed to meet the social objective of landing a high proportion of trophy sized (large) fish; only strategies resulting in high catch serviced that objective (at least in the short term). This pattern was similar across many indicators, with the strategies that performed well in terms of ecological objectives doing less well on the social objectives.

The modelling work drove home to stakeholders that while sanctuaries can be useful in controlling a possible increase in fishing pressures, they are not particularly effective in dealing with potentially impending environmental change. Only control of catch, or even effort (if technological creep can be controlled), was capable of doing this. Moreover, the modelling demonstrated that if environmental change impacts upon natural mortality rates that even in the absence of fishing it is possible that the population would never recover to historic unfished biomass level. Discussion around the model results was also lively when it came to socially conditioned management options, such as self imposed "wilderness fishing" bag limits (which had performed well in the NTDM) or catch and release fishing, both of which were attractive to the local community. Regulators were sceptical as to the effectiveness of such options, which rely on socially enforced compliance, in a place with such a high transient population.

Shuttle model – ScenarioLab

ScenarioLab (Boschetti et al 2010) is based on two principles: (i) the evaluation of a modelling outcome is subjective and contextual, with different users judging an outcome based on their expectations, needs, assumptions and expertise; and (ii) that humans find it easier to express relative judgments (relative performance of scenarios in comparison with each other) than absolute ones (e.g. in the form of quantified score).

ScenarioLab was developed to allow users to control and evaluate model runs in parallel and to direct future modelling iterations. This meant that ScenarioLab was graphical user interface GUI oriented and designed to

- be comfortably controlled by non-expert modellers;
- have fast execution times;
- provide a flexible way to define the suitability of a strategy outcome; and
- allow modification of goals at any point (e.g. in response to information provided and workshop discussions).

The GUI was fed by a simulation model (representing the behaviour of the socio-ecological system) and could be supplemented by an optimisation routine (a genetic algorithm). Figure S1 represents the typical workflow: the user adjusting the parameter settings for the simulation model, in order to explore management options and their effects; judging the output according to criteria (which may be subjective); exploring those options in detail; or expanding the exploration via an optimisation routine that automatically works through the space and provides new potential management scenarios for further evaluation. For Ningaloo the socio-ecological system was the reef and recreational fishers using it (commercial fishing is banned within the confines of the marine park) and the aim of the model exploration was to devise a set of fishing regulations that would ensure a sustainable future for the park; preferably without severe reductions in recreational fishing, which currently represents one of the main drivers for local tourism.

The simulation model goes beyond the single species of ELFSim to include in simple 5 group foodweb: a lower trophic level prey (the basal food source); 3 intermediate species (two of which are targeted by recreational fishing); and a top predator. The non-target intermediate species and the top predator could be taken as bycatch by the recreational fishers. While a gross simplification of reality (constrained for the sake of computational speed) the simple web does include the main predator-prey, competitor interactions which can lead to counter intuitive outcomes of management due to indirect effects. This food web was implemented in each of the spatial zones used to define the model's spatial domain (Figure S1).

A simple fishing sub-model used including fishing behaviour such as information sharing, gear selection, the choice of target species and basing effort allocation on maximising expected profit (in terms of catch versus costs outlaid to reach the location), based on learning and past records of catches per zone. Fisheries regulations were also represented, including: the extent of sanctuary zones, the number of fishing licences allowed, bag limits, and legal minimum and maximum length for the two main target species spangled emperor and chinaman cod (*Epinephelus rivulatus*). For each regulation option chosen by the user the model is run under 3 alternative ecological parameterisations, so that the user gets some sense of how uncertainty due to the lack of precise biological data, as well as the inherent uncertainty of biological and ecological processes, can influence lead to variable outcomes. Inexperienced users need to learn to expect variability in the modelled response even given precisely defined fishery regulations.

After the simulations are complete an evaluation page is launched by the GUI, showing three panels. The first (top) panel contains plots of biomass and catch for each set of runs of the simulation model (with the species identity and location chosen by the user); a second panel presents the best outcome across all simulations run so far (based on user rankings of the biomass and catch plots in the top panel in the current and previous iterations of the simulation); and a third panel is a menu allowing the user to summarise current results, initiate new simulations or start an assisted search using the genetic algorithm (with the user providing feedback to the algorithm, and effectively training it, on good versus bad outcomes via the ‘ranking’ option). Note that the rankings are user defined and can be personal subjective choices, or (in a workshop setting) the outcome of discussions and joint choices.

ScenarioLab was not used to provide formal analysis of the Ningaloo system, but acted as a multifunction platform. It simultaneously allowed for:

- exploration of the behaviour of the simulation model (letting users come to grips with the dynamics of a simple foodweb);
- numerical optimisation to identify the best performing regulatory options given the user defined rankings (objectives);
- participatory modelling, with the modelling acting as an avenue for communication around the management problem; and
- a teaching tool that can help people little used to modelling and complex systems how to deal with models and how to think about issues associated with an interconnected socio-ecological system.

This flexibility was a major strength of the approach as it allowed people who thought of themselves as non-modellers to combine different approaches (e.g. human-driven optimisation and more formal quantitative model exploration) in a way they felt comfortable with, which facilitated more rapid learning without getting into the jargon of global versus local optimisations (etc). The multifaceted nature of the platform also allowed experience modellers to lead new users through model exploration, showing how model outputs relate to the input parameters. Similarly facilitators used ScenarioLab to assist discussions around defining management strategies and objectives to be used with the other Ningaloo models. With the model as a talking point potentially diverging views can be given a hearing without prejudice.

Shuttle model – Ecopath with Ecosim

Ecopath with Ecosim (EwE) (Christensen 2011) is a widely used modelling platform which was originally developed to explore marine food webs and the potential consequences of fishing or environmental disturbances. The Ningaloo-EwE implementation uses all three of the main components of the software - the trophic mass balance module (Ecopath); the temporally dynamic modelling module (Ecosim) that takes the Ecopath values as initial conditions and runs it forward under fishing or environmental drivers; and the spatial module (Ecospace), which replicates Ecosim models over a spatial map grid to allow exploration of policies such as marine protected areas, while accounting for spatial dispersal/advection effects.

Ningaloo–EwE contains 53 ecological groups (Table A3), including both key terrestrial and marine components, ranging from primary producers (e.g. macrophytes, grasses or phytoplankton) to top predators (like demersal or pelagic sharks). The food web represents the major components pertinent to the human activities of interest (including conservation and exploitation). These species were selected based on abundance or biomass surveys of the system (i.e. dominant species that characterise the top 85-90% of the biomass in the system), network analysis of data on diets and habitat dependencies and expert ecological advice about system structure and key dynamics. The regular colouration clustering method (Johnson et al, 2003) was used to help identify useful levels of ecological aggregation when creating the ecological structure of the model. In the Gascoyne region the close connection of coastal terrestrial and marine activities meant that it was important to extend the ecological representation to terrestrial habitat (pasture and bush), domestic and feral livestock and key native fauna (macropods). The final food web structure formed the basis of the InVitro (whole-of-system) model (see below).

While EwE was originally written to consider the effects of fisheries it is relatively straightforward to extend it to include the impacts of a broader set of human activities. In Ningaloo-EwE the footprint of coastal agriculture, shipping, camping and tourism were included in addition to commercial, charter and recreational fishing. These activities were spatially structured so that output from NTDM could be used to drive Ecosim and Ecospace scenarios. This combination of relatively detailed trophic representations (including the potential for multiple age stages of things like turtles) with a pressure-response representation of human activities makes EwE a perfect shuttle-model; not only for looking into the potential ecological structure of the system, but also for introducing users to the use of system-level models. EwE is much easier and faster to parameterise and easier to learn. This made it a very useful tool for workshop settings were key stakeholder groups (e.g. staff form the Department of Environment, Department of Fisheries, planners, council members and conservation NGO representatives) could experiment with the model and collective talk through and trial management ideas. Conversations held during the workshops indicated that the participants came to appreciate that ecosystems do not respond in a linear fashion and are a lot more interconnected than they had previously appreciated.

For example, there is a lot of pressure to upgrade or build new infrastructure along the Ningaloo coastline to facilitate tourist and recreational access. The upgrade of a boat ramp near Exmouth (at Tantabiddi) was of interest to planners in Perth as well as locals in Exmouth. The proposed upgrade was to create a two lane ramp to reduce congestion. The greater size facilitates more and larger boats and EwE scenarios employing that level of visitation projected >35% drop in the local biomass of spangled emperor and ultimately a 66% drop in the catch rates of trophy fish. This highlighted to local planners that there can be a tradeoff between recreational experience and environmental outcomes. The boat ramp was already in the final stages of state planning steps however and has since been built. Fish surveys in the area have seen a >40% drop in the biomass of lethrinids, including spangled emperor (Russ Babcock, CSIRO, pers. com).

Whole-of-system model – Ningaloo InVitro

The InVitro modelling framework (Gray et al. 2006) is a hybrid agent-based approach that couples sub-models of processes at a range of scales using a scheduler similar to that found in modern multi-tasking operating systems. The flexibility of the approach facilitates the creation of models of the interrelation of the major processes of interest in coastal socioecological systems. As it brings together the main system components (physio-chemical, ecological, social and economic), it captures feedbacks in the system and helps highlight tradeoffs between the demands of different economic activities and the requirements for social and ecological sustainability.

The cross-scale capability is achieved by combining analytical, equation-based formulations for physical, chemical and lower trophic level processes with algorithmic, rule-based, formulations for higher trophic level processes and human activities and behaviour (Table A4 provides a list of the agent types used in Ningaloo-InVitro). Each sub-model acts at time and spatial scales appropriate to the processes it represents. For the Ningaloo implementation the model includes a food web containing 54 groups (those of EwE plus large lutjanids), detailed representation of several physical processes (e.g. oceanography, weather and climate, geomorphology, contaminants, etc.) and industry sub-model for commercial and recreational fisheries, tourism, oil and gas exploration and extraction, salt production, mariculture, coastal development and infrastructure, urban services and amenities, port operations, shipping, road transport, regional economics, catchment use (including agriculture), recreation and conservation (Fulton et al., 2011). Few models have attempted to represent so many industries to the same level of detail, but as the aim of the study was to support sustainable multiple use management (and the system was so interconnected) it proved necessary to represent each of the major industries dynamically and in some detail - e.g. their regulation, production and environmental impacts.

The effects of these human activities on the marine and coastal environments are represented using a combination of analytical decision models, response functions, specified rules, historical data and scenarios. Stochastic uncertainty is included in each of these options, capturing the natural ambiguity of human and animal behaviour, as well as missing or incorrect information and unpredictable events.

The final form of the model displayed a range of emergent properties, including seasonally shifting ecological community structure, the evolution of services and industry mixes, regional prosperity, urban development and levels of regulatory intervention. These shifts were driven by mechanistic adaptive behaviour routines included in the demographic and industry models. These behavioral rules attempted to meet acceptable levels of (rather than maximize) agent specific objectives using the agent's existing (imperfect) knowledge of the system and any available (also imperfect) information sources. Organizational level objectives included economic returns and the social license to operate, while individual operators or demographic actors made decisions defined in terms of income versus costs, the degree of social network support, access to recreational or lifestyle "amenities", and experience versus expectations (conditioned on attitude profiles). While both approaches included objectives in actuality there is a significant difference between modelling management bodies and modelling lower level agents (e.g. fishers, pastoralists or tourists). Management models can typically be constructed using real guidelines and regulation, which are explicit in detail and of public record. Modelling individuals is much more complex. Many things that influence behaviour at this level are not codified and the relevant individuals may be incapable or reluctant to pass on their motivations. Psychology and personality profiles can help, but their responses to novel regulations or situations remain highly uncertain.

Initial values for state variables are taken from data collected in the region as part of the broader Ningaloo research program (which ran 2005-2010), published literature, national databases (e.g. ABS Census data), annual reports by industry members, information from government departments (local, state and federal) or from expert advice (such as records from the local pastoralists) and regulatory documents (e.g. fisheries license conditions and council zoning plans).

Extensive interaction with groups interested in the Ningaloo-Exmouth region was used to elicit information on useful indicators that model should report, objectives for the region, and to define a wide range of management strategies and contextual scenarios that could describe alternative futures for the region. These strategies and scenarios were driven by key questions around the effects of a range of proposed developments (e.g. the existing Ningaloo Regional Coastal Strategy, to hypothetical developments based on new camp sites, a large resort, the paving of the Gnaraloo road and resident developments driven by the growth of the oil and gas industry in the region) and management strategies (including extended spatial management, alternative fishing regulations and increased education and enforcement).

The most likely future state of the system, should current trends continue unaltered (e.g. developments already underway), would see more tourists, residents and more investment from the resource sector – which results in more employment, more infrastructure development, more recreational activities (fishing and snorkelling), and more pressure on local resources (water and electricity) with noticeable impacts on the environment, fish stocks and catches (Figure S2). The greatest increase in the gross economy is when the system undergoes considerable development – either in the form of high industrial growth or a large resort development. Although if there is no associated expansion in infrastructure, services, housing then the local economic benefits are minimal, as any potential benefits of the industrial expansion are either channelled out of the region or prevented altogether by flying labourers in and out, bypassing the local economy. In contrast the strongest local life style outcomes are associated with scenarios where there is a sufficient initial development (or the promise of it) to deliver infrastructure to population centres, but further development is aborted or there are access failures (either via regulations that cap local population sizes and visitor numbers, or the failure to construct roads and sector specific infrastructure, such as boat-ramps); so the locals receive all the “life style” benefits while avoiding the substantial effects due to crowding, growing utility demands or environmental degradation.

Climate change impacts and the legacy of past use of the system means the ecosystem (in terms of biodiversity, habitat, iconic species and fish stocks) will continue to show some level of degradation for many decades, even with no further growth. Any form of heavy use of the region under the 2010 management arrangements leads to a degradation of the system. Although fish stocks can be conserved under modified management arrangements (e.g. modified bag limits), if these are stringently applied - otherwise increases in recreational fishing pressure (as a result of industrial development in the region) in conjunction with climate and ocean acidification impacts can overwhelm any positive changes due to altered management arrangements. Despite the area still being thought of as “remote and untouched” by many Australians, the model work indicates that unconstrained use of the system is no longer possible.

The regional future will be affected by global drivers, like climate change and external industrial development (e.g. in the neighboring Pilbara), but also by local intervention points (e.g. the availability of utilities and housing), sanctuary zone boundaries, opening or closing of specific infrastructure (e.g. boat ramps) and road access. While some of these drivers (e.g. the level of development and visitation, housing, access points, toilets and some of the environmental pressures) had already been identified by stakeholders familiar with regional issues, and aspects of the general InVitro results were evident in other smaller models of the system (see Jones et al., 2011; Little et al., 2011), the full extent of the potential interconnections were only evident once the system information was integrated and assessed in the InVitro model.

As a set the InVitro simulations highlighted the complex relationships between development and environmental status in the region. The fish stocks have already been depleted due to increasing fishing pressure (especially recreational pressure) over the last 20 years. The simulations clearly show that any further growth in this pressure leads further decline – with additional recreational pressure applied by oil and gas workers perhaps sufficient to cause a local collapse in some key target species (e.g. spangled emperor). However, without some form of development there is a significant risk of social issues for residents of the area, as younger generations would be apt to move outside the region and the remaining working age population turning over frequently (i.e. entering the region, working for a short period, and exiting again). Taken together these findings suggest that there is a direct conflict between economic and conservation objectives. Sustainable futures are possible, but typically only if they are focused on targeted growth (so there is not excess pressure on housing and utilities) and with significant changes to the regulations in place as of 2010; even then some components of the system may be very difficult to protect against the effects of climate change and ocean acidification (e.g. turtles who suffer as nesting beaches are inundated by storm surges on the back of sea level rise).

A valuable lesson for stakeholders from these results was that while the models can explore the implications of alternative proposals they will not “spit out” the best form of development. Instead, people interested in and responsible for the system (e.g. local shires) need to discuss options, to pose questions the model can help address.

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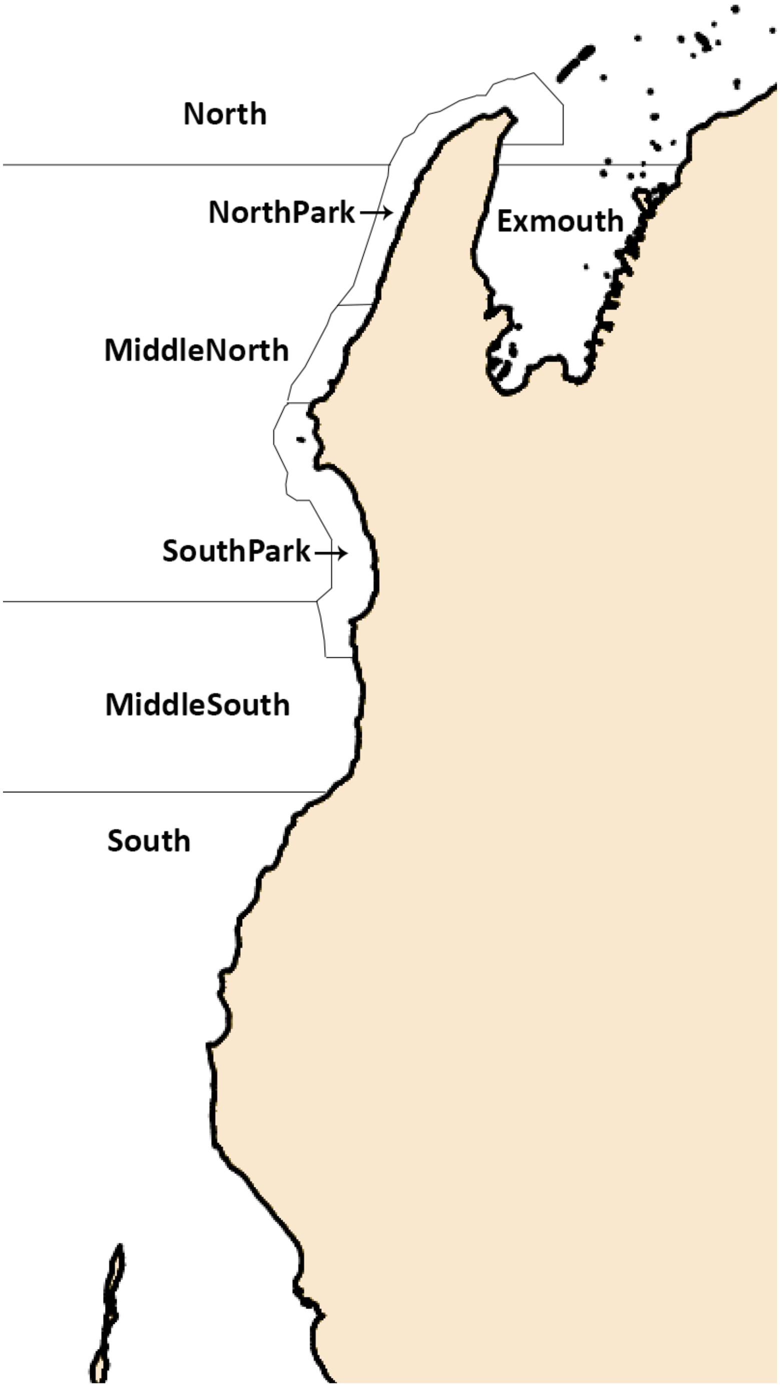
Supplementary Material - Figure Captions

Figure S1: Map of the spatial areas used in ScenarioLab.

Figure S2: Example output for Ningaloo-InVitro model – continued growth scenario (i.e. resource sector developments continue as planned) displayed in the 3 ways found to be most useful across the broad range of stakeholder backgrounds and preferences: (a) as a barplot of the magnitude of relative change; (b) as a radial plot; and (c) as change icons. The size of the change shown in the bar and radial plots is the magnitude of change (so +2 means double the original level whereas -2 is half the original level); this scale was used so that change could be considered symmetrically (if a simple ratio or percent change is used then it is possible to get very large increases in one indicator (e.g. 1000% increase), which dwarfed the possible declines in another (it is not possible to decline more than 100% as then that system feature is completely gone)). In the radial plot the black circle indicates the zero mark (i.e. no change vs 2010), with values further out than that zero mark being better outcomes and inwards worse and for turtles the solid line indicates the case without fox baiting and the dashed line indicates the value with fox baiting maintained, note in some cases it makes little difference.

Figure S1



North
NorthPark
Exmouth
MiddleNorth
SouthPark
MiddleSouth
South

Figure S2

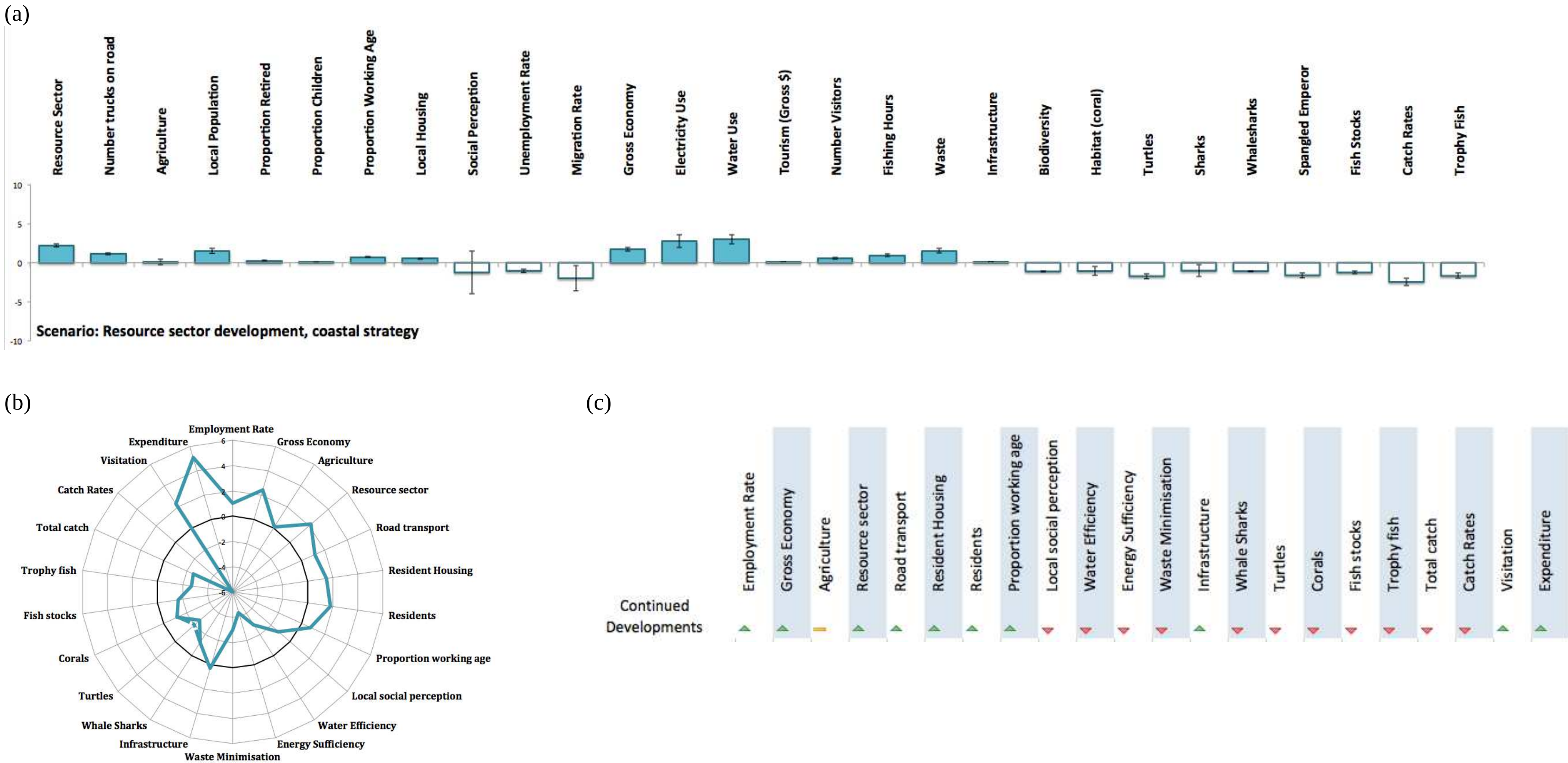

(a)
Resource Sector
Number trucks on road
Agriculture
Local Population
Proportion Retired
Proportion Children
Proportion Working Age
Local Housing
Social Perception
Unemployment Rate
Migration Rate
Gross Economy
Electricity Use
Water Use
Tourism (Gross $)
Number Visitors
Fishing Hours
Waste
Infrastructure
Biodiversity
Habitat (coral)
Turtles
Sharks
Whalesharks
Spangled Emperor
Fish Stocks
Catch Rates
Trophy Fish
10
5
0
-5
-10
Scenario: Resource sector development, coastal strategy
(b)
Employment Rate
Gross Economy
Agriculture
Resource sector
Road transport
Resident Housing
Residents
Proportion working age
Local social perception
Water Efficiency
Energy Sufficiency
Waste Minimisation
Infrastructure
Whale Sharks
Turtles
Corals
Fish stocks
Trophy fish
Total catch
Catch Rates
Visitation
Expenditure
6
4
2
0
-2
-4
-6
(c)
Employment Rate
Gross Economy
Agriculture
Resource sector
Road transport
Resident Housing
Residents
Proportion working age
Local social perception
Water Efficiency
Energy Sufficiency
Waste Minimisation
Infrastructure
Whale Sharks
Turtles
Corals
Fish stocks
Trophy fish
Total catch
Catch Rates
Visitation
Expenditure
Continued Developments

Table A1: Four archetype scenarios developed for NTDM by workshop participants.

Scenario	**Description**
Scenario 1: A large increase in visitor numbers (with and without market control of visitor type)	Addresses the impacts of growth in visitor numbers and, if you can control growth in particular market segments (or visitor types, for example in terms of a particular accommodation type) and for particular activities, what will be the costs and benefits to the environment, community and economy?
Scenario 2: Changes to governance	Addresses questions about governance raised in particular in Exmouth and Coral Bay. If there are changes in governance over accommodation and activities, what will be the impacts on tourism? Will they be substantial or minor? Particular concerns were over tourism license tenure and land release (zoning).
Scenario 3: Varied rates and uncertainties of growth	Addresses a second aspect of growth. What if there are unexpected interruptions in tourism numbers? What are the best strategies for a fast recovery following an unexpected event or variations in visitor numbers to the region? The scenario also addresses the issue of capacity constraints by testing a variety of land release policies.
Scenario 4: Green technologies and development strategies	Addresses how adoption of green technologies could affect the capacities of the town sites to expand in the short, medium and long term, given current constraints on water, electricity and waste water, and the spatial allocation of tourists. It also addresses the costs and savings over different time periods.

Table A2: Management objectives for the recreational fishery on Ningaloo reef. The general levels of landed catch, discards, catch variability and the number of fishing trips ending without catching a fish were also tracked, but were not associated with a specific management objective.

Objective	**Rule**
Ecological objectives	
Spawning biomass in sanctuaries	Should be above 75% of pre-exploitation spawning biomass 75% of the time
Average age in the population	Should equal unexploited average age ± 1 year 75% of the time
Average length in the population	Should equal unexploited average length ± 10cm 75% of the time
Spawning biomass outside sanctuaries	Should be greater than spawning biomass in 2007
Spawning biomass	Should be greater than 40% of the pre-exploitation spawning biomass 75% of the time
Social objectives	
CPUE (of landings and discards together, i.e. true catch)	Should be greater than CPUE (for true catch) in 2007 75% of the time.
Size (length) of catch	25% of the catch should be greater than 50cm in length 75% of the time

Table A3: Functional groups and human activities included in the Ningaloo Ecopath with Ecosim (EwE) model. Note adult = ad, juvenile = juv.

Functional Groups		**Human Activities**	**Carnarvon**	**South coast**	**Coral Bay**	**Pastoral stations**	**North coast**	**Bundegai**	**Exmouth Gulf**	**Murions**
Terrestrial fauna	*Terrestrial flora*	*Tourism activities*								
Foxes	Buffell grass	Whale watching			Y		Y		Y	
Marsupial grazers	Native grass	Snorkelling		Y	Y		Y	Y		Y
Goats and sheep		Dune activities*	Y	Y	Y	Y	Y	Y	Y	Y
Ospreys		Camping	Y	Y	Y	Y	Y		Y	
Coastal seabird										
Primary producers	*Habitat*	*Other activities*								
Macrophytes	Large Coral	Agriculture	Y	Y		Y				
Phytoplankton	Small Coral	Boat strikes	Y		Y		Y	Y	Y	
	Coral Spawn	Fox baiting		Y	Y	Y	Y	Y	Y	
Invertebrates	*Reef fish*	*Fisheries*								
Squid	Lethrinids adults	Charter	Y		Y		Y		Y	Y
Octopus	Lethrinids juv	Recreational boating	Y		Y	Y	Y	Y	Y	Y
Kingprawn	*Lethrinus nebulosus* (ad)	Shoreline recfishing	Y	Y	Y	Y	Y	Y	Y	
Bananaprawn	*Lethrinus nebulosus* (juv)	Commercial-finfish	Y	Y						
Lobster	Small lutjanids	Prawn trawl							Y	
Crabs	Serranids									
Shells	Tuskfish									
Urchins	Saurids									
Benthos	Nemipterids									
Zooplankton	Herbivorous fish									
	Small reef fish									
Other fish	*Sharks and raus*									
Shallow demersal fish	Demersal sharks									
Trevallies	Pelagic sharks									
Mackerels	Manta Rays									
Queenfish										
Tuna and billfish										
Reef Associated										
Pelagics										
Small pelagics										
Marine Mammals	*Turtles*									
Dolphins	Adult Turtles									
Whales	Hatchlings									
Whale sharks	Turtle eggs									
Dugongs										
Detritus										
Litter										
Discards										
Detritus										

* Such as quadbike tours or hikes

Table A4: List of agent types used in Ningaloo-InVitro. For agents listed as using nodes, see nodes marked on Figure 1.

Agent	Agent-type
bathymetry, geomorphology	static or series of data layers
light, wind, currents, temperature, rainfall, turbidity	spatial time series
detritus	gridded
coral, seagrass, algae, sponges	gridded meta-population (cellular automata)
coral spawn	gridded (populated by coral agent)
nutrients, phytoplankton, zooplankton	gridded differential equations (standard nutrient-phytoplankton-zooplankton model)
commercial prawns, small reef fish, tusk fish, small lutjanids, large lutjanids, herbivorous fish, serranids, lethrinids, saurids, nemipterids, other demersal fish, small pelagic fish, large pelagic fish, tuna and billfish, octopus, squid, mackerel, queenfish, trevallies, crabs, urchins, other benthos, seabirds	meta-population (age, size and spatially structured)
Lethrinous nebulous	meta-population in combination with individual based model (for oldest age classes)
lobster	multiple linked meta-population models (per life history stage)
manta rays, demersal sharks, pelagic sharks, whale sharks, whales, dolphins, dugong	individual based model (using small groups per "individual")
turtles	meta-population for eggs and juveniles, switching to individual based for adults (using small groups per "individual")
pasture	gridded rangeland differential equations, including soil layers
sheep, goats, kangaroos	individual based livestock model
pastoralists (farmers)	individual based model (with personality type and social network)
pastoral stations	polygon data layer (wit homestead node)
shoreline recreational fishers	tithe applied on spatial nodes (fishing sites) with magnitude dictated by (i) distance and (ii) resident and tourism models
charter boat recreational fishers	individual based model (kalman filter used for decision updating), based out of home ports
small boat recreational fishers	individual based model (numbers dictated by resident and tourism models), launched from access points along the coast (e.g. boat ramps)
commercial fishers (prawn, finfish)	operators represented by individual based model, with associated survey vessel (fisheries surveys are done pre season for prawn fishery)
fisheries statistics reporting	table (temporal tally per species per vessel)
fisheries management	region wide rule set that sets quotas, gear restrictions, size limits and spatial zoning
spotter plane	grid, cells filled in with biomass/abundance values of target species if searched (defined on search patterns associated

Agent	Agent-type
	with either the prawn fishery or the dive boats, depending on what they are servicing)
oil and gas exploration and extraction	differential equation model (per company)
oil spill	times series of footprints (defined by a separate connectivity model)
trucking	differential equation model (per company)
shipping	individual based model (travelling between way-points, volume based on level of industry and market scenarios)
port	rule based (level of use and need for extension driven by demand from industries)
petrol prices	time series
road network	data layer (that can be updated based on scenario details)
tourism tours	individual based model
tourism accommodation	rule based (capacity set by development and build scenario), use set by tourism demand
tourists	individual based model (where an “individual” depends on the tourist group type – individual, family group, tour group)
tourism management	region wide rule set that sets restrictions and spatial zoning
dive boats	individual based model
regional economy	input-output table
urban settlements	nodes, with each node gridded (current occupancy, zoning)
human resident population	1-to-1 individual based model (gender, age, training, employment, housing, family and social connections)
monitoring (by management or researchers)	grid, cells filled in based on surveys)