Modelling regional futures at decadal scale: application to the Kimberley region

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Abstract

We address the question of how to provide meaningful scientific information to support environmental decision making at the regional scale and at the temporal scale of several decades. Our application is the management of a network of marine parks in the Kimberley region of Western Australia, where the key challenges to environmental sustainability are slow-dynamics climate change processes and one-off investments in large infrastructure, which can affect the future of a region for decades to come. In this situation, strategic, rather than reactive planning is necessary and thus standard adaptive management approaches may not be effective. Prediction becomes more urgent than adaptation, in terms of assessing the long term consequence of specific economic and conservation decisions. Working at the interface between future studies, socio-economic modelling and environmental modelling, we define 18 scenarios of economic development and climate change impacts and 5 management strategies aimed at ensuring the sustainability of the marine environment. We explore these potential future trajectories using coupled models of terrestrial land use and marine ecosystem dynamics. The Alces model simulates the dynamics of bio-physical and socio-economic processes on land and the pressures these impose on the coastal and marine environment. This forces an Ecopath with Ecosim (EwE) model used to simulate marine processes, foodweb dynamics and human activities in the marine environment. We obtain a projection of the Kimberley marine system to the year 2050, conditional on the chosen scenarios and management strategies, which is compatible with the best available knowledge of the current system state (as codified in the models' input) and system functioning (as represented in the models' dynamics). Our results suggest that climate change, not economic development, is the largest factor affecting the future of marine ecosystems in the Kimberley region, with sedentary species such as reef fish at greatest risk. These same species also benefit most from more stringent management strategies, especially expansion of sanctuary zones and Marine Protected Areas.

1 Introduction

The Kimberley region of Western Australia comprises ~420,000 km^2 on land and ~320,000 km^2 in the marine domain with a population of ~40,000. It is renowned for its remoteness, physical beauty, pristine ecosystems, diverse biota, complex coastline, and rich Aboriginal history. Large portions of the Kimberley are recognized as part of a conservation reserve network, including national parks and indigenous protected areas. It also possesses considerable natural resources in terms of minerals and offshore/onshore hydrocarbons, food production (agriculture, fishing and aquaculture) and a growing tourism industry. Both State and regional governments are committed to balance growth in population, economic activity and land, coastal and marine uses to ensure employment and improved standard of living for its current and future population with environmental and social objectives, including preservation of the natural heritage and the cultural values of its Aboriginal population.

To support coastal planning, reserve management, and future marine parks, the Western Australia Marine Science Institute addressed the bio-physical, ecological and social processes affecting the Kimberley marine environment. Our team was tasked with integrating information relevant to long term (up to the year 2050) management and decision-making, with specific focus on the management of a network of marine parks. In 2012 the Western Australia government established the North-west Network of Marine Parks in the Kimberley to protect one of the world's most ecologically diverse marine areas[20]. The network includes 13 Marine Parks located in the Commonwealth waters, between three and 200 nautical miles offshore. We included nine of these marine park in our study (Table 2, first column, nine top rows) covering ~90,000 km^2 (~30% of the total marine area) and contains seven proposed Sanctuary Zones covering ~10% of the marine parks, in which no fishing is permitted, plus six proposed Special Purpose Zones, which allow recreational but not commercial fisheries. (For details, see Supplementary Note, online.)

The standard conservation management method of adaptive management[1] is not suitable for this management task, for three reasons. First, economic development in the sparsely populated, remote and resource-rich Kimberley region will depend largely on one-off decisions regarding investment in large infrastructure such as roads, ports, mining sites and off-shore rigs. Once built, this infrastructure remains in place for decades, cannot be moved, and is amenable to only minor modifications. As a result, it can impose path-dependence on subsequent regional development and thus is not suitable to adaptive management style decision making. Second, one of the key management instruments currently available in the marine environment is the establishment of Marine Protected Areas (MPAs). This is subject to complex political processes and usually depends on one-off favourable circumstances largely disconnected from the normal functioning of adaptive management cycles. As a result, while adaptive management techniques are suitable for the management of existing MPAs, they are not generally appropriate for the designation of new MPAs. And third, the effects of climate change--one of the key stressors on the system in the future--are likely to unfold on a time scale too slow to provide appropriate feedbacks for adaptive management.

As an alternative to adaptive management, our approach borrows from the Future Studies and Foresight literature[2-6]. First, we involved the project's stakeholders in defining the stressors and sources of uncertainty which are perceived to have the largest impact on the future of the region. There was general consensus that the two key drivers are climate change and population growth/economic development, so our analysis explores scenarios representing various intensities of these two factors. Next, we asked stakeholders to define a set of available management strategies (means) able to achieve the stated aspiration of ensuring environmental sustainability together with economic growth and resilience to climate change (management end). Finally, we use computer modelling to explore the dynamics of biophysical and socioeconomic processes under a series of environmental scenarios and management strategies for the future. The outputs of our models represent the projection of the Kimberley marine system to the year 2050 conditional on the chosen scenarios and management strategies.

While the focus of the Kimberley Marine Research Program is the establishment and management of marine parks, it has been clear from the inception of our project that the impact of terrestrial processes on marine environments also had to be accounted for in order to provide useful management advice at a regional scale. To address this, our analyses include both a marine ecosystem model (Ecopath with Ecosim, or EwE[7]) and a terrestrial model (Alces[8]). (See Methods for a description of these models.) To our knowledge, this is the one of the first times that the output of a spatially explicit terrestrial ecosystem model has been used to drive a spatially explicit marine model.

Our approach is similar to the adaptive management in the involvement of stakeholders in the definition of ends and means of the management process. It differs in two important ways. First, it renounces the use of the adaptive cycle of implementation, evaluation, and modification, as deemed ill-suited for the problem at hand. Second, it places stronger requirements on the computer models because of both the spatial and temporal scales involved in the model projections. Well established, state-of-the-art model approaches and accurate parametrisation become even more essential than in standard modelling tasks. Here, we use well validated models to establish climate change as the most significant factor affecting the future course of marine ecosystems in the Kimberley region. We also identify groups of marine organisms at greatest risk from environmental change, and show that marine protected areas can mitigate at least some of that risk.

2 Results

2.1 Alces results

The output of the Alces model provided time series (2015-2050) of key drivers such as human population growth, change in areal extent of wetland and estuaries, increment in sediment yield transported by rivers, and change in water quality and quantity due to human activities. Projections of future population using low (1.5%/yr), medium (2.0%/yr), and high (2.5%/yr) growth rates suggest that the Kimberley region's population will grow from its current ~40,000 individuals to ~60,000-~120,000 by 2050, with concomitant increases in demand for housing, food, water, and electricity. Planned and proposed expansion of crop agriculture, grazing, and mineral and hydrocarbon extraction will also contribute significantly to future environmental impact.

This information was integrated into the EwE marine ecosystem model as forcing functions affecting marine primary production, consumption rates and natural and fishing mortalities. The Alces model predicted future trajectories of terrestrial habitat quality as a function of climate, grazing, crop agriculture, and other parameters. These projections, in turn, affect freshwater runoff and nutrient loading into the estuarine and marine environment and were used as ecological drivers affecting key parameters in EwE. For example, changes in terrestrial wetland extent based on human activity and climate change were used in EwE as ecological forcing with proportional effects on natural mortality, vulnerability to predation, and relative feeding rates of species associated directly with wetlands, such as migratory shorebirds, seabirds, juvenile fishes, prawns, oysters, and estuarine fishes. Similarly, predicted growth in tourist pressure leads to proportional changes in recreational fishing mortality, resulting in increments of mortality rates of 1.5% $year^{-1}$ (total 68% for low growth), 2% $year^{-1}$ (total 99% for medium growth) and 2.5%$year^{-1}$ (total 137% for high growth). Supplementary Table S1, online, shows in detail how outputs from Alces were linked to EwE species.

In at least some scenarios, incorporating terrestrial inputs from the Alces model significantly changed the outcome of the EwE marine simulations. To show this, we compared the output of EwE with vs without Alces input for the high climate impact, high development, wet scenario. For this scenario, Alces predicted a 17.9% gain in wetlands and estuaries at 2050. For comparison, we ran the same scenario in EwE with all terrestrial forcing removed.

Figure 1 shows the state of coastal functional groups and species in 2050, expressed as a ratio of a group's biomass with vs without Alces input. Incorporating Alces input changed final biomass by ~30-40% for several functional groups (seagrass, macrophytes, banana prawn, other prawns, estuarine fish, juvenile barramundi, and birds), with smaller changes for additional groups (crabs, green sea turtle, juvenile crocodile, and herbivorous fish).

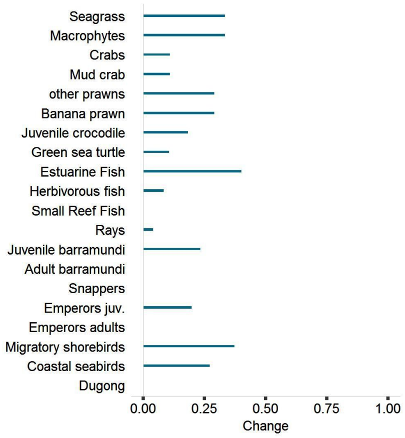


Figure 1. Ratio of change of the values at the end of the simulation of the High Climate, High Development, Wet scenario accounting for Alces input vs the same scenario *not* accounting for Alces input.

2.2 Dynamics of the marine ecosystem

Figure 2 shows the change in biomass of all indicator taxa over the 35 years of the EwE simulations. The plot aggregates the outcome across all 18 climate change/development scenarios (low, medium and high climate change for dry and wet conditions) under the status quo management strategy. Values <0 (>0) imply decrease (increase) in biomass over the simulated timespan.

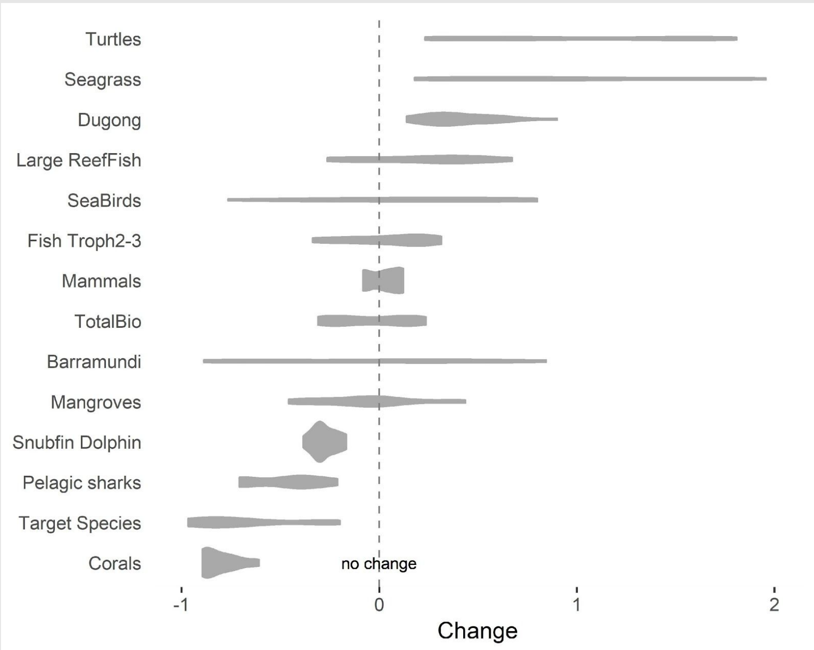


Figure 2. Violin plot of the state of all indicators (y axis) at the end of simulation (2050), expressed as ratio of change over the value at the beginning of the simulation (2015). For each indicator, the violin plot shows the probability density of the data at different values, aggregated across all scenarios.

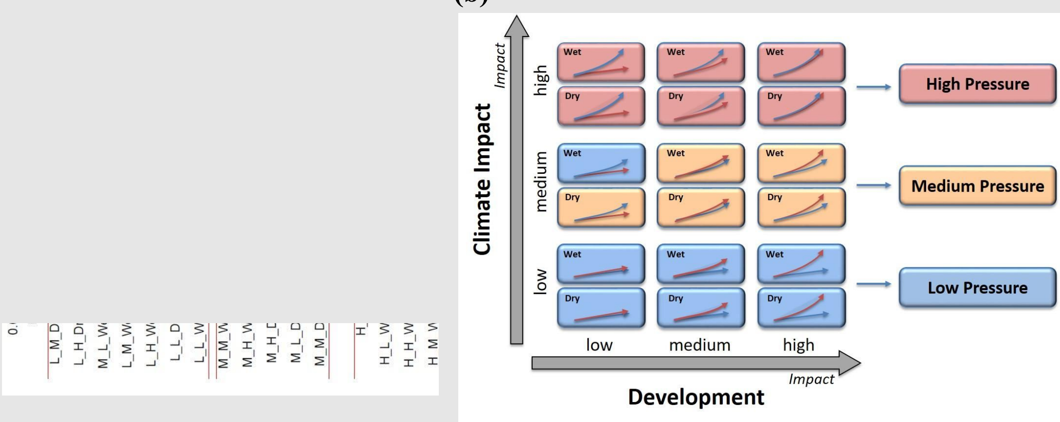
The indicators can be grouped into four types according to the location and width of their distributions:

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 2, implying that biomass changes are >0 for all scenarios. These include seagrass and, as a result, turtles and dugongs that 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 2, implying that biomass changes are <0 for all scenarios. These include target species, corals, snubfin dolphins and pelagic sharks.
3) Low scenario-sensitivity: these are the groups whose final biomass is not much affected by the different scenarios, as shown by a narrow plot. 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 the scenario; and
4) High scenario-sensitivity: the groups whose final biomass is significantly affected by the different scenarios, as shown by a wide plot. These include: seagrass, turtles and seabirds.

The response of each indicator to each specific scenario is provided in Supplementary Figure S1, online.

Next, we focus on the scenarios. To explore whether the 18 modelled scenarios for climate change and human development fall into natural groupings, we performed cluster analysis using Total Divergence (see Supplemental Material) in biomass at the end of each scenario. Figure 3a shows the result of hierarchical clustering applied to the 18 scenarios. The scenarios clearly fall into 3 clusters as in Figure 3b, which are supported by bootstrap analysis (see Supplementary Note, online).

(b)



(a)

Figure 3. Result of the hierarchical clustering applied to the 18 scenarios (3 climate scenarios * 3 development * 2 precipitation regimes). (a) The cluster dendrogram suggests that the scenarios can be grouped into 3 clusters. (b) The 6 x 3 Future plane consisting of the Climate Change and Development axes. Each axis is subdivided into low, medium, and high impact. In addition, each cell on the plane shows ‘drier’ and a ‘wetter’ sub-scenarios. 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 3b shows how the distribution of the clusters over the Future plane is controlled mainly by climate change (y axis). Within this main layering, forcing due to the precipitation regimes affects the middle cluster by assigning the Medium Climate - Low Development - Wet Precipitation scenario to the Low Climate cluster. Forcing due to socio-economic development (x axis) does not affect the clusters. As a result, our analyses of the impact of different management strategies will focus on the three climate-change clusters. In particular, we selected one scenario to represent each cluster, which we will refer to as ‘High’ (High Climate, High Development, Dry Precipitation), ‘Medium’ (Medium Climate, Medium Development, Dry Precipitation) and ‘Low Pressure’ (Low Climate, Low Development, Wet Precipitation),

Next, we assessed the impact of management strategies. None of the management strategies significantly altered the assignment of indicators to “winner” and “loser” categories (data not shown). Figure 4 shows the impact of management strategies on total marine biomass in 2050. More stringent conservation management leads to a small but definite increase in total biomass under all levels of climate pressure.

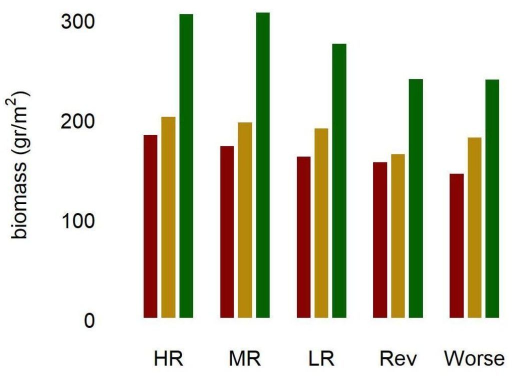


Figure 4. Simulated changes in the absolute total biomass at the end of simulations (2050) under different management strategies. HR = high regulation; MR = medium regulation; LR = low regulation (status quo); Rev = reversal of current conservation regulation; Worst = collapse of all regulation (see Methods for further description). Red, yellow and green bars represent ‘High’, ‘Medium’ and ‘Low’ pressure, respectively.

Figure 5 shows biomass changes for specific functional groups of management significance, and Supplementary Figure S2, online, shows biomass changes for all indicators for each management strategy. While increased regulation benefits all groups to at least a small degree, the effect of more stringent regulation is much stronger for certain groups, notably relatively sedentary species, such as reef fishes. For many groups, the main factor affecting biomass in 2050 is climate change. For example, biomass is severely reduced under the High pressure scenario, especially for snappers, barramundi, and seabirds. Nevertheless, within each scenario, management strategies can still play a crucial role in allowing the preservation of species such as snappers and barramundi, which otherwise may see their biomass decrease below critical levels.

More stringent management strategies include both larger and more numerous MPAs and more restrictive fishing regulations. To show that MPAs are an important management tool, we compared model output biomass with and without the MPA network under the same fishing regulations for the H_H_Dry scenario. Results are shown in Supplementary Figure S3, online. Biomass for most species decreases in the absence of MPAs. Species showing the largest effect are barramundi, snappers, emperors, and dugongs. In contrast, their prey show an increase in biomass in the absence of MPAs.

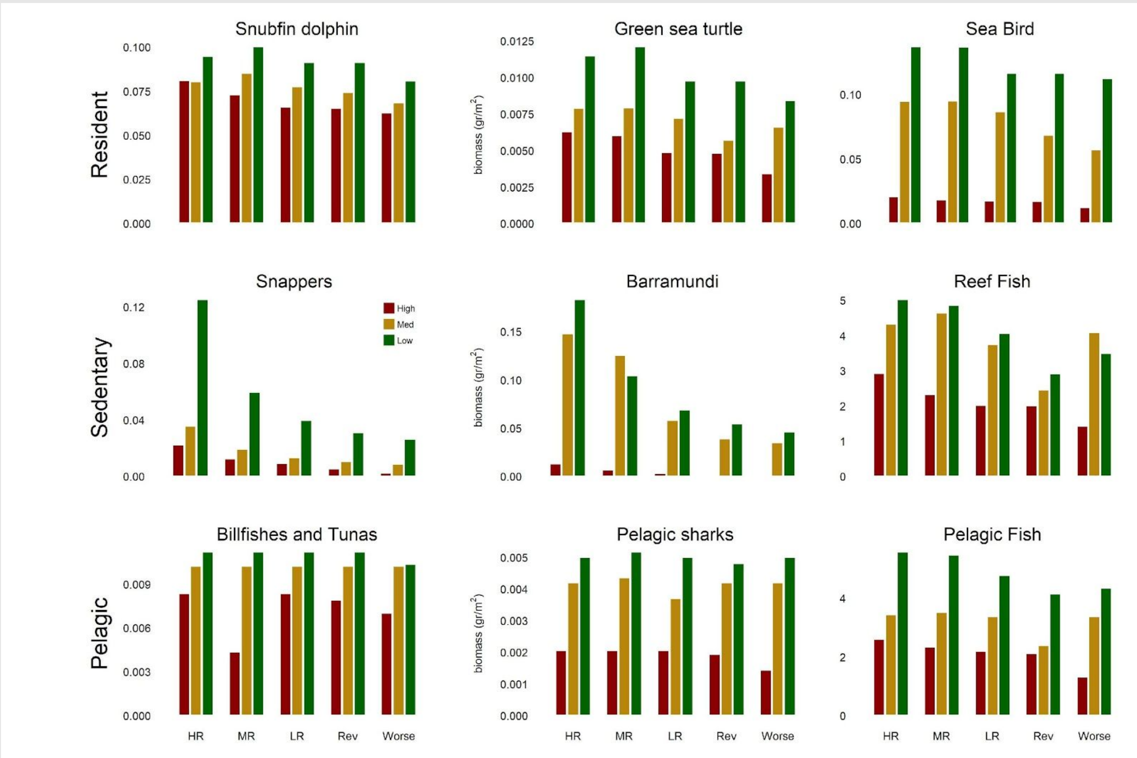


Figure 5. Simulated changes in the absolute biomass of the functional groups at the end of simulations (2050) under different management strategies. Top row, resident reef species; middle row, sedentary species; bottom row, pelagic species. Red, yellow and green bars refer to 'High', 'Medium' and 'Low' pressure, respectively. Management strategies as in Figure 4.

3 Discussion

Our study couples a detailed spatial model of the impacts of terrestrial land use (Alces) to a similarly detailed spatial model of marine trophic networks (EwE). Few other studies have integrated terrestrial and marine dynamics [9-11]. Our results show that even for the sparsely populated Kimberley region, where the anthropogenic footprint is extremely light, incorporating the effects of terrestrial land use can alter model outputs of marine biomass by 30 to 40% for some groups. In other locations where human activity is more intense, we would expect that terrestrial land use might have an even larger effect on marine ecosystem models. Similarly, if economic development proceeds in the Kimberley region much more quickly than our models envision, its impact on the marine environment is likely to be larger than our models indicate. Moreover, we would expect land use to have more noticeable effects on marine systems at a local scale, particularly at or near river mouths and centers of population or industrial activity. Such local effects can be tracked in the Alces model, but are beyond the scope of this study.

Our results suggest that different portions of the marine ecosystem may respond differently to different climate and development pressures. By the year 2050, the state of some groups (e.g., seagrass, turtles, and dugongs) varies dramatically from scenario to scenario, while others (e.g. corals, snubfin dolphins, mammals, mangroves) may show little variation (Figure 6, x axis). Groups predicted 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 factors driving this sensitivity. Second, the sensitivity of some marine communities to climate change provides a good indicator for the early detection of system responses that can help identify which, among the modelled scenarios, the system is heading towards [12,13].

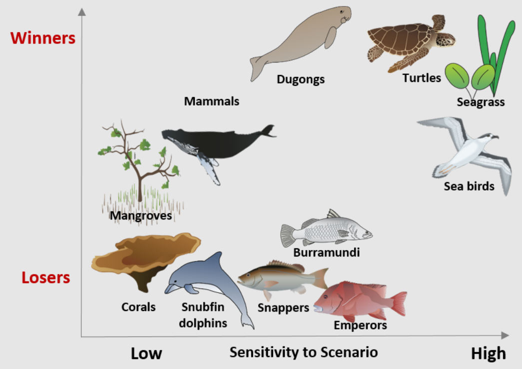


Figure 6. Plot of some functional groups over 'sensitivity to scenario' vs 'winners-losers' axes. The 'sensitivity to scenario' axis indicates how much the response of a function group varies between different scenarios. The 'winners-losers' axis shows the extent to which the group biomass increases or decreases during the simulation as a function of the scenario.

Some functional groups (corals, snubfin dolphins, pelagic sharks) are consistently losers and others (seagrass, dugongs and turtles) are consistently winners under a wide variety of scenarios, while other groups' performance depends considerably on the precise scenario which may eventuate (Figure 8, y axis). These results can provide managers with an indication of the expected direction, magnitude, and consistency of a group's response to changing climate or development and thus the extent to which a management intervention targeted at a specific group is likely to succeed. Of particular note, corals show pronounced declines in biomass under all climate change scenarios, in some cases falling below 20% of 2015 biomass. Corals could struggle to survive to 2050 under a high climate change scenario unless some means can be found to increase their adaptive capacity, either through natural evolution or human intervention, as has been proposed for the Great Barrier Reef[14,15].

Our comparisons of the outcome from different climate change and development scenarios suggests that climate change is the primary factor affecting the future course of ecosystem response (Figure 2), although the effects of economic development acting through terrestrial inputs will sometimes have measurable effects as well (Figure 1). The climate scenarios modelled in this work are the ones recommended by the Intergovernmental Panel on Climate Change (IPCC) [16]. These represent expected warming under different pathways of future anthropogenic CO_2 emissions. While there is uncertainty on which pathway will materialise (as well as on the level of warming produced by a given pathway[17]), anthropogenic CO_2 emissions change slowly and their impact on the climate has a delayed response[17]. This means that the likelihood of occurrence of each modelled scenario can be assessed in advance and will become better defined in the years to come. This has two implications: i) CO_2 emission changes will likely occur smoothly, time for contingency planning is available and ii) impact of management actions will also be slow and subject to system inertia, which recommends strategic, rather than reactive, management.

The analysis of the available management options we have explored (Figure 4, 5) suggests that a 20% to 30% increase in Sanctuary Zone extension over present levels would lead to an increase in total system biomass under most scenarios. More specifically, Sanctuary Zone extension can be particularly beneficial to exploited species such as Barramundi, Snapper and Emperors and for relatively sedentary species such as reef fishes. These results suggest that sanctuary zones within the marine parks can be an important tool to meet conservation objectives in the face of changing climate.

Large knowledge gaps still exist which, if addressed, could considerably improve our models' forecasts. In particular, little information now exists about the biology of many species. This leads to uncertainty about how climate change will affect life history dynamics, geographic ranges, or the timing of migration or spawning of these species.

Our models also do not incorporate the effect of ocean acidification on the marine ecosystems of the Kimberley. Currently, little information is available on the impacts or time course of ocean acidification, particularly in the Kimberley. To complicate things further, the response to ocean acidification is variable among species, including closely related ones, requiring caution when we try to generalize data from one species to another [18].

Overall, climate change produces negative effects on the total biomass, diversity and production of the Kimberley system by 2050. It also serves as an "accelerant of instability"[19] because uncertain precipitation regimes lead to unpredictable variation in sediment runoff and area of wetlands, estuaries, and mangroves[20].

Our study shows the utility of ecological modelling as an alternative to adaptive management in guiding key decisions about the designation of marine protected areas as a conservation response to climate change. The model outputs highlight the role of MPAs as a valuable tool to mitigate the effects of climate change in the marine environment of the Kimberley region. Sedentary finfish species such as Barramundi, emperors, snappers and reef fish species are particularly negatively impacted by climate change, and these show the greatest benefits from expanded MPAs.

4 Methods

4.1 The Models.

The Alces model (www.alces.ca) is a landscape/landuse simulator suitable to explore the cumulative effects of land uses (residential, transportation, croplands, livestock, mining, oil and gas, forestry, tourism/recreation) and natural disturbances regimes (fire, insects, landslides, storms, climate, climate change) upon a comprehensive set of economic, social, and environmental outcomes. The model uses a map-based representation (5 x 5 m grid) layered with geospatial data on land uses (including residential, transportation, croplands, livestock, mining, oil and gas, forestry, and tourism/recreation), physical/climatic features (topography, soils, drainage, vegetation, temperature, precipitation, etc.) and natural disturbance (fire, insects, storms, etc.). It has been widely employed to explore future environmental trajectories and guide land use decisions in North and South America, Australia, India, and elsewhere[8].

In this project, the model is used to simulate the key dynamics of terrestrial land uses and landscapes in the Kimberley region, and to generate output that is relevant to the interface between terrestrial and marine ecosystems. The model was calibrated with best available data after extensive consultation with Australian federal, state, and regional governments, research institutes, resource companies, and other stakeholders. (For details of data sources, see [21].) We then use the model to explore 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 as forcing to the marine system model.

Ecopath with Ecosim (EwE; www.Ecopath.org) was used to characterise the trophic structure, ecosystem attributes and impact of fishing, other human uses and climate change on the marine environment. Ecopath is a mass-balance model that accounts for trophic interactions among organisms at multiple trophic levels by describing matter and energy flows[7]. Ecosim and Ecospace use the Ecopath model as initial conditions for temporal and spatial simulations of foodweb dynamics due to human activities and environmental drivers. The model covers an area of 316,966 square kilometres (17°34´S, 125°46'E) and contains 59 functional groups (~110 species), including two non-living groups (terrestrial inputs and organic detritus). A number of single species functional groups were defined for species of commercial or recreational fishing significance (e.g. Barramundi, Threadfin, Spanish mackerel). The model also represents marine mammals, sea birds, invertebrates and plants. An interactive visualisation of this food web can be found at http://www.per.marine.csiro.au/staff/Fabio.Boschetti/KimberleyMSE/network.html.

The EwE model was calibrated using time series (2010-2014) data of relative abundance estimates (catch per unit of effort CPUE) and catch data [22] of the major target finfish species (Barramundi, Threadfin , Gold snapper, Emperors and Mackerel) in the Kimberley .We adjusted estimates of predator-prey parameters that influence degree of density dependence and thus, the rates of change in the biomass of fished species[23]. In general, the predicted biomasses were within 20% of the observed values. We used Ecosim to evaluate the effects of climate change (including sea surface warming, sea level rise and changes in precipitation regimes), key land-based processes (modelled by ALCES), fishing and the overall impact of human presence in coastal areas (waste, pollution, infrastructure development and tourism.

The EwE models allowed us to explore the effects of different management options, such as controls on fishing effort and spatial closures related to MPAs. For this, we defined 15 indicators, which fall into five classes:

1) Meta groups: including target species (emperors, snappers and Threadfin); marine mammals, seabirds, and fish with trophic levels 2 to 3 (planktivorous fish, small reef associated, herbivorous fish).
2) Keystone species (defined as "relatively low biomass species with a structuring role in the food web"[24]): sharks, snubfin dolphin, barramundi and large reef fishes.
3) Charismatic species which hold a particular economic, social or cultural value to stakeholder groups: corals (hard and soft corals), marine turtles and dugong.
4) Habitats: seagrass and mangroves.
5) System level indicators designed to reflect the state of the overall food web rather than of some of its component: Here we used the Total Divergence, a modification of the 'Kullback–Leibler' distance [25] which measures changes in relative biomass of species while accounting for changes in overall biomass (see Supplementary Note and Supplementary Figure S4, online, for further explanation).

4.2 The scenarios

Based on stakeholder consultations that identified climate change and population growth/economic development as the key drivers of future change in the Kimberley region, we used these two factors in laying out the scenarios to be explored by our models. These two drivers define the Climate Change and Development axes of the Future Plane shown in Figure 3b. We subdivide each axis into three levels of increasing pressure: low, medium and high. Because of uncertainty in how climate change may affect precipitation regimes in the region, and the significant impact that different precipitation regimes can have in terms of agricultural productivity and sediment runoff in the marine environment, each level of climate change pressure is further divided into two precipitation regimes, low and high. This results in 18 (6 by 3) scenarios, which allow for an exploration of the interplay between climate and development pressure into the future.

The climate change scenarios selected are based on the simulations produced by 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 [26]. The RCP8.5 is based on upon a revision and extension of the IPCC A2 scenario and represents a worst-case possible future climate trajectory under on-going high carbon emissions [16]. We adopted RCP8.5 (which projects average global warming of 2.0 ºC (1.4 to 2.6 ºC range) and mean sea level rise of 0.30 m (0.22 to 0.38 m range) by mid-century) as the High Climate Change scenario for our model simulations. Following communication with the authors of [26] the Medium and Low Climate Change scenarios were obtained by scaling the output of the OFAM3 model by associating a radiative forcing of 4.5 W/m^2 and 2.6 W/m^2, respectively. These correspond to the RCP4.5 projections of 1.4 ºC (0.9 to 2.0 ºC range) warming and 0.26 m (0.19 to 0.33 m range) sea level rise and the RCP2.6 projections of 1.0 ºC (0.4 to 1.6 ºC range) warming and 0.24 m (0.17 to 0.32 m range) sea level rise, respectively[17].

To model 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 as provided in [27,28]. This forcing takes 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 [28,29] were incorporated as time series of forcing functions affecting directly biological production. This allowed us to represent physical factors affecting the Kimberley food web. The forcing function modified the rate of consumption (Q/B) of consumers affecting the growth rates and biomass production[7].

To explore the potential effects of climate change on the terrestrial domain, the Alces Kimberley simulator was forced with projected changes in temperature and precipitation as described under scenarios RCP 2.6, 4.5, and 8.5 provided by CLIMSystems. Temporal and spatial changes in temperature and precipitation were then used as forcing variables (through multiplicative modifiers) to assess their effects on sediment and nutrient transport relative to current and projected changes in land use sectors (crops, livestock, human population, tourism/recreation, mining, oil and gas). The equational logic describing these climate-induced modifiers is provided in the full technical Alces report at ??????.

The Development scenarios account for many sectors, including population, tourism, infrastructure development, agriculture, aquaculture, transport, mining and Oil & Gas. All these types of development are often correlated, and at the scale of this study, individual events often average out so that the broader trends resulting from their correlations matter most. Exact details about these scenarios, the rationale for their choice and the implications for each sector can be found at: http://www.per.marine.csiro.au/staff/Fabio.Boschetti//KimberleyMSE/PDF/Alces%20Synopsis.pdf).

We define three development scenarios, as summarized in Table 1. The scenarios were used to parameterize the Alces model of land use. Development scenarios are incorporated into the EwE model only indirectly, via the outputs of Alces. We load time series of Alces as reference data to force changes in Ecopath: (i) consumption rates (Q/B) and production rates (P/B); and in Ecosim changes involving: (i) vulnerability to predation, and (ii) natural mortality (M).

Table 1. Brief description of the Development scenarios. Unless otherwise specified, growth is expressed as annual means.

Development scenarios	**Low**	**Medium**	**High**
Average population growth / year	1.5%	2%	2.5%
Cropland Area (1,000 ha) (Ord River Basin 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 by mid-century	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 by mid-century)	7.7 M (1.5% growth)	9.8 M (2% growth)	12.5 M (2.5% growth)
Oil (m^3/yr) & LNG (peak Mtpa) by mid-century	As current	~400k Blina & Ungani Fields ~7.5 Browse Basin & Concerto	~600k Blina & Ungani Fields ~10 Browse Basin & Concerto

4.3 The Management Strategies

Potential management strategies reflect a spectrum of political attitudes toward marine conservation. Our approach 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 considering 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 decades to 2050, 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 consultation with the Department of Biodiversity, Conservation and Attractions and Department of Primary Industries and Resources, we defined five broad levels of regulation pressure which reflect political and social attitudes towards environmental conservation: 'High' (reflecting an increasing appetite for environmental conservation), 'Medium' (based around current regulations and expectations about proposed regulations currently in the pipeline), 'Low' (based around current regulations, in which the proposed regulations currently in the pipeline do not materialise), 'Reversed' (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) and 'Worst Case' (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. 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 spawning biomass that is allowed to be taken, as well as 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. 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. Details of the five management strategies are presented in Table 2.

Table 2. Description of the proposed Management Strategies. Description of the proposed Management Strategies with regards to fishing regulations. Description of the proposed Management Strategies with regards to Other Human Uses

Management Tools / Regulation pressure	High	Medium	Low	Reversed	Worst Case
Existing MPAs[1]	Yes	Yes	Yes	Yes	No
Proposed MPAs[2]	Yes	Yes	No	No	No
Sanctuary Zone extension (% of total park area)	30%	20%	10%	0	0
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

[1] 80 Mile Beach, Marine Park, Lalang-garram / Camden Sound Marine Park, Yawuru Nagulagun / Roebuck Bay Marine Park, North Lalang-garram Marine Park, Lalang-garram / Horizontal Falls Marine Park, North Kimberley Marine Park

[2] 80Mile Beach Commonwealth Marine Reserve, Roebuck Commonwealth Marine Reserve, Kimberley Commonwealth Marine Reserve

Accepted cumulative tourism-induced mortality[3]	0.3%	1%	5%	No limit	No limit
Accepted cumulative mortality[4] from other marine uses	0.3%	1%	5%	No limit	No limit

4.4 Sensitivity analyses

A sensitivity analysis of EwE outputs is presented in Supplementary Figure S5, online.

5 Availability of materials and data

The metadata associated with this project can be viewed at http://marlin.csiro.au/geonetwork/srv/eng/search#!078ffe36-d5f4-0f56-e053-08114f8c04ed. Both model input data and model simulation data are available at https://data.pawsey.org.au/public/?path=/WA%20Node%20Ocean%20Data%20Network/WAMSI2/KMRP/2.2/2.2.8/ALCES/Input_data.

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[3] 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.

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

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8 Author contribution statement

FB has led the overall project management and stakeholder engagement. HLM has implemented and run the EWE model. MH and JBS have implemented and run the ALCES Online model.

9 Competing interests

The authors have declared that no competing interests exist