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Knowledge Integration and Management Strategy Evaluation (MSE) Modelling

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WAMSI Kimberley Marine Research Program

Report

Project 2.2.8

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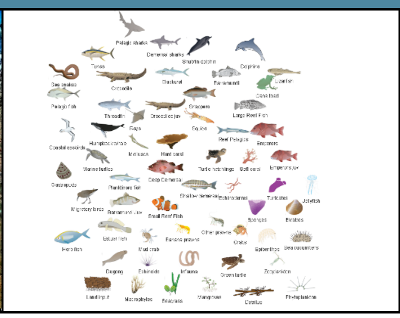

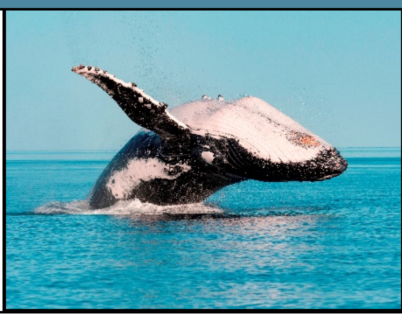

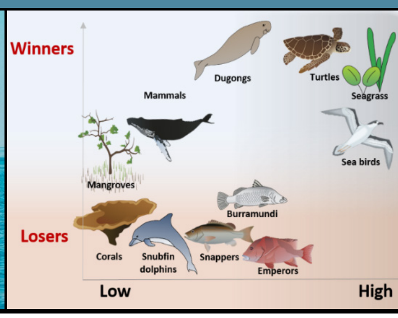

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ALCES
An Integrated Landscape Management Tool

WAMSI Kimberley Marine Research Program

Initiated with the support of the State Government, the Kimberley Marine Research Program is co-invested by the WAMSI partners to provide regional understanding and baseline knowledge about the Kimberley marine environment. The program has been created in response to the extraordinary, unspoilt wilderness value of the Kimberley and increasing pressure for development in this region. The purpose is to provide science based information to support decision making in relation to the Kimberley marine park network, other conservation activities and future development proposals.

Front cover images (L-R)

Image 1: Satellite image of the Kimberley coastline (Image: Landgate)

Image 2: Ecopath with Ecosim foodweb (Source: Fabio Boschetti, CSIRO)

Image 3: Humpback Whale (Image: Pam Osborn)

Image 4: Summary of result of scenario analysis, showing 'winners' and 'loser' species as well the species wit highest and lowest sensitivity to scenario variability (Source: Fabio Boschetti, CSIRO)

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Author Contributions: FB has led the overall project management and stakeholder engagement. HLM, CB and JS have parameterised the EwE model. MH and BS have parameterised the ALCES model.

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Contents

Executive Summary

The Kimberley Marine Research Program (KMRP) Project 2.2.8 represents the first attempt to integrate a large amount of data, knowledge and state-of-the-art understanding of the bio-physical, ecological and social processes affecting the Kimberley marine environment drawing in new information generated by several of the KMRP projects within the Western Australian Marine Science Institution (WAMSI) program. This information was used to parameterise two computer models (ALCES and Ecopath with Ecosim [EwE]) to simulate land, coastal and marine processes.

A careful examination of a large volume of publications from the academic, private and public sectors allowed a number of climate and social economic development scenarios that the Kimberley region may experience in the decades to come to be developed. Computer simulations were used to test the Kimberley system's responses to these alternative scenarios under a number of management strategies including current and proposed marine parks under different options of zoning and multiple uses. Both the scenarios and management strategies were selected and agreed upon in consultation with a number of stakeholder groups, including the Department of Biodiversity, Conservation and Attractions (formerly Department of Parks and Wildlife), The Kimberley Development Commission, WA Department of State Development, Department of Primary Industries and Resources (formerly Department of Fisheries), Department of Mine, Industry Regulation and Safety (formerly WA Department of Mines and Petroleum), among others. The analysis of the impacts of these scenarios and management strategies sheds light on a range of future states the Kimberley marine environment may experience during the 2015 to 2050 period.

Before the core results are summarised, it is important to remind the reader that a model simulation is not an absolute prediction (a 'prophecy') of how the Kimberley region will look in 2050. Rather, it is an attempt to say something of decision-making significance about how the system may respond to the specific conditions summarised in the scenarios and management strategies, which is consistent with our current scientific knowledge and our current understanding of how the Kimberley system functions. It follows that while insight on system behaviour gained from consideration of these scenarios can provide guidance on potential patterns of responses, care must be taken when considering circumstances outside the specifics of the scenarios and management strategies modelled and particular account must be made of the uncertainty in our current knowledge.

The outcome of this project is a very large set of simulation outputs representing the dynamical evolution of the land, coastal and marine environments over 35 years. This includes hundreds of regional maps and thousands of time series of environmental, social and economic indicators. All these results are now publically available and can be viewed at www.wamsi.org.au/research-site/modelling-future-kimberley-region.

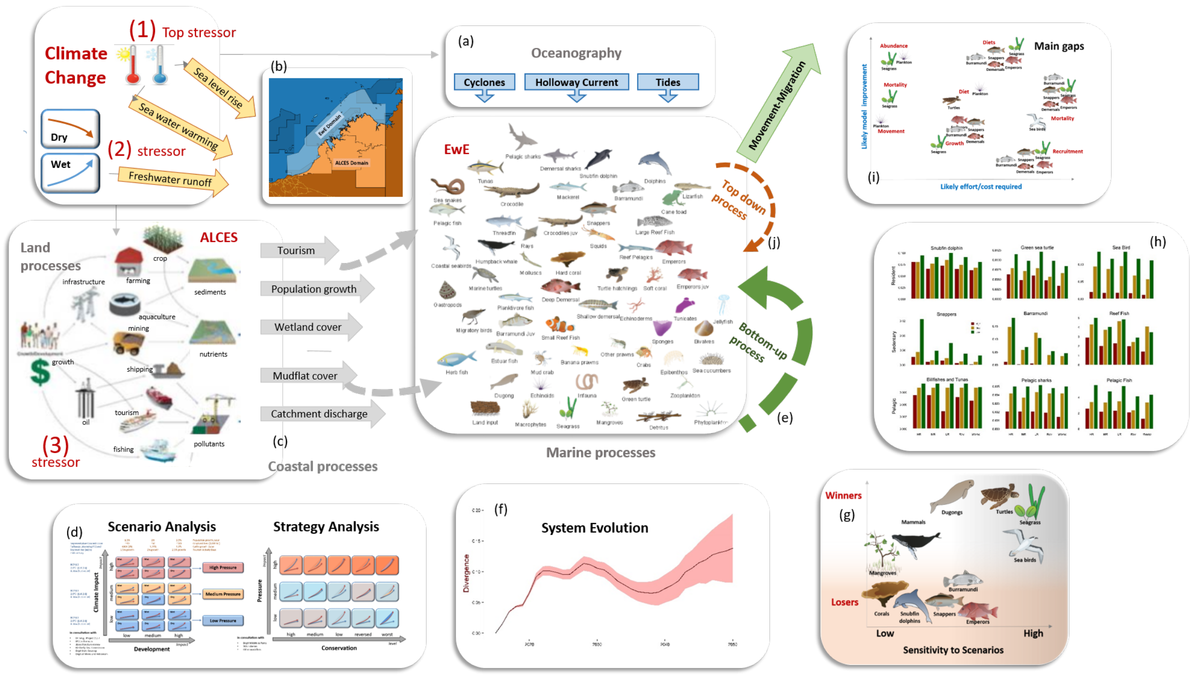


Figure 1. Conceptual model of the functioning of the Kimberley system, including the main result from this project.

This report summarises the approach taken to data collection and model implementation, the method employed to identify the scenarios and management strategies of interest, how we interpreted the models' results and the core messages of management significance as graphically captured in Figure 1.

Key Results and Implications for management

1. Functional groups and system indicators may respond differently to different climate and development pressures. By the year 2050, the state of some groups (e.g. seagrass, turtles, dugongs) and system indicators may vary dramatically from scenario to scenario, while others (e.g. corals, snubfin dolphins, mammals, mangroves) may show little variation (Figure 1, panel g, X axis).

   Implications for management. Groups and system indicators which are expected to be most sensitive to different climate and development pressures should have high priority for long-term monitoring for two reasons. First, this will improve our knowledge in key aspects of these groups' life history (such as changes in habitat range, recruitment, growth and survival rates). This will lead to better model parameterisation and thus an improved understanding of the very drivers of this sensitivity. Second, the sensitivity of some marine communities to climate change provides a good indicator for the early detection of system response which can help identify which, among the modelled scenarios, the system is heading towards.

2. Some functional groups (corals, snubfin dolphins, pelagic sharks) are consistently losers and others (seagrass, dugongs and turtles) consistently winners under a wide variety of scenarios, while other groups' success depends considerably on the precise scenario which may eventuate (Figure 1, panel g, Y axis);

   Implications for management. This result can provide managers with an indication of the expected direction and magnitude of a species' response to a specific scenario and thus the extent to which a management intervention targeted at a specific group is likely to succeed. However, this likelihood is also inherently linked to the target and scope of the intervention and cannot be evaluated without information about its purpose. If specific interventions are considered, the models presented in this work can be used to explore their potential impact. The models discussed in this report can incorporate new information and the feedback from monitoring, which is a core aspect in the Management Strategy Evaluation (MSE) process.

3. Whatever the final state of the system in 2050, we should not expect the system to transition linearly, or even monotonically, to such state over the coming decades. Rather, we should expect system level indicators, like total biomass and diversity, to display non-linear oscillatory behaviour. While the exact details and timing of these oscillations are largely uncertain, the general form is similar under all modelled scenarios. This leads us to conclude that this behaviour is due to internal system dynamics, rather than external forcing and as such deserves further investigation (Figure 1, panel f);

   Implications for management. This result highlights the importance of i) adopting a system view to management and ii) the potential impact of relative timing of system perturbations. Large changes in biomass distribution (change in both absolute and relative biomass of different species in a food web) can affect a food-web's stability and resilience to pressure. It follows that the system's response to natural or man-made hazards of a given magnitude may change depending on the timing of these events in relation to the system's internal dynamics. Monitoring these system's properties is difficult since it requires information over a large number of functional group and over long time intervals. However, it can provide a deeper understating on the health and sustainability of the system, which could not be obtained by collating disparate observations.

4. The analysis of the difference between the end states of the system under different scenarios suggests that the modelled scenarios can be grouped into three main clusters and that the nature of these clusters is largely determined by climate forcing in the form of sea surface temperature rise. This confirms that, given current expectations about the ranges of climate and development pressures the region may experience, climate is likely to have a significantly larger impact than population growth and economic development on the final system state (Figure 1, panel d);

   Implications for management. The climate scenarios modelled in this work are the same as recommended by the Intergovernmental Panel on Climate Change (IPCC). These represent expected warming under different pathways of future anthropogenic CO2 emissions. While there is uncertainty on which pathway will materialise (as well as on the level of warming given this pathway), anthropogenic CO2 emissions change very slowly and their impact on the climate has a delayed response. This means that the likelihood of each modelled scenario to occur can be assessed in advance and will become better defined in the years to come. This has two implications: i) changes will occur smoothly, time for contingency planning is available and abrupt surprises are unlikely; on the other hand, ii) impact of management actions will also be slow and subject to system inertia, which recommends strategic, rather than reactive, management.

5. Careful analysis of model behaviour shows that the lower part of the food web is a key component in the functioning of the Kimberley marine system. Benthic primary production associated with seagrass and macroalgal assemblages provide food resources and shelter to diverse communities of invertebrates and finfishes (Figure 1, arrow e);

   Implications for management. It is important that the critical role played by seagrass and macroalgal assemblages is accounted for in the MPA planning and management to ensure these habitats have adequate protection.

6. The analysis of the available management options we have explored suggests that a 20% to 30% increase in Sanctuary Zone extension (compared to today) would benefit the system total biomass under most scenarios. These results also suggest that sanctuary zones within the marine parks are an important tool to meet conservation objectives. More specifically, this has a number of implications:

   Implications for management.

   - Sanctuary Zone extension can be particularly beneficial to exploited species such as Barramundi, Snapper and Emperors (Figure 1, panel h).
   - The effectiveness of the management strategies varies between functional groups, being more effective for relatively sedentary species such as reef fishes than for migratory species such as sharks, billfishes and tunas (Figure 1, panel h).

Key residual knowledge gaps and Implications for management

Despite the advancements resulting from this research, large knowledge gaps still exist which if addressed could considerably improve this modelling work. In order of highest priority:

1. Better characterisation of the dynamics of primary producers is needed, given i) the strong bottom up structure of the Kimberley food web and ii) their role as main driver of the oscillations in the system discussed above.

   Implications for management. The parameterisation of these groups in the EwE model, our understanding of their interaction and their inter-seasonal and inter-annual natural variability are largely uncertain. Addressing this gap could considerably improve the reliability of the model results. This highlights the need to establish a long-term monitoring program for the habitat forming species, like seagrass and mangroves.

2. Information about distribution, biology and population dynamics of some finfish groups, which at the moment is largely unknown, is needed;

   Implications for management. Climate change is causing fish species to shift their phenology, or the timing of recurring events such as migration and spawning. If these shifts occur in the Kimberley, they can result in changes in the distribution of habitat and food resources, which can affect population dynamics and ecosystem functions. The model results highlighted some important top-down interactions in the ecosystem (Figure 1, arrow j) associated mainly with coastal predatory fishes that support important recreational fisheries in the Kimberly (e.g. Emperors, Snappers, and large reef fishes). Long-term monitoring of these populations will provide useful information on how these target species respond to climate change and other impacts in the Kimberley.

3. The impact of climate change on the biology and metabolism of marine species, in particular corals, seagrass, plankton and fish will have important Implications for how adaptable these species may be to climate change. This information is currently missing not only in relation to the Kimberley region but also in the scientific literature at large.

   Implications for management. This information is likely to come from both laboratory experiments under controlled conditions and field observations, both local and global. Given the unique nature of the Kimberley marine ecosystem, local observations and laboratory experiments recreating specific conditions likely to be experienced in the Kimberley marine system in the coming years will be fundamental to our understanding and anticipation of likely changes to species and ecosystem functioning. This information can then be added to a growing literature of global observations and can significantly improve the reliability of modelled scenarios.

Products and tools

In addition to the results of management significance described above, this project also leaves an important legacy to future scientific and management work in the region. This includes:

1. Two fully parameterised models which can be used to answer further specific scientific and management questions. These models could be readily updated should further information, knowledge and data become available; an activity involving a fraction of the effort it has taken to develop them in the first place;
2. The model parameterisation (also made publicly available) represents the most accurate snapshot of the Kimberley system in 2015 (start year of the simulations). It includes all information made available to the project, from within and outside the WAMSI program, including an assessment of its uncertainty;
3. A conceptual model of the functioning of the Kimberley land, coastal and marine system, as captured graphically in Figure 20. This conceptual model may help stakeholders and local managers understand how the management of different components and processes in the region fits with the overall aspiration of the WAMSI program as well as how further knowledge and information may improve such understanding.

1. Introduction

Meaningful decision-making requires prediction. The important question is: What type of prediction best supports decision-making? Computer models allow us to integrate a large amount of data, knowledge and state-of-the-art understanding of social, economic and ecological processes while accounting for uncertainty and missing information. More importantly, models are the best tools we currently have to explore the possible consequences between a large number of natural processes and human actions. They help us to understand a system and make better decisions.

Management decisions for the Kimberley marine environment (Western Australia) look to find a compromise between protecting one of the few remaining near pristine coastal and marine environments in the world, while supporting the region's social and economic development agenda. The future of the Kimberley system will be determined by the interaction between many forces (economic, ecological and social processes, climate change, human population dynamics, resource extraction and others) as well as by the management strategies we implement.

Prior to the Kimberley Marine Research Program (KMRP), very little was known about how this socio-ecological system functions and as a result the support science could provide to decision making was limited. KMRP Project 2.2.8 has integrated new knowledge gathered as part of the KMRP into two computer models (ALCES and Ecopath with Ecosim [EwE]) to simulate land, coastal and marine processes into the future.

In this project we have identified and then modelled, the future of the Kimberley, the possible scenarios and the increasing pressures that each scenario may generate in the marine environment. KMRP Project 2.2.8 aimed to achieve the following objectives:

1) To improve our understanding of the likely impacts of increasing human pressure and climate change at a regional scale;
2) To integrate the knowledge and information generated by other projects into a unified modelling framework;
3) To employ the Management Strategy Evaluation framework to engage key stakeholders in designing and imaging likely and desired regional futures and explore the consequence of different trends and management options; and
4) To communicate the modelling results to key decision makers in such a way that their results are understood and can be incorporated into the decision making process

In this section we summarise the overall modelling approach used in this work, which consisted of exploring the possible and desired futures of the Kimberley region as determined in consultation with a number of stakeholders and interested parties.

Modelling is an important tool to support and inform decision-making, but has both strengths and limitations. The contribution that modelling tools can make to the decision making process can be enhanced by having a clear understanding of how these tools can be utilised.

Modelling is a process of asking questions and answering these questions to the best of our knowledge. Crucially, modelling helps clarify the extent of this very knowledge. Understanding how the process of asking-answering questions via modelling enfolds can clarify how modelling can contribute to decision-making. Here we describe this process.

1.1 Why computer models?

Meaningful decision-making requires prediction. In the absence of guiding information, without some rough, possibly vague, guesses at the consequences of different available decisions, we have no reason to prefer one decision over another. The availability of structured information (i.e. a model) can provide insight and guidance and act to clarify the consequences and desirability of specific decisions. Consequently, the important question is what type of model (prediction) best supports decision-making.

We need to study the Kimberley system as a whole, addressing specifically the cumulative effects of various human uses and activities. This is a challenging task. There is a high level of uncertainty about how the Kimberley system works and what future stressors it may encounter. Uncertainty is not the only challenge. The future of the Kimberley system will be determined by the interaction between many forces: the economy, ecological processes, social development, climate change, human population dynamics, resource extraction and many others. Notice that these processes influence one another, leading to potentially very complex dynamics.

A vast literature agrees that humans, including very bright individuals and experts, can be very poor at predicting how systems behave when they undergo complex dynamics (Dorner 1996, Moxnes 1998, 2000, Sweeney & Sterman 2000, Halford et al. 2005, Moxnes & Saysel 2009). In fact, most people fail even when they analyse embarrassingly simple systems (Sterman 2008, Cronin et al. 2009). Computer models help us reduce the extent of these mistakes. In general, model predictions are more reliable than the ones we (experts included) may produce without models. Of course, models will not precisely predict what will happen to the system. Rather, they are designed to say something physically and ecologically meaningful, and dynamically consistent about general trends and responses, providing guidance based on best available information on what may happen to the system should it undergo specific pressures.

Our models are not microcosms. They are neither virtual laboratories nor digital representations of the immense complexity and richness of the Kimberly region. They are tools which allow us to integrate the available knowledge, include the state-of-the-art understanding of social, economic and ecological processes and account for uncertainty and missing information. We can use them to explore the possible consequence of different human decisions and actions, circumventing many of the well-known limitations of the human brain at handling complex dynamics and information. They help us understand the system and make better decision.

1.2 What do we mean by 'future' and what can be said about it?

1.2.1 What do we mean by ‘future’?

Here a ‘future’ is what may happen to the Kimberley region up to the year 2050. This will depend on i) how the Kimberley system works (model specification), ii) what events may occur (development scenario) and iii) what we do and how we react (management strategy) to these events. We define these as follow:

- As we do not know precisely how the Kimberley system works, a number of hypotheses were developed. Each working hypothesis resulted in a model specification which defined how the EwE and ALCES models run and represents a snapshot of how we believe the system is and works now. Uncertainty is represented via alternative model specifications, which are implemented by varying the model structure, input parameters and specific model components;
- A development scenario defines what event(s) may occur or how different trends may play out into the future. Unlike model specifications, scenarios describe events or processes considered external to the Kimberley system, like extreme natural events, demographic changes, global and national economic crises, industrial and infrastructure development, etc. Scenarios are used to set the external drivers of the models (e.g. the pattern of increase in temperature from predicted global warming applied in the model);
- A management strategy is a course of action, policy or intervention we can use to respond to various scenarios. It constrains or promotes specific human activities to achieve agreed environmental, social or economic objectives. These strategies define the rules applied to human activities in the model and their performance is judged in terms of whether or not (or to what degree) the objectives are met; and
- A future is an estimation of what the system may look like several years down the track, according to the model. It results from the interplay between model specifications, scenarios and strategies.

1.2.2 Asking questions about the 'future'

What kinds of questions can we ask about the future? We cannot ask absolute questions like "what will happen?" Among other reasons, this is because the future is not pre-determined and our actions will affect it. We can ask hypothetical or conditional questions, like "if this event occurs, then what may the future look like?' This is a more desirable approach to describing the "future" because it defines the events and conditions which may affect it.

We use models to answer these conditional questions and the elements we described above fit nicely into this question-answer structure. The scenario, management strategy and model description represent the conditioning of the question (If the scenario occurs and we implement this management strategy and the system works as the model says…) and the model provides the conditional answer (…then the future may look like the model output).

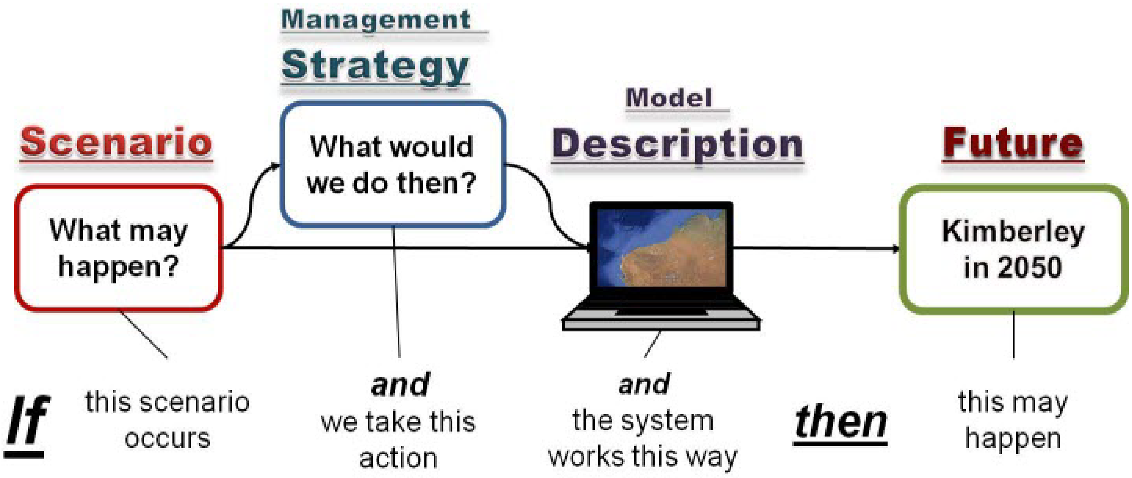


Figure 2. Modelling is like asking the following question: 'If a specific event occurs (scenario) and we take this action (strategy) and the system works this way (model description), then what may happen?'. The model output is a possible answer to the question.

1.3 The Management Strategy Evaluation

'Management Strategy Evaluation' is a fairly impressive sounding term for a simple idea – we should evaluate how well management strategies deliver on the desired objectives. This sounds obvious, but in actuality is rarely done, in part because answers are almost never definite or conclusive. In the real world, answers to complex problems almost inevitably lead to more questions. This is because the process of answering the initial questions leads to better system understanding and new ideas about alternative management strategies. This concept is inherited from Adaptive Management, which has a well-established tradition in environmental conservation. Adaptive Management acknowledges that our actions affect the system we manage, that actions often have unintended consequences and that as a result management strategies need to be reassessed, and possibly revised, when more information becomes available. Management Strategy Evaluation speeds up that learning process, allowing for appreciation of potential outcomes and unintended consequences without having to live through the experience in reality. This means many alternatives can be explored and (especially) in the context of climate change or once-off decisions learning can be sped up.

Here we have employed the concept of Management Strategy Evaluation (MSE) in two ways. First, in its most basic form, the concept has been used to structure the model-based examination of scenarios and strategies, so that the resulting information can provide information in support of decision making. Secondly, we used

MSE to manage this project by having the initial model results and initial stakeholder discussions refine the questions the models need to answer.

2. The models

In KMRP 2.2.8, two computer models were used: ALCES and Ecopath with Ecosim (EwE). The purpose of using these models is to integrate existing and new knowledge about the Kimberley system and to provide an estimation of the likely impacts of different stressors on the land (ALCES) and marine (EwE) environments.

Before the models can start answering management questions, they need to be set up for the specific needs of a given task. This involved three interrelated steps:

1) Choosing the model domain (this defines what is 'internal' vs 'external' to our system);
2) Defining the models' structure (this defines what components of the system we include); and
3) Parameterising the models (we need to provide the model information about the system).

These steps require expertise and technical knowledge but also experience and good judgement. They define what is often called 'the art of modelling'. To make sure that the ALCES and EwE model can communicate, steps 1 and 2 need to account for the needs of both models. A detailed description of ALCES and EwE domains and structure can be found at http://www.per.marine.csiro.au/staff/Fabio.Boschetti//KimberleyMSE/EwE.htm and http://www.per.marine.csiro.au/staff/Fabio.Boschetti//KimberleyMSE/PDF/Alces%20Synopsis.pdf.

Step 3 (parameterisation of the models) deserves specific consideration. A model parameterisation takes currently available information about the state of the system of interest (i.e. the Kimberley) and codifies it in a way that can be used by a computer model. The role of this step is at times misunderstood and undervalued. Three concepts are particularly important not only for this modelling project but also for the overall Kimberly research effort. First, the outcome of a model parameterisation is not just a model input but also a **snapshot of what we know about the system**. The actual extent of this knowledge is often laid bare by the very process of model parameterisation. The need to provide a model with a numerical value for (say) turtle biomass and age structure forces the modellers to look for and certify this information if available and to extrapolate credible ranges from other sources if not available. Often it is not until this process needs to be carried out that the extent of our (lack of) knowledge is made clear. In Donald Rumsfeld's parlance, this process turns some data gaps from 'unknown unknowns' into known ones. Second, since data collection always needs to be prioritised, model sensitivity analysis may provide information on **what type of information could provide the largest impact on management-relevant knowledge**. Third, the existence of large data gaps at times leads critics to question the value and reliability of a modelling effort. This overlooks the fact that ultimately decisions will have to be made even in the presence of data gaps and that any gaps leading to scepticism of model performance apply equally to the potential outcomes of any decisions made. Rather than being invalidated by large data gaps, <u>modelling provides a way to recognise, formalise and evaluate the relative impacts of these data gaps on system understanding and anticipated outcomes of any decisions made</u>.

2.1 ALCES

ALCES Online (www.alces.ca) is a landscape/landuse simulator used by the ALCES Group to explore past, present and future relationships involving land uses (residential, transportation, croplands, livestock, mining, oil and gas, forestry, tourism/recreation) and natural disturbances regimes (fire, insects, landslides, storms, climate, climate change). An overview of the structure and function of ALCES Online can be found at https://www.dropbox.com/sh/83rx7o9jhb65t41/AABihxAZfmWXMdAv4geBVRgva?dl=0.

The ALCES component of the project functions to model terrestrial land use and landscape dynamics. The primary purpose of the ALCES model is to track the key first-order dynamics of terrestrial land uses and landscapes, and to generate output that is relevant to the interface between terrestrial and marine ecosystems in the Kimberley Region. It models proposed future trajectories in human populations, settlements, mining, energy, croplands, livestock, tourism, and transportation, and generates spatial and temporal information on land use and natural disturbance regimes. The influence of these on marine and coastal systems can then be incorporated into the marine dynamics explored within EwE.

Additional information about the ALCES tools can be found at www.alces.ca. Full details of ALCES application to this specific project are available at:
http://www.per.marine.csiro.au/staff/Fabio.Boschetti/KimberleyMSE\PDF\Alces Synopsis.pdf while a summary of these results can be found at:
http://www.per.marine.csiro.au/staff/Fabio.Boschetti/KimberleyMSE/Alces.htm.

2.2 Ecopath with Ecosim (EwE)

Ecopath with Ecosim (EwE) is used to characterise the trophic structure, ecosystem attributes and impact of fishing, other human uses and climate change in the region. It consists of a number of modules. Ecopath is a mass-balance model that accounts for trophic interactions among organisms at multiple trophic levels by describing matter and energy flows. Ecosim and Ecospace use the mass-balanced model generated by Ecopath as initial conditions for temporal and spatial simulations of dynamical changes due to human activities and environmental drivers. For the Kimberley, the environmental drivers included climate change and related time varying processes (such as sea surface warming, sea level rise, changes in precipitation regimes), while the activities considered were fishing, tourism and the overall impact of human presence in coastal areas (waste, pollution, infrastructure development) and the effects of different management options, such as controls on fishing effort and spatial closures. The outcomes of these changed activities and drivers were assessed in terms of the effects on fished species, catches, the trajectories of conservation species and trophic interactions in the Kimberley marine ecosystem. More details about EwE modules can be found at http://www.ecopath.org/.

Full details of Ecopath with Ecosim application to this specific project are available at http://www.per.marine.csiro.au/staff/Fabio.Boschetti//KimberleyMSE/EwE.htm, which includes a full description of EwE model domain and structure, foodweb and diets, input data sources and a number of performance diagnostics.

2.3 ALCES-EwE integration

Figure 3 shows a schematic representation of the interaction between the Alces and EwE models. It shows how some global and regional processes (climate change, human and economic pressures, oceanic and weather phenomena) affect both land and marine environments, whereas some regional and local terrestrial processes only affect the local marine environment via the large rivers entering at estuaries – i.e. directing surface water and its dissolved and suspended elements (sediment, nutrients). An over-arching assumption is that all terrestrial and marine land uses require a labour force, which in turn promotes residential population growth. These regional populations are generally located on or near the coast, and hence can have significant effects on coastal biota at scales varying from local to regional. Quantifying the magnitude and direction of this effect is the key objective of the Alces model, while assessing the ultimate impact on the marine food web is the key objective of the EwE model.

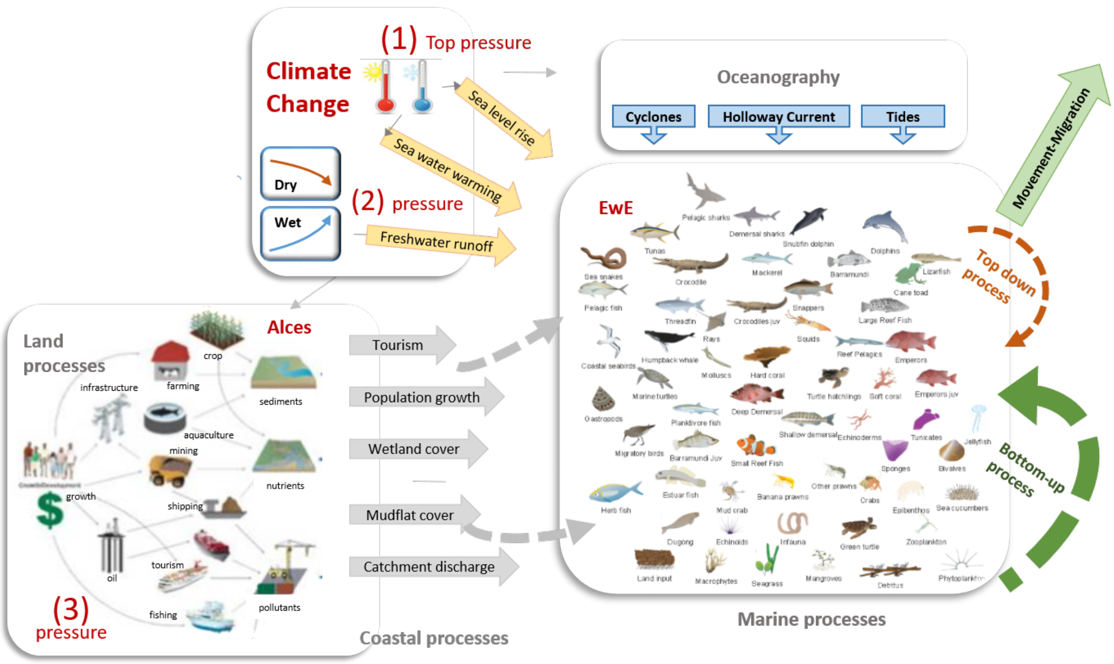


Figure 3: The icons represent the components of the Alces and EwE models and the arrows denote the interface between the land-based model (Alces) and the ocean-based model (EwE) as well as their relation to climate and oceanographic forcing.

3. Scenarios and management strategies

We have defined a 'future' as a model simulation of what may happen to the Kimberley region by the year 2050 as a function of:

i) Model specifications (how the Kimberley system works);
ii) Development scenarios (what events may occur); and
iii) Management strategies (what we do and how we react to these events).

In this section we describe the precise development scenarios, management strategies and model specifications we selected to represent the possible futures under analysis. Both the scenarios and management strategies were selected and agreed upon in consultation with a number of stakeholder groups, including the Department of Biodiversity, Conservation and Attractions (formerly Department of Parks and Wildlife), The Kimberley Development Commission, WA State Development Department, Department of Primary Industries and Resources (formerly Department of Fisheries), Department of Mines, Industry Regulation and Safety (formerly WA Department of Mines and Petroleum), among others.

3.1 The scenarios

3.1.1 Scenario selection

Scenarios are generally defined as "*plausible, challenging, and relevant stories about how the future might unfold*" (Raskin et al. 2005, Bezold 2010, Hunt et al. 2012). To be relevant to this study, a scenario needed to be pertinent to the ecological, economic and social development of the Kimberley region and its marine environment. In addition, a scenario needed to be amenable to computer simulation. Obviously, the number of scenarios of interest which may occur is too large to model exhaustively and to analyse comprehensively. This problem is common to any project which attempts to say anything meaningful about the future and requires a careful selection of a small set of scenarios which is representative of the overall range of '*relevant stories*' of interest (Hunt et al. 2012, Boschetti et al. 2015).

Selecting a manageable set of scenarios is carried out differently in different disciplines but usually involves defining the main components of a scenario as a first step, that is, what core issues or events a scenario needs to include. In our case, this means asking what events or issues may be most relevant to the future of the Kimberley marine environment. This includes, for example, weather, climate and other natural processes as well as human and social processes like population growth, resource use and development (for different industrial, agricultural and commercial sectors), attitudes towards the environment, political choices, etc.

One approach to defining scenarios focusses on the combinations of the paths each of these events or issues may take. This ensures that a wide range of future events are considered but quickly leads to a very large number of scenarios. For example, considering 10 issues or events, and assuming that each issue could play out in three different ways (low, medium or high change), would lead to ~60,000 scenarios. Not only would all these scenarios be difficult to simulate, but they would be very difficult to analyse in a meaningful way and, importantly, to compare with one another. In addition, experience has shown that complex systems (e.g. ecosystems) have general classes of behaviour and that many scenarios ultimately lead to similar patterns of behaviour so that it is possible to capture most responses with a much smaller set of well-chosen contrasting scenarios.

A different approach is followed in the Future Studies and Foresight literature (Bezold 2009, Curry & Schultz 2009, Bootz 2010, Kok et al. 2011, Alford et al. 2014). In this tradition, a future is usually explored via stakeholder engagement rather than via modelling. Participants are asked to identify the two most critical and uncertain drivers of change which define the axes of a 2D plane. This plane is then divided into four quadrants, each defining a single scenario as the interplay of the two axis (Curry & Schultz 2009, Hunt et al. 2012, Ramirez & Wilkinson 2013, Raven 2014). This approach is often referred to as 'double uncertainty' or '2 by 2' and the 2D plane is referred to as the Futures Plane (Boschetti et al. 2015). The 'double uncertainty' approach results in no more than a handful of scenarios (as recommended in the Future Studies literature (De Vries 2007, Durance & Godet 2010)), which can be analysed at depth and easily compared. This is important since, as discussed in Section 1.1, limitations in human mental abilities make it difficult for people to effectively deal with more than a handful of options simultaneously.

The approach followed in this study was a compromise between the two described. Its rationale is that events in the real world do not happen randomly or even independently. For example, weather events are highly correlated, which is why the concept of 'climate' is useful. Similarly, population growth, economic growth, resource use and development are often correlated, which is why at times we talk of political or economic 'climate'. Even more important, at the time and spatial scales addressed in this study, individual events often average out and it is the broader trends resulting from their correlations which matters most.

As a result, following the Future Studies and Foresight literature, we employed a 'double uncertainty' approach in which trends in climate change and economic development were identified as the two most critical and uncertain drivers of change in the Kimberley region. These drivers of change were also acknowledged as the most important stressors on the Kimberley marine environment by most of the stakeholders engaged in this exercise and reflect the core aspiration of ensuring:

i) Environmental and cultural sustainability;
ii) Economic and social progress; and
iii) Resilience to climate change.

The Climate Change and Development axes thus define the Future Plane shown in Figure 4. We depart from the Future Studies and Foresight literature in three ways important. First, rather than focussing on 4 quadrants we subdivide each axis into three levels of increasing pressure: low, medium and high. This results in 9 (3 by 3) scenarios, and allows for a finer exploration of possible futures. Second, for each axis, we spell out how each specific process pertaining to that dimension contributes to that level of pressure (see sections below). Third, for some scenarios, we performed a sensitivity analysis by studying how small variations in pressure impact the model output.

This approach offered the most effective option, given the resources available to the project and the need to provide model results in a way that means they are easily understood, compared and incorporated into the decision making process. In summary:

1) We analysed nine scenarios resulting from the interplay of Low, Medium and High Climate Change and Development impacts;
2) Some of these scenarios were subjected to stochastic Monte Carlo analysis to establish the model sensitivity to small changes in impacts;
3) Each dimension (Climate Change and Development) accounts for a number of components (see below). These components are assumed to be highly correlated and thus will change in unison, that is, changes to each individual component are not analysed separately in this study,
4) How each component contributes to a dimension is spelled out in the model input. As a result, should a specific trend in a specific component be deemed important at a later stage, this could be easily addressed in a separate project.

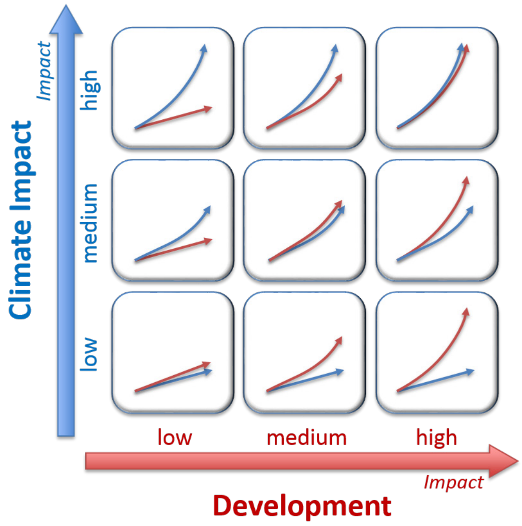


Figure 4. The '3 by 3' Future plane consisting of The Climate Change and Development axes. Each axis is subdivided into low, medium and high impact, resulting in 9 scenarios describing the interplay between Climate Change and Development stressors.

3.1.2 Climate Change Scenario

Climate models explore the global climate impacts of different pathways of greenhouse gas emissions, arising from different scenarios of population growth, economic development, technological progress, and policy choices. The climate change scenarios selected are based on the simulations produced by the WAMSI KMRP Project 2.2.7 'Knowledge integration and predicting biophysical response to climate change' (Feng et al. 2017). The project used a near-global eddy-rich Ocean General Circulation Model – OFAM3, to downscale the future changes of global ocean circulation based on the Representative Concentration Pathways (RCP) 8.5 climate model projections (Riahi et al. 2011). The RCP8.5 is based on upon a revision and extension of the IPCC A2 scenario (Riahi et al. 2007) and represents the possible future climate trajectory under on-going high carbon emissions.

Of all the RCP projections, RCP8.5 assumes the highest greenhouse gas emissions resulting from high population growth, slow average income growth, modest rates of technological change and energy intensity improvements, and poor climate change policies. In other words, RCP8.5 represents a worst case scenario of business-as-usual carbon intensive economic growth in the absence of coordinated mitigation initiatives, leading to a radiative forcing of 8.5 W/m^2 by the end of the century, a projected average global warming of 2.0 ^{o}C (1.4 to 2.6 ^{o}C range) and a projected global mean sea level rise of 0.30 m (0.22 to 0.38 m range) by mid-century (2046 to 2065). The RCP8.5 was adopted as the High Climate Change scenario for the model simulations. Information about all the RCP scenarios and projections is also available at http://sedac.ipcc-data.org/ddc/ar5_scenario_process/RCPs.html.

As a result of discussions with the WAMSI KMRP Project 2.2.7 lead, Dr Ming Feng, it was agreed that the Low and Medium Climate Change scenarios would best be obtained by scaling the output of the OFAM3 model produced by the WAMSI KMRP Project 2.2.7 (Feng et al. 2017). In particular, this scaling was carried out by associating a radiative forcing of 4.5 W/m^2 and 2.6 W/m^2 to the Medium and Low Climate Change scenarios, respectively, which correspond to the RCP4.5 scenario of 1.4 ^{o}C (0.9 to 2.0 ^{o}C range) warming and 0.26 m (0.19 to 0.33 m range) sea level rise and the RCP2.6 of 1.0 ^{o}C (0.4 to 1.6 ^{o}C range) warming and 0.24 m (0.17 to 0.32 m range) sea level rise scenario, respectively. The Climate Change scenarios are summarised in Table 1.

Regarding the impact of climate change on the marine food web, EwE was forced with the projected changes in biomass of exploited species in the Australia EEZ (relative to baseline: mean 1981-2000) under RCP 2.6 and RCP 8.5 respectively as provided in (Cheung et al. 2009, Cheung et al. 2016). This forcing has taken the form of time-series of annual multipliers of fish productivity, mortality and predator search rates in Ecosim. Lacking more detailed information, the mean of the forcing for scenarios RCP2.6 and RCP8.5 was used for scenario RCP4.5. In addition, published trajectories of simulated changes in pelagic and benthic primary producers were incorporated as time series of forcing functions affecting directly biological production.

Table 1. Description of the Climate Change scenarios.

Scenarios	**Average global warming (°C) by mid-century**	**Average global sea level rise (m) by mid-century**
Low [RCP2.6]	1.0 [0.4-1.6]	0.24 [0.17-0.32]
Medium [RCP4.5]	1.4 [0.9-2.0]	0.26 [0.19-0.33]
High [RCP8.5]	2.0 [1.4-2.6]	0.30 [0.22-0.38]

3.1.3 Development Scenario

The Development scenarios account for a large number of sectors, including population, housing, tourism, agriculture (including the Ord River Irrigation Scheme and other forage and horticultural crops), cattle farming, aquaculture (pearl, prawns and barramundi), transport, infrastructure, mining (iron ore, diamonds, gold, copper zircon and gravel) and Oil & Gas. Exact details about these scenarios, the rationale for their choice and the implications for each sector can be found in the attached document 'A Synopsis of ALCES Online Methodology and Key Land Use Trajectories Coefficients for the WAMSI Kimberley Project' produced by the ALCES modelling team (available at:

www.per.marine.csiro.au/staff/Fabio.Boschetti//KimberleyMSE/PDF/Alces%20Synopsis.pdf).

Table 2 summarises the key features of each scenario. Unless otherwise specified, growths are expressed as mean annual growth. Road and infrastructure upgrading affects both human behaviour (in the case of road by allowing to access otherwise hard-to-reach areas) and environmental impacts (changes in erosion and watershed patterns). Similarly, industrial and tourism activities impact the region's economy, access to remote areas and can lead to environmental impacts of different nature.

Table 2. Brief description of the Development scenarios developed.

Development scenarios	Low	Medium	High
Average population growth / year	1.5%	2%	2.5%
Cropland Area (1,000 ha) **(Ord River by mid-century)**	~40	~60	~100
Cattle - heads by mid-century **(average growth / year)**	600K (0%)	1.1M (1.25%)	1.24M (1.5%)
Roads	As current	• Paving Cape Leveque Hwy • Upgrade Gibbs River Rd	• Upgrade Gibbs River Rd • an increase in the number of roads to the coast, or the upgrading of existing tracks • upgrade or the Kalumburu Rd
Tourism (Tourism **Activity Days -TADs);**	7.7 M (1.5% growth)	9.8 M (2% growth)	12.5 M (2.5% growth)
Oil (m^3/yr) & LNG (peak Mtpa)	As current	~400k Blina & Ungani Fields ~7.5 Browse Basin & Concerto	~600k Blina & Ungani Fields ~10 Browse Basin & Concerto

3.2 The Management Strategies

In the context of this study, management strategies include actions which can be taken to pre-empt or react to stressors and events which may affect the Kimberley marine environment. A wide range of intervention options are available to manage the marine environment which can be applied at different spatial and temporal scales. At the local scale, a manager may need to consider small scale, possibly temporary interventions to address a specific problem at hand. At the regional scale, it is important to ensure a certain level of coordination to reduce possible conflicts or increase synergies between multiple interventions. At a national or international level, interventions also need to both reflect and adhere to current political and social expectations towards conservation, which often apply to several environmental issues simultaneously. It is for this reason that in the Future Studies and Foresight literature, it is common to address environmental management in terms of political and social appetite for or acceptance of different levels of regulations. In this literature, regulations are broadly understood as determining the politically and socially acceptable balance between individual freedoms and enterprise (favouring resource exploitation) vs socially negotiated institutions (favouring resource conservation) (see reviews in (Hunt et al. 2012, Boschetti et al. 2015) and (Pinnegar et al. 2006) for an application to marine ecosystems).

Our approach in defining the management strategies is based on the belief that while these strategies will be applied at the regional *__scale__*, they need to reflect both a regional and national *__scope__*, for several reasons. First, this project addresses a regional spatial scale and a multi-decade temporal scale. This prevents us from addressing local, short-term interventions. Second, because of the national, iconic significance of the Kimberley environment, efforts to protect its marine environment cannot be disconnected from the overall national attitude towards conservation. Third, over the next 35 years, this attitude may change considerably: it may oscillate towards and against more environmental conservation and may even reverse conservation values which we now consider unshakable.

In the Future Studies and Foresight literature, appetite for or acceptance of different levels of regulations are treated as *scenarios*: they are understood as large-scale social processes beyond management control. In this project, we explored *strategies*: interventions which are under management control. Here is where the interface between regional and national *scopes* mentioned above is crucial: management strategies available at the regional scale will likely be constrained and negotiated within the scope of the acceptance for environmental regulation at the national level.

Within the limitations of the resources available to this project, the definition of the management strategies attempts to capture this tension. In consultation with the Department of Biodiversity, Conservation and Attractions (formerly Department of Parks and Wildlife) and Department of Primary Industries and Resources, five broad levels of regulation pressure were defined which reflect political and social attitudes towards environmental conservation (columns in Table 3), 'High', 'Medium', 'Low', 'Reversed' and 'Worst Case':

1) 'High' regulation pressure is based around an increasing appetite for environmental conservation;
2) 'Medium' regulation pressure is based around current regulations and expectations about proposed regulations currently in the pipeline;
3) 'Low' regulation pressure is based around current regulations, in which the proposed regulations currently in the pipeline do not materialise;
4) 'Reversed' regulation pressure describes a U turn in political and social mood which reverses most current conservation initiatives and reflects a society which is increasingly unconcerned or sceptical towards environmental conservation, or one where other considerations (e.g. food security) have come to over-rule conservation concerns; and
5) 'Worst case' represents the collapse of most forms of regulation.

Within these broad levels of regulation pressure, we assume that interventions under management control are based around three broad management tools (refer to Table 3). The first tool consists of the existing and proposed marine parks, including the restrictions on the activities allowed in different zones within these parks. The second management tool consists of regulations on fishing (as one of the key pressures on marine resources), which include the amount of virgin (or spawning) biomass that is allowed to be taken through commercial or recreational fishing across the region, as well as strategies such as reducing bag and size limits for specific species. The third tool consists of regulating the impact of other human uses, such as tourism and mineral, oil and gas exploration and extraction.

Table 3, Table 4 and Table 5 show how these three management tools may be implemented (rows) within the five levels of regulations pressure (columns). As for the scenarios above, we assume that the political and social acceptance of different levels of regulations will impose a strong correlation in the use and implementation of the available management tools. However, different strategies can be tested independently should some scenario outcome require it so.

Table 3. Description of the proposed Management Strategies with regards to Marine Protected Areas.

Management Tools / Regulation pressure	High	Medium	Low	Reversed	Worst Case
80 Mile Beach Marine **Park**	Yes	Yes	Yes	Yes	No
Lalang-garram / Camden Sound Marine **Park**	Yes	Yes	Yes	Yes	No
Yawuru Nagulagun / Roebuck Bay Marine **Park**	Yes	Yes	Yes	Yes	No
North Lalang-garram Marine **Park**	Yes	Yes	Yes	Yes	No

Lalang-garram / Horizontal Falls Marine **Park**	Yes	Yes	Yes	Yes	No
North Kimberley Marine Park	Yes	Yes	Yes	Yes	No
80Mile Beach Commonwealth Marine Reserve	Yes	Yes	No	No	No
Roebuck Commonwealth Marine Reserve	Yes	Yes	No	No	No
Kimberley Commonwealth Marine Reserve	Yes	Yes	No	No	No
Sanctuary Zone extension (% of total park area)	30%	20%	10%	0	0

Table 4. Description of the proposed Management Strategies with regards to fishing regulations.

Management Tools / Regulation pressure	High	Medium	Low	Reversed	Worst case
Fishing regulation (% virgin biomass)	20%	50% (prawns) 50% (finfish)	90% (prawns) 70% (finfish)	90% (prawns) 70% (finfish)	90% (prawns) 70% (finfish)
Fish size limits	Current fish size (status quo)	Current fish size (status quo)	Status quo + ~10 cm	Status quo + ~15 cm	No limit
Bag size limits	Current bag size (status quo)	2 * Current bag size	5 * Current bag size	10 * Current bag size	10 * Current bag size

Table 5. Description of the proposed Management Strategies with regards to Other Human Uses.

Management Tools / Regulation pressure	High	Medium	Low	Reversed	Worst case
Accepted cumulative tourism-induced mortality*	0.3%	1%	5%	No limit	No limit
Accepted cumulative mortality§ from other marine uses	0.3%	1%	5%	No limit	No limit

* This includes overall mortality due to presence on tourism in remote region as a result of pollution from boats, human presence on reefs/coastline, etc.

§ This includes overall mortality due to other human uses, including Oil and Gas exploration and extraction, due to pollution, infrastructure, boat collisions, etc.

4. Results

A modelling work of this complexity generates a large amount of data: the combination of functional groups in the modelled foodweb, times the number of scenarios, times the number of management strategies result in thousands of time series from EwE, plus several hundred maps from ALCES. All model outputs are publicly available as per WAMSI requirement. In addition, visualisation of all results is available at http://www.per.marine.csiro.au/staff/Fabio.Boschetti//KimberleyMSE/.

In this section a summary of the key insights which arise from the interpretation of these results is provided. This summary is structured as follows:

1) Details on how ALCES results were imported into EwE and how the scenario definition was modified in the light of these results;
2) A description of the indicators used to assess the state of the marine environment;
3) The types of visualisation used to display the model results;
4) A summary of the main outcomes from studying the dynamics of the marine ecosystem via the Ecosim component of the EwE model; and
5) Analysis of the likely impact of the management strategies via the Ecospace component of the EwE model.

4.1 ALCES results

The full description of all Alces results is available at:
www.per.marine.csiro.au/staff/Fabio.Boschetti//KimberleyMSE/Alces.htm.

ALCES results were used as input to EwE as described in Section 5. Of particular significance for the EwE simulations, is the decision made by the ALCES team to treat Climate Change induced temperature and precipitation changes independently due to uncertainty on how climate change may affect precipitation regimes in the Kimberley. As a result, each Climate Change scenario (Low, Medium and High) was split into two scenarios (for example: Low Climate Change warming and lower precipitation (Low C Dry), Low Climate Change warming and higher precipitation (Low C Wet) etc. As a consequence, the 3 by 3 Future plane in Figure 4 was modified into a 6 by 3 plane as shown in Figure 5.

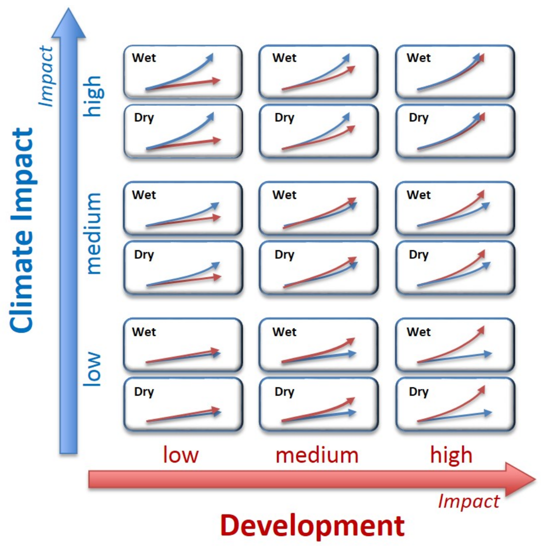


Figure 5. Modified ‘3 by 3’ Future plane consisting of The Climate Change and Development axes. Each climate change scenario has been divided into a ‘drier’ and a ‘wetter’ sub scenario, reflecting the uncertainty of how climate change may affected precipitation regimes in the Kimberley.

4.2 EwE indicators

The EwE food web includes 59 functional groups, and functional groups represent one or more marine species. While model output for all the 59 groups are available at www.per.marine.csiro.au/staff/ Fabio.Boschetti// KimberleyMSE/, a smaller number of indicators is needed to simplify our understanding of the overall system response to the different modelled scenarios. Four types of indicators were used to summarise the output of the EwE model (see Figure 6):

1) 'Meta groups': a combination of a number of functional groups in the EwE foodweb. These included:
    a. Target Species: Emperors, Snappers and Threadfin;
    b. Marine mammals: Humpback Whales and Dolphin species (Dugongs are includes as charismatic species below);
    c. Sea Birds: Coastal Seabirds and Migratory Shorebirds;
    d. Fish Trophic levels 2 to 3: Planktivore Fish, Reef Associated Pelagics, Herbivorous Fish, Small Reef Fish; and
    e. Corals: Hard Corals and Soft Corals.
2) 'Keystone species': defined as "relatively low biomass species with a structuring role in the food web" (Libralato et al. 2006) and identified as such by EwE:
    a. Pelagic Sharks;
    b. Snubfin Dolphins;
    c. Barramundi; and
    d. Large Reef Fish.
3) 'Charismatic species': specific functional groups in EwE food web which hold a particular economic, social or cultural value to different stakeholder groups:
    a. Corals;
    b. Turtles: Green Sea Turtle and Marine Turtles; and
    c. Dugongs.
4) 'Habitats': functional groups which define specific habitats, including Seagrass and Mangroves
5) 'System level indicators': designed to reflect the state of the overall food web rather than of some of its component. These include:
    a. Total biomass;
    b. Divergence: a measure of how the distribution of biomass between species change over time. We adopted the 'Kullback–Leibler' distance (Cha 2007) as a measure of divergence; and
    c. Total Divergence. This is a modification of the divergence measure to account for changes in overall biomass (as divergence is insensitive to this fundamental system property) - this is done by assigning change in overall biomass to a fictitious ('dummy') species in the food web. This measure circumvents the problem that two ecosystems with same biomass ratio between species, but largely different overall biomass, would look the same under the Kullback–Leibler' distance. This implies that no system change would be detected in a system undergoing proportional biomass loss. This measure has been designed specifically for this project and we intend to publish it in the near future.

Meta groups
- Target Species
- Mammals
- Sea Birds
- Fish: Trophic levels 2 - 3

Keystone species
- Pelagic sharks
- Snubfin Dolphin
- Barramundi
- Large Reef Fish

Charismatic species
- Corals
- Turtles
- Dugong

Habitats
- Seagrass
- Mangroves

Total biomass
Divergence

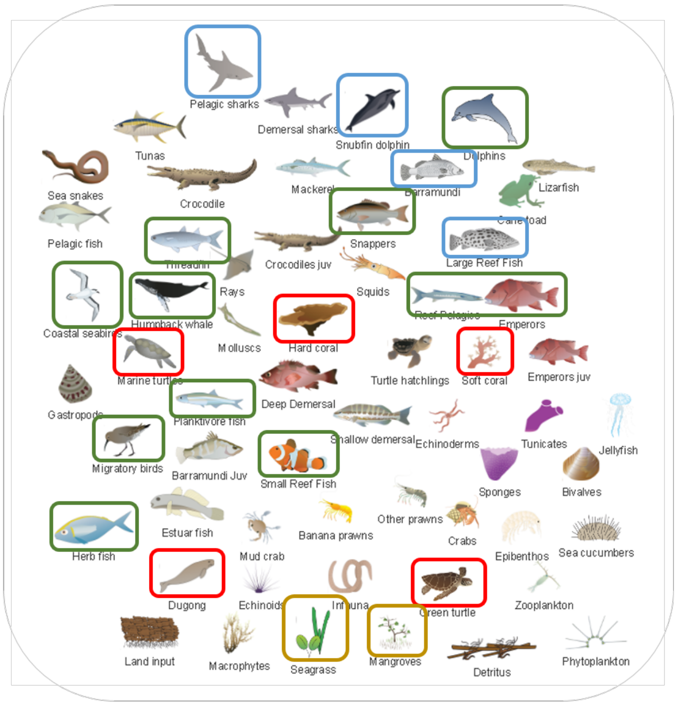


Figure 6. Indicator list (left) and their position in the food wed (right).

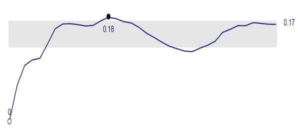
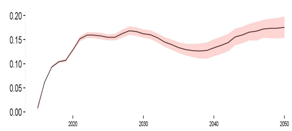
4.3 Types of visualisations

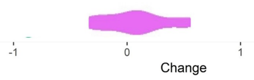
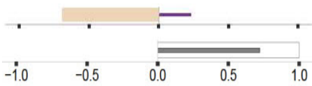
Visualisation of the EwE results were undertaken using guidelines suggested in (Tufte 1990) which suggested:

i) maximise the amount of information included in a figure, rather than oversimplifying it; and
ii) avoid information overload by adopting a minimalistic design.

Three types of visualisations were adopted and included time series, bar plots and violin plots as described in Table 6:

Table 6. Visualation types adopted for EwE outputs.

Visualisation type	Example	How to read it
Spark Line: Time series of a single indicator/species for a specific scenario		Evolution of a variable over time. Rather than including a Y axis to show the value of the time series, only the minimum (white dot), maximum (dark dot) and last value are shown. The grey ribbon shows the interval containing 50% of the time series values. It helps focussing on the core feature of the time series by removing most details of minor significance.
Ribbon plot: time series of multiple indicator/species. It shows the mean (think line) and standard deviation (ribbon) over all scenarios		At each point in the X axis, it shows the mean (black line) and the standard deviation (ribbon) of the distribution of time series.

Violin plot: state of an indicator/species at the end of the simulation (2050) for all scenarios		Distribution of values of a variable. It is similar to a box plot, except that it gives an indication of the probability density of the data at different values. For each point on the X axis, it shows the probability of value occurring in the distribution.
Bar plot: states of an indicator/species at the end of the simulation (2050) for a specific scenario		Rate of change of variable (e.g. biomass at the end of a simulation*)*, relative to a reference baseline, as $\frac{biomass-baseline}{baseline}$. Positive (negative) values mean the variable increased (decreased). We use two different colour sets: • Scenarios: the baseline is taken as the value of the variable at the beginning of the simulation. The beige bar refers to the low precipitation regime and the black bar to high. • Strategies: the baseline is taken as the value of the variable at the beginning of the simulation. The light bar show the biomass change as above. The dark one shows the contribution of a strategy to that biomass, compared to the Medium Strategy.

4.4 Ecosim Results: dynamics of the marine ecosystem

Ecosim is the non-spatially explicit component of EwE which models the time dynamic evolution of the marine ecosystem. It shows us how the marine food web responds to different levels of pressure. These results are important not only because they reveal how different components of the food web interact during the system evolution, but also because this understanding is then ported into the spatially-explicit component of EwE: Ecospace. Here we summarise the main insights obtained by the analysis of the Ecosim results.

4.5 The state of the Kimberley marine environment in 2050

Figure 7 shows the box plot of the state (x axis) of all indicators (y axis) at the end of the Ecosim simulations (2050) aggregated over all 18 modelled scenarios. The values are expressed as a ratio of change over the value at the beginning of the simulation (2015). Values <0 (>0) imply decrease (increase) in biomass over the simulated timespan. For each indicator, the thick black vertical line represents the median of the distribution of the values over the 18 scenarios and the thick bar shows the interval between the first and third quantile. The thin line gives a fuller representation of the overall distribution[1].

By analysing the location and width of these distributions, indicators were grouped according to their responses to the 18 different modelled scenarios. In particular, we focus on the results of four groups:

1) Winners: these are the indicators for which the distribution lays completely to the *right* hand side of the dashed "no change" line in Figure 7, implying that biomass changes are >0 for all scenarios. These include seagrass and, as a result, turtles and dugongs who feed on it.
2) Losers: these are the indicators for which the distribution lays completely to the *left* hand side of the "no change" line in Figure 7, implying that biomass changes are <0 for all scenarios. These include target species, corals, snubfin dolphins and pelagic sharks.

[1] Technically, it extends to either the minimum value of the distribution or the 1.5 of the interquartile range divided by the square root of the number of samples.

3) Low scenario-sensitivity: these are the groups whose final biomass is not much affected by the different scenarios, as shown by a narrow boxplot. These include: mangroves, corals, snubfin dolphins and mammals. These groups may be winners, losers or show little change at all, the important consistent feature is that their biomasses converge to a particular level regardless of what else is occurring in the system; and
4) High scenario-sensitivity: the groups whose final biomass is significantly affected by the different scenarios, as shown by a wide boxplot. These include: seagrass, turtles and seabirds.

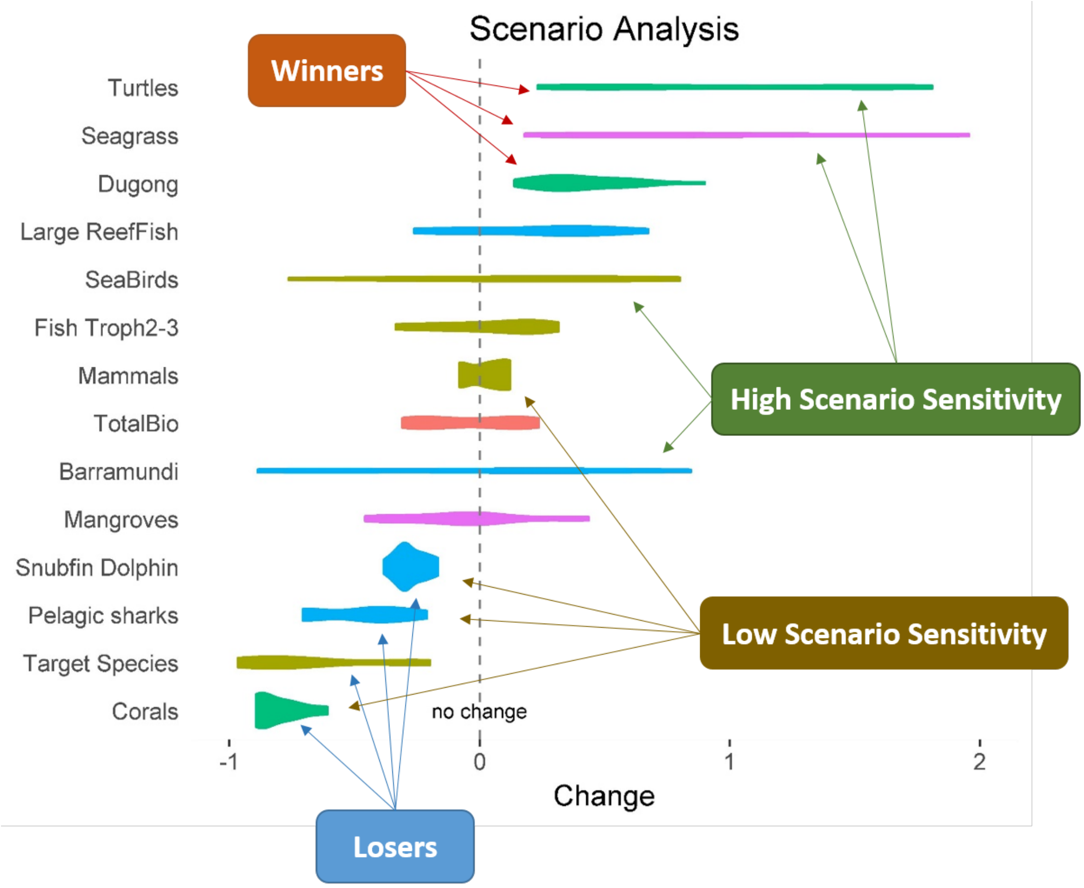


Figure 7. Violin plot of the state of all indicators (y axis) at the end of Ecosim simulation (2050), expressed as ratio of change in biomass over the value at the beginning of the simulation (2015). For each indicator, the violin plot summarises the distribution of the end states.

Figure 7 shows the distribution of biomass changes as a function of the modelled scenarios, without specifying how the scenarios affect an indicator's distribution. The latter is shown in Figure 8. Here, for each scenario, the bars map the change in biomass as *departure from the median* shown in Figure 7. For each of the 3*3 scenario, the pink/blue bars represent the dry (low precipitation) and wet (high precipitation) conditions, respectively. To simplify the analysis of the figure, only indicators whose final states change more than 40% compared to the median are included in this plot. The plot shows clearly the effect of the climate forcing in terms of warming, since the bars on the top row (High Climate Change) are mostly on the left hand side (<0) of the panels, while the bars on the bottom row (Low Climate Change) are all on the right hand side (>0) of the panels. The plot also shows the forcing due to the precipitation regimes, in particular in the middle row (Medium Climate Change) with the pink and blue bars pointing in opposite directions. On the contrary, the forcing due to socio-economic development is less clear. This last point is further analysed in the Section 13.

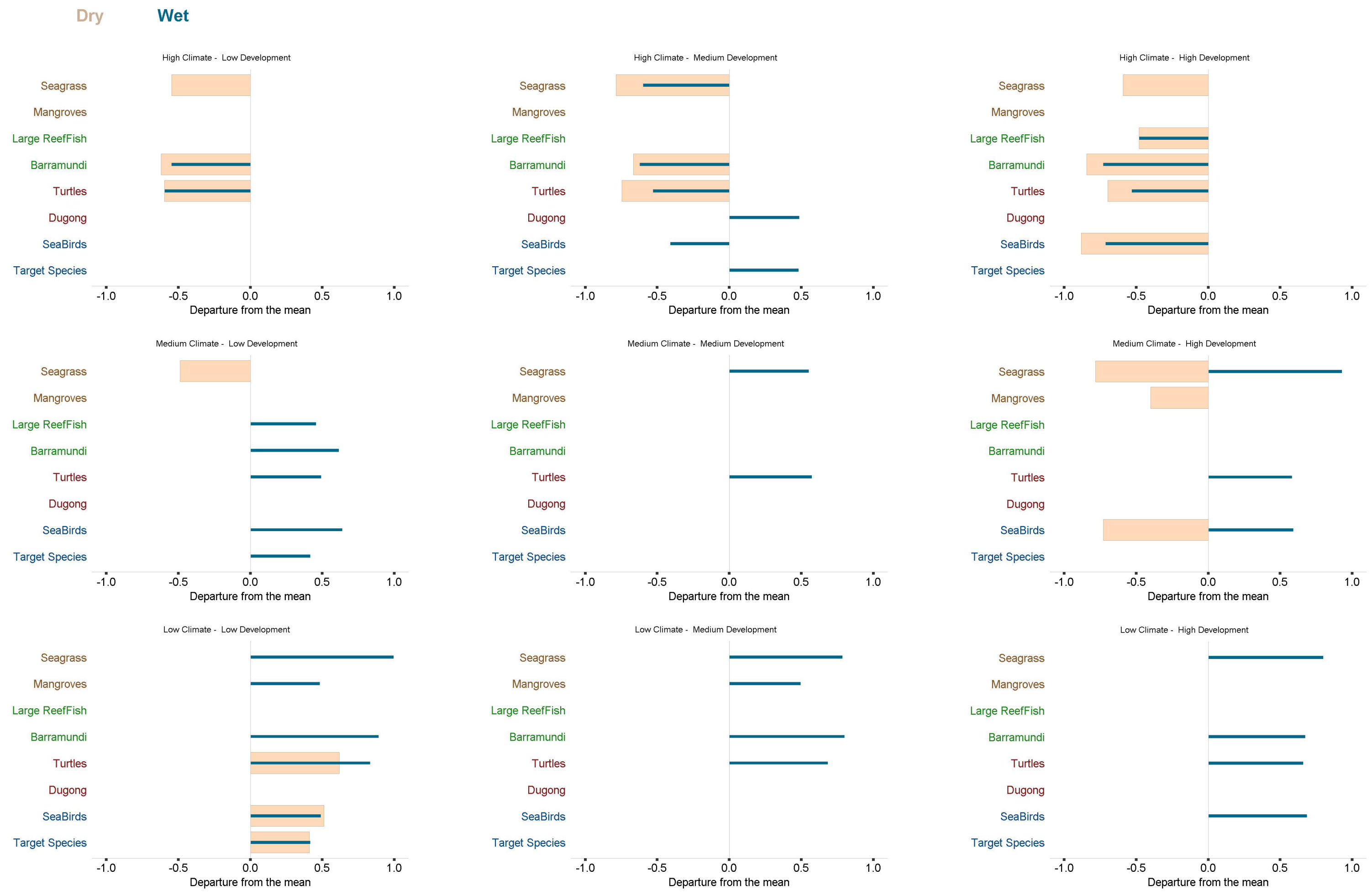


Figure 8. Bar plot of the state of all indicators (y axis) at the end of Ecosim simulation (2050), expressed as ratio of change over the value at the beginning of the simulation (2015). Only indicators whose final state change more than 40% compared to the mean shown in Figure 7 are included in this plot.

Bar plots of biomass changes for each indicator are not included in this report but are available on line at http://www.per.marine.csiro.au/staff/Fabio.Boschetti//KimberleyMSE/Ecosim-All-Results.htm, where bar plots for each of the 59 functional groups in the EwE food web can also be found.

4.6 Sensitivity analysis

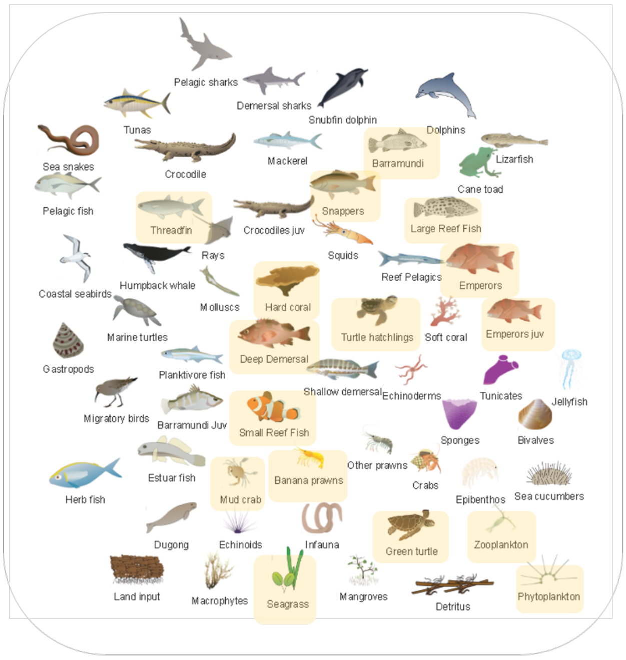
In any modelling study it is essential to carry out an assessment of the model sensitivity to different parameters as well as to different model components (system structure). On the other hand, in models as complex as EwE, with 59 spatially distributed functional groups, a careful serial numerical analysis of the impact on each model parameter is computationally infeasible wit current computing capacity. Fortunately, EwE provides two tools which help obtain a simplified model sensitivity analysis.

The first tool is provided by the computation of the ectotrophic efficiency in the Ecopath calibration step. Unrealistic values highlight functional groups whose parametrisation is unreliable. Second, parameters are assigned a pedigree (rank of reliability) as the Ecopath model is developed and once Ecosim is parameterised and running, a Monte Carlo analysis of the impact of changing input parameters for each functional group can be carried out. These two results can be interpreted by an experienced EwE user to pinpoint the functional groups for which better and more reliable input parameters are likely to mostly affect the model performance. These represent the knowledge gaps to which priority should be assigned should an opportunity for further work be available. These functional groups are highlighted in yellow in Figure 9. As can be seen, these include mostly primary producers and finfish.

Guidelines for future research and monitoring

Monte Carlo Analysis

Group name	% Change
Seagrass	30.16
Phytoplankton	29.36
Zooplankton	12.43
Salps and jellyfish	10.33
Macrophytes	6.66
Bivalves	5.69
Turtle hatchlings	5.42
Small Reef Fish	4.35
Herbivorous fish	3.60
Estuarine Fish	3.32
Echinoids	2.60
Mud crab	2.57
Infauna	2.38
Gastropods	2.15
Planktivore fish	1.83
Banana prawn	1.60



Unrealistic Ecotrophic efficiencies generated by the first run of the model in its pre-balance mode

Group name	Ecotrophic efficiency
Lethrinids juv.	842.6
Pelagic fish	744.8
Mud crab	516.4
Turtle hatchlings	453.2
Deep demersal fish	334.6
Squids	265.3
Banana prawn	132.1
Sea snakes	96.1
Large Reef Fish	87.0
Marine turtles	73.5
Spanish Mackerel	71.8
Green sea turtle	60.3
Tunicates	46.4
Snappers	44.1
Salps and jellyfish	33.0
Hard corals	23.4
Macrophytes	19.2
Epibenthos	10.0
Echinoderms	9.8
Threadfin	8.3
Bivalves	7.5
other prawns	5.6
Molluscs non shelled	5.5
Adult barramundi	4.9
Small Reef Fish	3.8
Juvenile crocodile	3.7
Sponges	2.8
Estuarine Fish	1.9
Snubfin dolphin	1.5
Planktivore fish	1.5
Lethrinids adults	1.3

Groups that need more and better data

Figure 9. Approximate sensitivity analysis on EwE. Highlighted in yellow in EwE food web are the function groups whose parameterisation is most uncertain and whose improvement can mostly affect the model reliability.

Not all input data and parameter values are equally easy to obtain. Data may have been collected but not analysed, while other data is absent and requires collection. Some data may be obtained in a lab, other may require expensive field experiment. Our approximate assessment of the relation between ease of collection and likely impact on the model performance for a number of key EwE functional groups is shown in Figure 10. The figure shows that data on these groups' abundance, seagrass growth and mortality and plankton movement and migration are likely to represent the best 'improvement per effort' should more modelling work in the region be required.

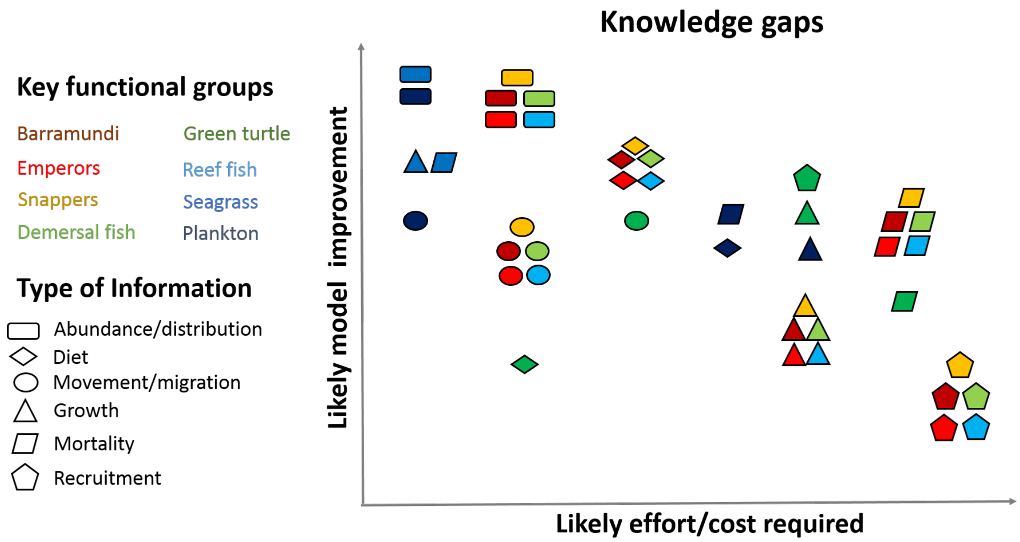


Figure 10. Our approximate assessment of the relation between ease of collection and likely impact on the model performance.

4.7 System evolution

In Section 11 we discussed the state of the system at the end of the simulation (2050) compared to the start of the simulation (2015). In this section we analyse the system's dynamical evolution, that is, how the system changes *during* the simulation. In a system as complex as the one we model, we should not expect such dynamical evolution to be monotonic, let alone linear.

Figure 11a shows the ribbon time series of three system level indicators, the Divergence and Total Divergence (Y axis on the left) and Total biomass (Y axis on the right). The meaning of these indicators is explained in Section 10 above. We include this plot to show how the Total Divergence (pink) captures features of both Divergence (green) and Total biomass (blue), as it was designed to do. The Divergence measure (green) naturally starts at zero (left Y axis) and oscillates during the simulation. The total biomass (blue, right Y axis) is expressed as the ratio of all biomass in the EwE model at each year, over the total biomass at the simulation start (2015). Naturally, it starts at the value of one, departs from one early in the simulation and slowly returns to values close to one in the later part of the simulation. The Total Divergence (pink) roughly follows the oscillatory behaviour of the Divergence (green) but shows a smaller departure from the original system in the later part of the simulation, reflecting the role of the Total biomass.

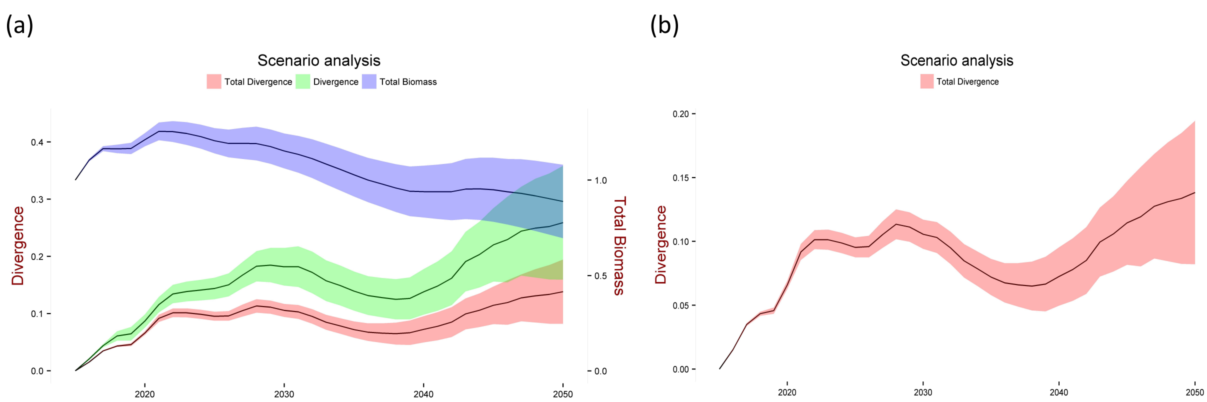


Figure 11. (a) Ribbon time series of the Divergence and Total Divergence (Y axis on the left) and Total biomass (Y axis on the

right). Divergence indicators measure the difference between the state of the system in each year (X axis) and the system at simulation start (2015). Total biomass shows the ratio of the biomass change over the total biomass at simulation start. The dark lines show the mean of the indicators over all scenarios. The ribbons show the standard deviation over all scenarios.
(b) Ribbon time series of the Total Divergence, enlarged for easier visual analysis.

Because we are satisfied that the Total Divergence captures the overall change in system state during the simulation, we focussed the rest of the analysis on this measure. For clearer visual inspection, we show an enlarged plot of the time evolution of the Total Divergence in Figure 11b. Two features are particularly significant:

1) There is a clear oscillatory behaviour in this indicator, with a period of ~25 years, to which a possible secondary oscillation of period ~10 year is superimposed; and
2) The variance (pink ribbon) over the mean (dark line) is fairly narrow. By this we mean that the variance itself does not obscure the general oscillatory behaviour of this indicator.

The previous point suggests that the 18 modelled scenarios have some impact on this indicator but not such to obscure its overall dynamics. It follows that this oscillatory behaviour appears to be a feature of the *system's internal dynamics*, as opposed to a feature of the *forcing* (scenarios) on the system.

Numerical analysis of EwE output (not shown) suggests that this dynamic is largely controlled by primary producers. Because the parameterisation of primary producers in EwE is partly uncertain (see Section 12), it follows that some details in Figure 11b are also uncertain. For example, the timing of the oscillations described above should not be overanalysed for management purposes, since they may be sensitive to model parameterisation. Rather, we should interpret Figure 11b as showing that the system is likely to undergo strong oscillatory behaviour due purely to internal processes and that these deserve further analysis. For example, it is often assumed that large changes in biomass distribution over a food web may affect its stability and resilience to pressure. If this is true, then Figure 11b suggests that the system response to natural or man-made hazards (storms, oil spills, bleaching) may depend on the timing of these events. This is particularly significant in relation to the recently developed concept of 'perfect storm' (Dearing et al. 2012), which addresses how several pressures, each of which in isolation may not be able to significantly affect a system, may do so if their timing results in a cumulative alignment of the combined pressures. This adds a further concern (timing of a threat) to management planning which we suggest deserves further consideration.

4.7.1 Clustering of scenario results and analysis of stressors impact

The Total Divergence can be used not only to study the system's dynamical evolution but also as a measure of the difference among the end states of all simulated scenarios. In turn, these differences can be used to explore whether natural groupings in these scenario outputs exist, via cluster analysis. Figure 12a shows the result of the hierarchical clustering applied to the 18 scenarios. The cluster dendrogram suggests that the scenarios can be grouped into 3 clusters, which are visualised in Figure 12b. The choice of three clusters is made based on the relation between the inter-cluster distance (Y axis Figure 12a) and them mean distance between scenarios (0.06). Three clusters can bee clearly defined over a fairly large range of inter-cluster distances (0.06-0.14), while the number of clusters quickly increases for inter-cluster distances <= mean distance between scenarios, as we would expect.

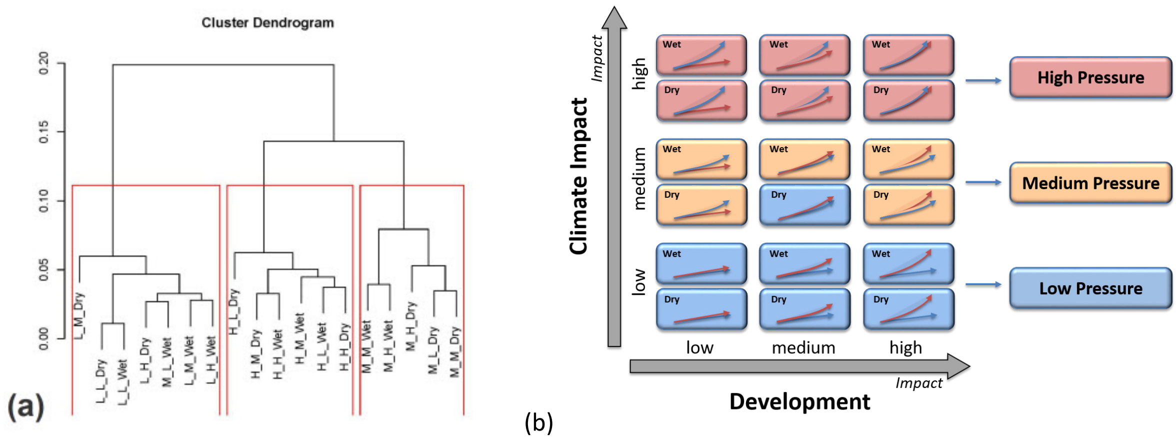


Figure 12. Result of the hierarchical clustering applied to the 18 scenarios in Figure 5 (3 climate scenarios * 3 development * 2 precipitation regimes). (a) The cluster dendrogram suggests that the scenarios can be grouped into 3 clusters. (b) Mapping the 3 clusters over the Future's plane clearly shows how the scenario clusters are controlled mainly by climate forcing in terms of warming.

Figure 12b confirms the tentative ranking of system pressures discussed in Section 11. The distribution of the clusters over the Future's plane clearly shows how these are controlled mainly by climate forcing in terms of warming (Y axis). Within this main layering, forcing due to the precipitation regimes affects the middle cluster by assigning the Medium Climate - Medium Development - Dry Precipitation scenario to the Low Climate cluster. Forcing due to socio-economic development (X axis) does not affect the clusters.

Figure 12b also shows that in order to simplify this work, analysis of the impact of the management strategies can be focussed on these three clusters rather than on the 18 original scenarios, as shown in the right hand side on Figure 12b. In the rest of this document, we selected one scenario to represent each cluster, which we will refer to as 'High', 'Medium' and 'Low Pressure'.

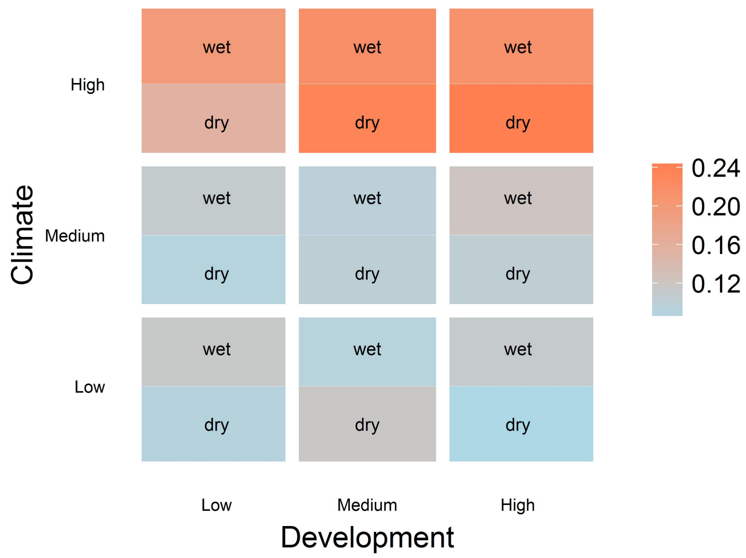


Figure 13. Total Divergence between the end states for each of the 18 scenarios and the state of the system, at the beginning of the simulations.

The cluster analysis in Figure 12 is based on the Total Divergence between the end states for each of the 18 scenarios; in other words, on the Total Divergence between the end states of each pair of modelled scenarios, resulting in an 18*18 matrix of values. In Figure 13, we show the Total Divergence between the end states for each of the 18 scenarios and the state of the system at the beginning of the simulations, resulting in a matrix of 6*3 values. Figure 13 tells us how much the state of the system changes during the simulation, for each scenario. Figure 13 can be understood as a low dimensional projection of Figure 12. As a result, it contains less information and should be interpreted as a coarse approximation of Figure 12. We show it here because it reinforces the message that warming, precipitation regime and development have impacts of different magnitude on the system state. In addition, by focussing on the 'high' climate change scenarios on the top row, Figure 13 also shows that climate and development impact do interact significantly. The end state of the system under 'high climate – high development' scenarios (wet and dry) are more different from the system in its 2015 state than both 'high climate - low development' and the 'low climate - high development'. In other words, while development impacts are overall less significant than climate impacts, *their interaction with climate can become significant when the system is already under climate stress and should not be ignored*.

4.8 Ecospace results: impact of management strategies

Following on the results of the cluster analysis applied to the 18 modelled scenarios, here we discuss the impact of the management strategies applied to the representatives of the 'High', 'Medium' and 'Low Pressure' scenario clusters (see Figure 14).

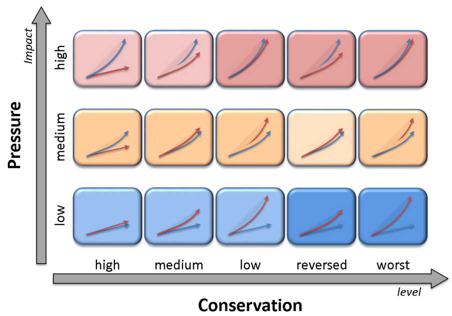


Figure 14. Structure of the management strategy analysis. For each of the three scenarios clusters defined in the previous section ("High",' Medium' and 'Low' pressure), we analyse the impact of the five management strategies discussed in the Section 8. Colours reflect the result of the cluster analysis carried out on the management strategies results.

Following the structure used to analyse the scenario results, Figure 15 shows the violin plot of the state of all indicators (y axis) at the end of Ecospace simulation (2050), expressed as ratio of change over the value at the beginning of the simulation (2015). These end states now reflect the impact of the management strategies. To help the comparison with the violin plots obtained from the scenarios analysis (without management strategies), the violin plots from Figure 7 (coloured violins) are also included in Figure 15, to which the distributions from the scenario analysis (black and white violins) are superimposed.

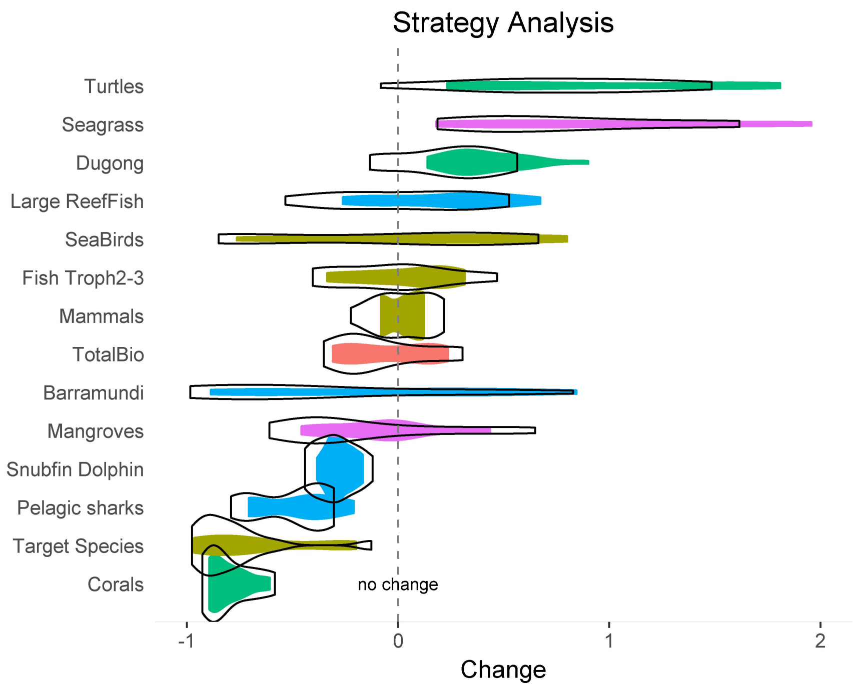


Figure 15. Violin plot (black and white) of the state of all indicators (y axis) at the end of Ecospace simulation (2050), expressed as ratio of change over the value at the beginning of the simulation (2015). For each indicator, the violin plot summarises the distribution of the end states. To ease the comparison, we include here the violin plots from the scenario analysis (coloured violins) from Figure 7.

From a simple visual inspection of Figure 15 we note:

1) No significant change in the 'winners' and 'losers' indicators can be found across the status quo or alternative management strategies.
2) Some changes in the width of the distributions are noticeable. Mammals are more sensitive to strategies than scenario variability; and
3) Overall, most distributions move slightly to the left, indicating an overall decrease in biomass, which is partly due to the poor performance of the ‘reversed’ and ‘worst’ strategies.

To interpret the last point, and to assess the role of the management strategies in more details, in Figure 16 we show the impact of the management strategies on a number of functional groups of management significance, as representative of resident species (top row), sedentary species (middle row) and pelagic species (bottom row). In addition, Figure 17 shows the same plot for the total biomass.

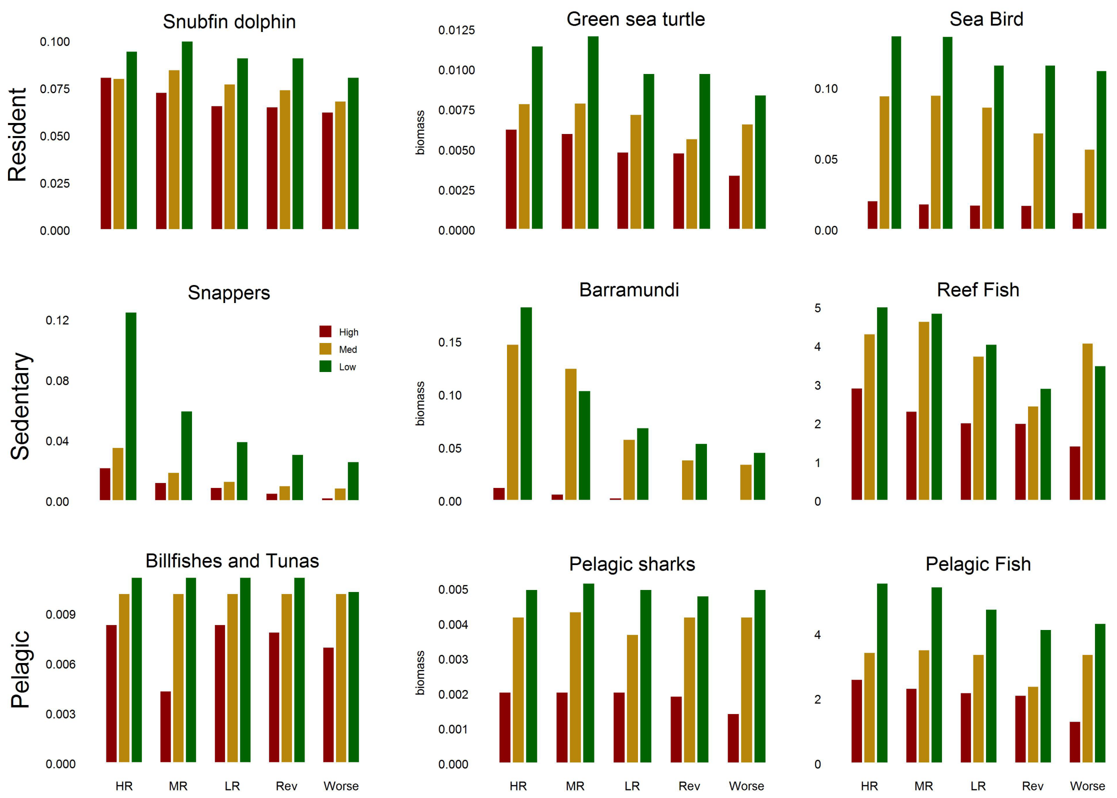


Figure 16. Simulated changes in the absolute biomass of the functional groups at the end of simulations (2050) under different management strategies. Red, yellow and blue bars refer to ‘High’, ‘Medium’ and ‘Low’ pressure, respectively.

The analysis of Figure 16 and Figure 17 leads to the following observations:

1) The introduction of larger Sanctuary Zones (Medium and High management strategies, which include 20% to 30% increase in Sanctuary Zones compared to today) would benefit the total biomass (Figure 17);
2) The marine parks effectiveness varies between functional groups. Marine parks appear more effective for relatively sedentary species such as reef fishes than for migratory species such as sharks, billfishes and tunas. Also, noticeable increments are shown for exploited species such as Barramundi, Snappers and Emperors. These results suggest that Sanctuary Zones within the marine parks are an important tool to meet conservation objectives (Figure 16); and
3) For some functional groups the main variability in biomass is due to the different scenarios (for example, biomass is severely reduced under ‘High pressure’ scenario, especially so for Snappers, Barramundi and Seabirds). Nevertheless, within each scenario, management strategies can still play a significant role in allowing the preservation of species (like Snappers, Barramundi) which otherwise may see their biomass decrease below critical levels.

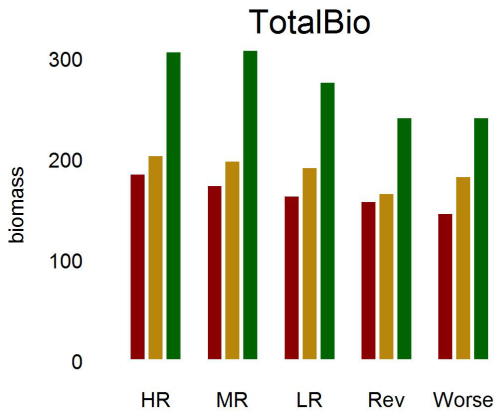


Figure 17. Simulated changes in the absolute total biomass at the end of simulations (2050) under different management strategies. Red, yellow and green bars refer to ‘High’, ‘Medium’ and ‘Low’ pressure, respectively.

To appreciate the impact of the management strategies on a larger set of indicators, in Figure 18 we show the bar plots of the state of all indicators (y axis) at the end of Ecospace simulation (2050). Beige bars show the ratio of change over the value at the beginning of the simulation (2015), similar to the scenarios in Figure 8. Purple bars show the contribution provided by a management strategy, compared to the performance of the ‘Medium Conservation’ management strategy. For example, in the bar plots for the ‘High Conservation’ (left-most column) almost all purple bars indicate positive values, reflecting the fact that a higher conservation initiative leads to an increase of biomass for almost all indicators. (Obviously, no purple bar plots can be seen for the ‘Medium Conservation’ - second column from the left - since its performance is compared against itself).

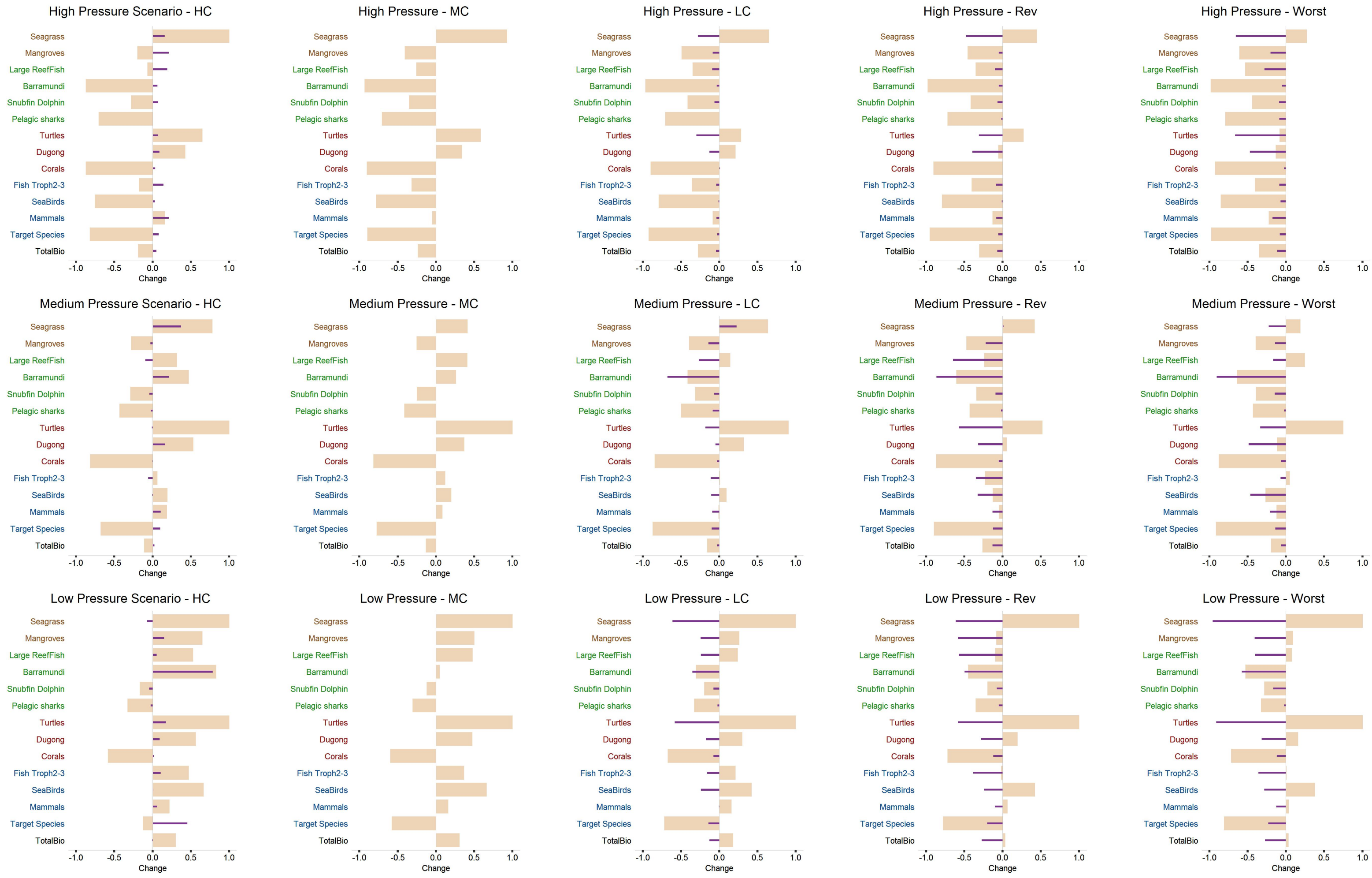


Figure 18. Bar plot of the state of all indicators (y axis) at the end of Ecospace simulation (2050). Pink bars show the ratio of change over the value at the beginning of the simulation (2015). Purple bars show contribution provided by a management strategy, compared to the contribution of the 'Medium' management strategy.

Finally, we have applied a cluster analysis to the end states of the system under different management strategies, as we did for the scenario analysis. The results are shown in Figure 14, where different clusters are represented with different colours. The visual inspection of these clusters confirms the general results described so far in this section. Pressure due to different scenarios ('High', vs 'Medium' vs 'Low') still has a clear impact on the clustering (vertical differentiation). However, the effect of the management strategies is also noticeable (horizontal differentiation) especially in the 'High' and 'Medium' strategies on the one hand, vs the 'Reversed' and 'Worst' strategies on the other.

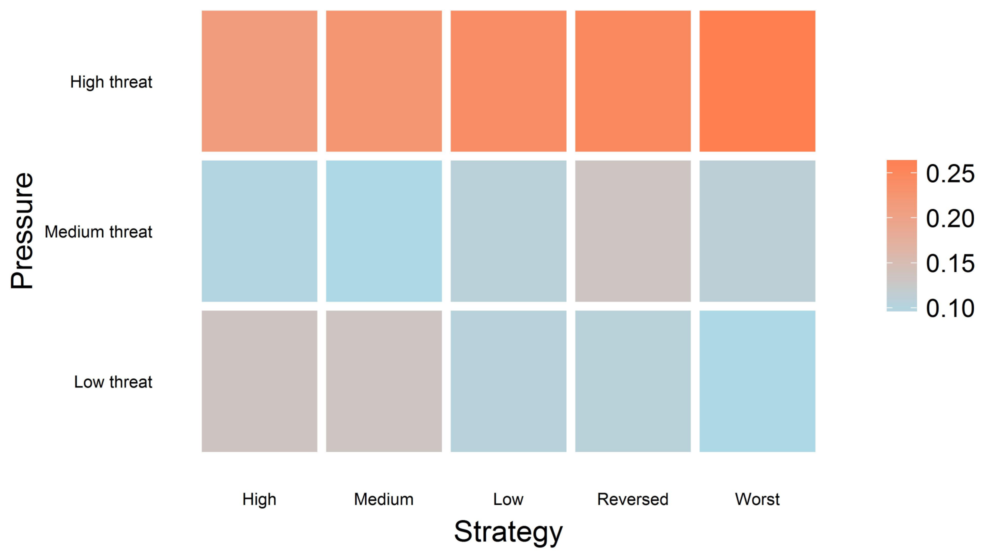


Figure 19. Total Divergence between the end states for each of the 5 management strategies under the 3 pressure scenarios and the state of the system, at the beginning of the simulations.

Figure 19 shows the Total Divergence between the end states for each of the system under different management strategies and the state of the system at the beginning of the simulations, as we did for the scenarios in Figure 13. Recall that this image is less informative than the result of the cluster analysis (see discussion in Section 13). Nevertheless, Figure 19 reminds us once again how the impact due to warming is the main stressor the region is likely to have to address and that the efficacy of any strategy will largely depend on this.

To conclude this section, it is important to remind the reader that the reliability of these results needs to be verified with local biomass sampling inside and outside of the sanctuary zones. Assumptions about movements and migrations also need to be verified and biomass estimates improved. Overall, a better model parameterisation would allow better analysis of trends in target species such as Barramundi, Threadfin, Spanish mackerel, Snappers and Emperors. For example, the dispersal rates for most of these target species is difficult to estimate given sparse information on movement behaviour of species in the Kimberley region, although it is likely to have important effects on the overall outputs. An improved understanding on the biology of key species would also strengthen some of the assumptions in the model parameterisation employed in this study.

5. Discussion and Conclusions

Figure 20 attempts to summarise this project, by trying to capture its scope, what was learnt about the functioning of the overall Kimberley and the core results generated by the research.

The marine ecosystem (EwE panel) receives pressure from both natural and anthropogenic land-based processes (ALCES panel) mediated by a number of coastal processes and socio-economic processes (panel c) which include tourism, population growth, changes in wetland and mudflat covers as well as catchment discharges in term of nutrient, sediments and pollutants. The marine ecosystem is also driven by oceanographic processes (panel a) which include cyclones, currents and tides. All these processes act at a regional scale, which motivated the choice of the model domains (panel c). Acting at an even larger scale, climate change has an impact on the marine environment both directly, in the form of sea level rise and sea surface warming and indirectly by altering precipitation regimes, affecting ocean currents and potentially impacting on a number of land processes (fire regiments, viability of agriculture and farming industry, etc). Climate change can also affect the marine ecosystem by altering some biological and metabolic processes in marine life forms, with potentially profound effects whose details are currently largely uncertain. The computer models used in KMRP Project 2.2.8 included all of these processes either directly as model components, or indirectly in the form of model parameters or external forcing. Parametrising EwE and the ALCES models so that they represented the Kimberley land and marine systems to the very best of our current knowledge should be considered as one of the main legacies this project will leave which will be available for further research.

These models have then been used to test the system's response to specific conditions (scenarios) and management options which the project stakeholders have recognised as most plausible and of management significance (panel d).

By using the models we have learnt that the number of scenarios we tested can be grouped into three main levels of pressure (Scenario Analysis in panel d) largely as a result of climate change induced warming being the stressor which largest impact on the system, followed by the changes in precipitation regimes and socio-economic development. Nevertheless, these stressors do interact. As a result, given a specific level of climate change warming, socio-economic development can add further significant pressure to a system already under stress (Strategy Analysis in panel d and panel h).

We have also learnt that, irrespective of the modelled scenarios, the system displays behaviours which are intrinsic to its own dynamics. These include a clear bottom-up dynamics (panel e) and an oscillation in the distribution of its biomass with a main period of around 20 years. While the details are largely uncertain, this internal dynamics deserves further investigation since it has the potential of affecting the system resilience to both major natural and man-made events.

Different species in the marine foodweb are likely to respond differently to the pressures described above. Panel g shows that some species are 'winners', that is are likely to see their biomass increase under most modelled scenarios, while others may lose out. Also, some species are likely to show more sensitivity to scenario variability than others.

Similarly, species may respond differently to the management strategies we modelled (panel h) and overall management of the marine parks in terms of sanctuary area extent, has the potentially to considerably alleviate the pressure imposed on the system by the interaction of climate and development stressors.

Obviously, almost every aspect of this work could be improved by including better information on local marine processes and more and better data on the modelled species. Should resource become available to further this work, choices will have to be made to decide what improvement should take priority. To this aim, in panel i we provide an approximate classification in terms of likely impact on the model performance vs the expected effort and cost in collecting better data.

We conclude by reminding the reader that the climate scenarios used in this work are the same as recommended by IPCC. These scenarios do not express the probabilities of different levels of warming by mid-century, but the expected warming as a function of anthropogenic CO_2 emissions. Because anthropogenic CO_2 emissions change very slowly and their impact on the climate has a delayed response, the likelihood of the modeller scenarios to occur will become better defined in the years to come. Monitoring the species which our models have identified as most sensitive to these scenarios should provide further evidence on whether the system is changing as our models suggest. Providing this opportunity to monitor, evaluate and anticipate expected changes is the second main legacy this project leave to the future management of the region.

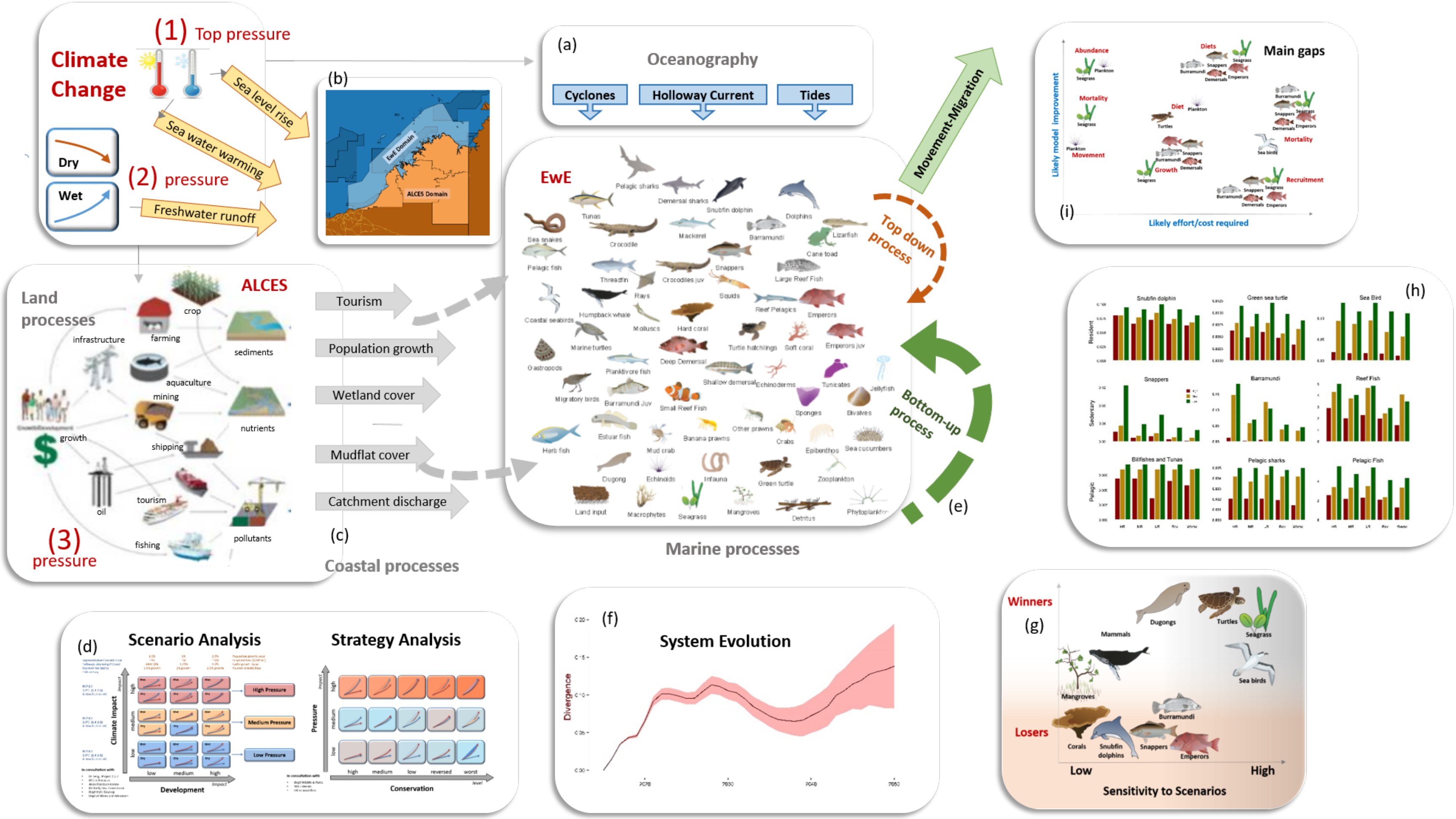


Figure 20. Conceptual model of the functioning of the Kimberley system, including the main result from this project.

6. References

Alford K, Cork S, Finnigan JJ, Grigg N, Fulton B, Raupach MR (2014) The Challenges of Living Scenarios for Australia in 2050. Journal of Futures Studies 18:115-112

Bezold C (2009) Jim Dator's Alternative Futures and the Path to IAF's Aspirational Futures. Journal of Futures Studies 14:123-134

Bezold C (2010) Lessons from using scenarios for strategic foresight. Technological Forecasting and Social Change 77:1513-1518

Bootz J-P (2010) Strategic foresight and organizational learning: A survey and critical analysis. Technological Forecasting and Social Change 77:1588-1594

Boschetti F, Price J, Walker I (2015) Myths of the Future and Scenario Archetypes. Technological Forecasting & Social Change in print

Cha S-H (2007) Comprehensive survey on distance/similarity measures between probability density functions. City 1:1

Cheung WWL, Jones MC, Reygondeau G, Stock CA, Lam VWY, Frölicher TL (2016) Structural uncertainty in projecting global fisheries catches under climate change. Ecological Modelling 325:57-66

Cheung WWL, Lam VWY, Sarmiento JL, Kearney K, Watson R, Pauly D (2009) Projecting global marine biodiversity impacts under climate change scenarios. Fish and Fisheries 10:235-251

Cronin MA, Gonzalez C, Sterman JD (2009) Why don't well-educated adults understand accumulation? A challenge to researchers, educators, and citizens. Organizational Behavior and Human Decision Processes 108:116-130

Curry A, Schultz W (2009) Roads Less Travelled: Different Methods, Different Futures. Journal of Futures Studies 13:35-60

De Vries B (2007) Scenarios: guidance for an uncertain and complex world? In: Costanza R, Graumlich L, Steffen W (eds) Sustainability or collapse? MIT Press, Cambridge

Dearing JA, Bullock S, Costanza R, Dawson TP, Edwards ME, Poppy GM, Smith GM (2012) Navigating the Perfect Storm: Research Strategies for Socialecological Systems in a Rapidly Evolving World. Environmental Management 49:767-775

Dorner D (1996) The Logic Of Failure: Recognizing And Avoiding Error In Complex Situations. Metropolitan Books, Ney York

Durance P, Godet M (2010) Scenario building: Uses and abuses. Technological Forecasting and Social Change 77:1488-1492

Feng M, Slawinski D, Shimizu K, Zhang N (2017) Climate variability and change. Book Final Report of Project 2.2.7. Western Australian Marine Science Institution, Perth, Western Australia

Halford GS, Baker R, McCredden JE, Bain JD (2005) How many variables can humans process? Psychological Science 16:70-76

Hunt DVL, Lombardi DR, Atkinson S, Barber ARG, Barnes M, Boyko CT, Brown J, Bryson J, Butler D, Caputo S, Caserio M, Coles R, Cooper RFD, Farmani R, Gaterell M, Hale J, Hales C, Hewitt CN, Jankovic L, Jefferson I, Leach J, MacKenzie AR, Memon FA, Sadler JP, Weingaertner C, Whyatt JD, Rogers CDF (2012) Scenario Archetypes: Converging Rather than Diverging Themes. Sustainability 4:740-772

Kok K, Gramberger M, Karl-Heinz S, Jager J, Omann I (2011) Report on the New Methodology for Scenario Analysis, Including Guidelines for Its Implementation, and Based on an Analysis of Past Scenario Exercises. The CLIMSAVE Project

Libralato S, Christensen V, Pauly D (2006) A method for identifying keystone species in food web models. Ecological Modelling 195:153-171

Miller AW, Reynolds AC, Sobrino C, Riedel GF (2009) Shellfish Face Uncertain Future in High CO2 World: Influence of Acidification on Oyster Larvae Calcification and Growth in Estuaries. PLOS ONE 4:e5661

Moxnes E (1998) Overexploitation of renewable resources: the role of misperceptions. Journal of Economic Behavior and Organization 37:107-127

Moxnes E (2000) Not only the tragedy of the commons: misperceptions of feedback and policies for sustainable development. System Dynamics Review 16:325-348

Moxnes E, Saysel AK (2009) Misperceptions of global climate change: information policies. Climatic Change 93:15-37

Pinnegar J, Viner D, Hadley D, Sye S, Berkhouf F, Simpson M (2006) Alternative future scenarios for marine ecosystems. The University of East Anglia

Ramirez R, Wilkinson A (2013) Rethinking the 2*2 scenario method: Grid or frames? Technological Forecasting and Social Change

Raskin P, Monks F, Ribeiro T, Van Vuuren D, Zurek M (2005) Global scenarios in historical perspective. In: Carpenter SR, Pingali PL, Bennett EM, Zurek MB (eds) Ecosystems and Human Well-being, Book 2. Island Press, Washington, DC.

Raven PG (2014) The future's four quarters: Proposing a quadrant methodology for strategic prototyping in infrastructural contexts. Technological Forecasting and Social Change 84:115-130

Riahi K, Grubler A, Nakicenovic N (2007) Scenarios of long-term socio-economic and environmental development under climate stabilization. Technological Forecasting and Social Change 74:887-935

Riahi K, Rao S, Krey V, Cho CH, Chirkov V, Fischer G, Kindermann G, Nakicenovic N, Rafaj P (2011) RCP 8.5-

A scenario of comparatively high greenhouse gas emissions. Climatic Change 109:33-57

Sterman JD (2008) Risk Communication on Climate: Mental Models and Mass Balance. Science 322:532-533

Sweeney LB, Sterman JD (2000) Bathtub dynamics: initial results of a systems thinking inventory. System Dynamics Review 16:249-286

Tufte ER (1990) Envisioning information. Graphics Press, Cheshire, Conn. (P.O. Box 430, Cheshire 06410)

7. Appendices

Appendix A: Communication Activities – Publications, Presentations, Media releases

Students supported
Journal publications **N/A**
Proceedings/Technical Reports
Submitted manuscripts **As above**
Presentations WAMSI Research Conference 2015, Title: Knowledge integration and MSE modelling, Perth, 30-31 March 2015 WAMSI Research Conference 2017, Title: Knowledge Integration and Management Strategy Evaluation (MSE) Modelling, Perth, 28-29 November 2017 AMSA Conference 2017, Title: Integrated land-sea modelling of the Kimberley, Darwin, 3-6 July 2017 DPAW Lunch n Learn Session – Title: Using models to predict future scenarios in the Kimberley region, 16th October 2017
Other communications achievements **WAMSI bulletin- Modelling a picture of the future Kimberley marine environment (published May 2017):** **http://www.wamsi.org.au/news/modelling-picture-future-kimberley-marine-environment**
Knock on opportunities created as a result of this project
Key methods for uptake (i.e. advisory committee, working group, website compendium of best practice.) **Fabio Boschetti - Lunch and Learn presentation at Parks and Wildlife – 16th October 2017 – Using models to predict future scenarios in the Kimberley region** **https://www.youtube.com/watch?v=l5DNttxz0IE&feature=youtu.be**
Other KMRP 2.2.8 Summary (August) – Modelling the future of the Kimberley region: **https://indd.adobe.com/view/7469ca20-97b2-4c97-ab1b-2978f2b2536f**

Appendix B: Management Questions

Key Question Informed Response
What are the main climate change threats to the marine biodiversity of this region (e.g. air and sea temperature rise, cyclone intensification, acidification, etc) and how will this impact the people that live in and use the Kimberley? a. How will existing marine habitats and communities and large marine fauna populations change? b. Which species and communities are threatened? a. Our results suggest that there is a strong link between climate (Sea Surface Temperature warming) and ecosystem productivity in the Kimberley. Both the total biomass of marine species and the distribution of biomass between these species are predicted to be affected by climate change. This impact is predicted to be particularly significant under the high climate change scenario associated with RCP8.5 emission scheme. In addition to warming, it is important to consider changes in the frequency of extreme weather events and in the patterns of rainfall and droughts observed in the Kimberley, which could also have significant impacts on biomass and biodiversity. In the current models, these are accounted for only as mean changes in precipitation, but the timing of these event and magnitude of outliers can also have a considerable impact on the marine environment. It is also important to obtain better knowledge of the possible impact of acidification on a number of marine species and the timing when this is likely to significantly affect the region. Currently, little information on the impacts of ocean acidification on several taxa is available, and even less for specific species in the Kimberley. Moreover, data produced in the laboratory are not easily transferred to the EwE framework. To complicated things further the response to ocean acidification is variable among species, including those that are closely related, requiring caution when we try to generalize data from one species to another (Miller et al. 2009). Based on the available literature, we imposed an additional 3% mortality (Ecosim) within five years to corals, crustaceans, echinoderms, molluscs and prawns. We acknowledge that the magnitude of this effect is a guess. b. The EwE Kimberley model predicts important changes in the energy pathways and trophic interactions in the food web under medium and high climate change by 2050. The lower part of the food web is a key component in the functioning of the Kimberley. Benthic primary production associated with seagrass and macroalgal assemblages provide food resources and shelter to diverse communities of invertebrates and finfishes. Under a high climate change scenario (RCP8.5) some “sedentary” fish species such as barramundi, emperors and snappers are negatively impacted. Coral species are also severely threatened by climate change. The future scenarios showed that corals could struggle to survive to 2050 under a high RCP8.5 scenario unless some means of increasing their adaptive capacity (either through natural evolution or human intervention, as has been proposed for the Great Barrier Reef) is found.
What are good potential indicators of asset (whales, corals) condition and pressure in relation to climate change? From our modelling results, we suggest the following groups as potential indicators of climate change induced pressure: 1. Species threated: biomass of corals and Barramundi 2. Species with intra-annual and inter-annual variation: seagrass abundance and distribution 3. “Sedentary” species with local spawning: emperors, snappers, reef fishes. 4. Habitats/species associated with runoff rivers: distribution and abundance of mangroves, migratory birds and prawns.

What are the stakeholders (incl. management agencies) capacities and requirements for adapting to climate change?

Adaptive capacity can be increased if useful information can be provided on future risks and opportunities. The ALCES and EwE Kimberley models are a valuable tool for management and adaptation for at least two reasons: First, they help assess the potential impact of climate change on marine resources. Second, they are an ideal tool for training and education, which can help build an intuition for how climate change can impact the region. For example, the ability to run specific climate change scenarios (e.g. impacts on mangroves) and produce outputs easy to understand (for example, changes in mangrove biomass and distribution) can be an important element to support both decision making and adaptation.

Stakeholders will need support (training) in how to access and interpret the models so that their value as a tool can be maximised. Consideration should also be given to ensure the effort is not undermined by personnel turnover.

How will climate change threats manifest in the Kimberley?

Climate change is likely to negatively impact the total biomass, diversity and productivity of the Kimberley marine system by 2050. It can also act as a source of system instability as in the case of high variability in extension of wetland, estuaries, mangroves, and sediments runoff under variable precipitation regimes which are currently hard to predict.

Climate change is likely to negatively impact the total biomass, diversity and productivity of the Kimberley marine system by 2050. It can also act as a source of system instability – as in the case of high variability in the extension of wetland, estuaries, mangroves, and sediments runoff under variable precipitation regimes, which are currently hard to predict. Climate change could also be seen as a “threat multiplier” when it was combined with development in the region, making other threats (e.g. pollution from tourism, habitat degradation) worse. Although the currently available information and associated model results suggest that the climate effects will dominate, it is also clear from the results that any management actions taken in conjunction with changing levels of human use in the system will need careful consideration given there is a non-linear interaction with the climate drivers

How they will respond e.g. shifts in distribution patterns, adaptation or local extinction.

The model outputs highlighted the role of marine parks as a tool to mitigate effects of climate change. “Sedentary” finfish species such as Barramundi, emperors, snappers and reef fish species were particularly negatively impacted by climate change. Pelagic species (E.g. billfishes and tunas) were less impacted probably for their high mobility. This highlight the need for future research to improve our knowledge of the biology (including distribution patters) of fish communities in the Kimberley and the degree to which they will shift geographically with time (to make sure Sanctuary zones continue to protect the most vulnerable species). The model identified corals as being highly vulnerability to climate change – with their biomass negatively depleted in all the 18 climate change scenarios (RCP2.6, RCP4.5, RCP8.5 under dry and wet conditions), in some cases (such as under ‘High Climate Pressure’) dropping to under 20% of the 2015 biomass estimate.

How will key biological and physical processes (e.g. calcification, connectivity, herbivory, predation) be influenced by climate change?

There are (at least) two sides to this question since climate change will affect both species interaction and the species own biology. For what regards species interaction, further modelling work could highlight how connectivity and energy pathways change as a function of the different scenarios. This analysis was not carried out in this work but it could with relatively little effort.

For what regards changes to species biology and metabolism, little is known in the literature. We carried out an extensive review and the limited information we found has been included in the current implementation of EwE.

This information however is largely qualitative and uncertain. Scientific development in this area are needed and could considerably improve further modelling.
Can the model be used to provide advice on the ratio and relative importance of pressures and from people and from climate change? This is addressed in sections 'Clustering of scenario results and analysis of stressors impact' and 'Ecospace results: impact of management strategies'.
NEW QUESTIONS POSED BY MANAGERS
These questions relate mainly to ecological layers and information. Will social and cultural layers be incorporated? This will improve the relevance of the project. Three types of data related to human behaviour were included in this work: i) projections of likely human pressure on the coast due to population pressure, recreational activities and tourism from the ALCES output, ii) projection of fishing effort and spatial distribution and ii) empirical evidence of coastal use from the KMRP Project 2.1.1. A decision was taken in the first year of the project not to include any cultural value since we do not believe that current modelling tools are effective in exploring cultural processes. Better information on human use could be included in future version of the models if made available.
Can this project cross reference with management questions from other projects to determine how this project can have additional input? As stated in the Introduction, this project addresses management questions at a regional scale. In doing so, it also provides a conceptual model of the functioning of the Kimberley system (Figure 20) which can help non-modellers better understand the interrelation between different management questions as well as how local information may improve the model and thus the overall system understanding.
What are the weakest information areas (data comparison)? This is addressed in Section 'Sensitivity analysis'. The Sensitivity analysis identified a number of groups, which include mostly primary producers and finfish, whose better parameterisation could mostly improve the EwE model (see functional groups highlighted in yellow in Figure 9). As can be seen, these include mostly primary producers and finfish. In Figure 10 we also provide an approximate assessment of the relation between ease of collection and likely impact on the model performance. The figure shows that data on groups' abundance, seagrass growth and mortality and plankton movement and migration are likely to represent the best 'improvement per effort' should more modelling work in the region be required.
What is the interaction between pressures? This is addressed in Section 'Clustering of scenario results and analysis of stressors impact'.
What impact is barramundi fishery having on mangrove habitat? We are not currently able to answer this question. However, with relatively little further investment in time and effort, modifications to the model and scenarios could be carried out to explore this issue. To do so, more Information on mangrove cover area, barramundi abundance, and local fishing data of landings and effort are needed.