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Challenges of crossing scales and drivers in modelling marine systems

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As system-level concerns increasingly dominate thinking and questions to do with resource management it is necessary to include an expanding list of processes, scales and drivers. This poses a large number of challenges when dealing with model components with different resolutions and native scales. Differential equations and other 'classical methods' are well suited to the representation of large bodies or large areas, but often fail when fine scale detail is critical. In contrast, individual based models (IBMs) are well suited for fine scale questions but are inappropriate (typically due to computation demands) for representing all components of a regional system-level model. Bringing both of these model types together in one framework shows great promise not only for representing ecological systems, but for addressing management questions. Lessons learnt from such an exercise on the Ningaloo Reef system (Western Australia) highlights the pitfalls and potential of taking marine management to regional, multiple use and fully dynamic scales. In particular, the work highlights how failing to take such approach can compound a failure to appreciate tradeoffs in the system with the human tendency to underestimate the impact of cumulative non-linear impacts.

Ningaloo-Exmouth region is an area of exceptional beauty and productivity that is supporting a diverse range of local activities (e.g. farming, fishing and oil and gas exploration), while also attracting national and international tourists. The proximity of Ningaloo reef to the coastline and the presence of Cape Range National Park in the same area mean that any development or growth of industries (including tourism) needs to be done with sustainability foremost in mind and with a minimum of unintended effects.

Avoiding unintended consequences is particularly important given the vulnerability of the area to cumulative impacts and the implications for pressure on water resources in such an arid area. The greatest influences on coastal systems like those in the Ningaloo-Exmouth region are: climate change; eutrophication and associated nuisance algal blooms; habitat degradation and destruction; species extinctions and introductions; pollutants; changes in water cycles; disturbance of biogeochemical cycles and physical properties like temperature, salinity and pH. Individually, each of these pressures can pose serious management challenges, but in combination their cumulative impacts can rapidly degrade the state of a system.

The new set of environmental conditions likely to be created in the Ningaloo-Exmouth region under global climate change (e.g. changes in weather patterns and oceanic water column properties like temperature and pH) are likely to impact the availability of water in the region and may also affect the resilience of the reef to other pressures. This makes any decision that may affect water or the reef of potential concern to the community, management bodies and every industry in the area. Regardless of what the final set of decision is, there will be tradeoffs between sectors and system components and potentially even between generations when addressing questions regarding

- the use open or restricted access (by area or activity) for managing load on the system;
- the speed of infrastructure and coastal development; and
- the relationship between environmental load, eco-efficient practices and technology, the sustainability of regional development and the carrying capacity of the area.

Preliminary results show that due to the location, isolation and the distribution of resources in the region, just a few decisions separate a possible future where governance and development encourages growth and sustainable industries, and a possible future where the capacity of the system is exceeded, at great environmental, social and economic cost.

Keywords: *ecosystem model, marine systems, management strategy evaluation*

1. INTRODUCTION

Through the course of the last century management focus has shifted from managing single components (species or industries) through to managing whole systems – i.e. the shift from single species management to ecosystem-based management in fisheries (Pikitch et al 2004). This is particularly important in coastal areas and on shelves, where there is the greatest overlap of human pressures and critical ecological processes and ecosystems services (Figure 1). The greatest influences on these coastal systems include: natural and anthropogenically driven climate change; eutrophication and associated nuisance algal blooms; habitat modification, degradation, destruction and fragmentation; species endangerments, extinctions and introductions; pollutants (including organic compounds and heavy metals); changes in water cycles; disturbance of biogeochemical cycles and physical properties like temperature, salinity and pH (Botsford et al 1997). In isolation each of these can pose serious management challenges, but in combination their cumulative impacts can bring on serious consequences more rapidly (Figure 2).

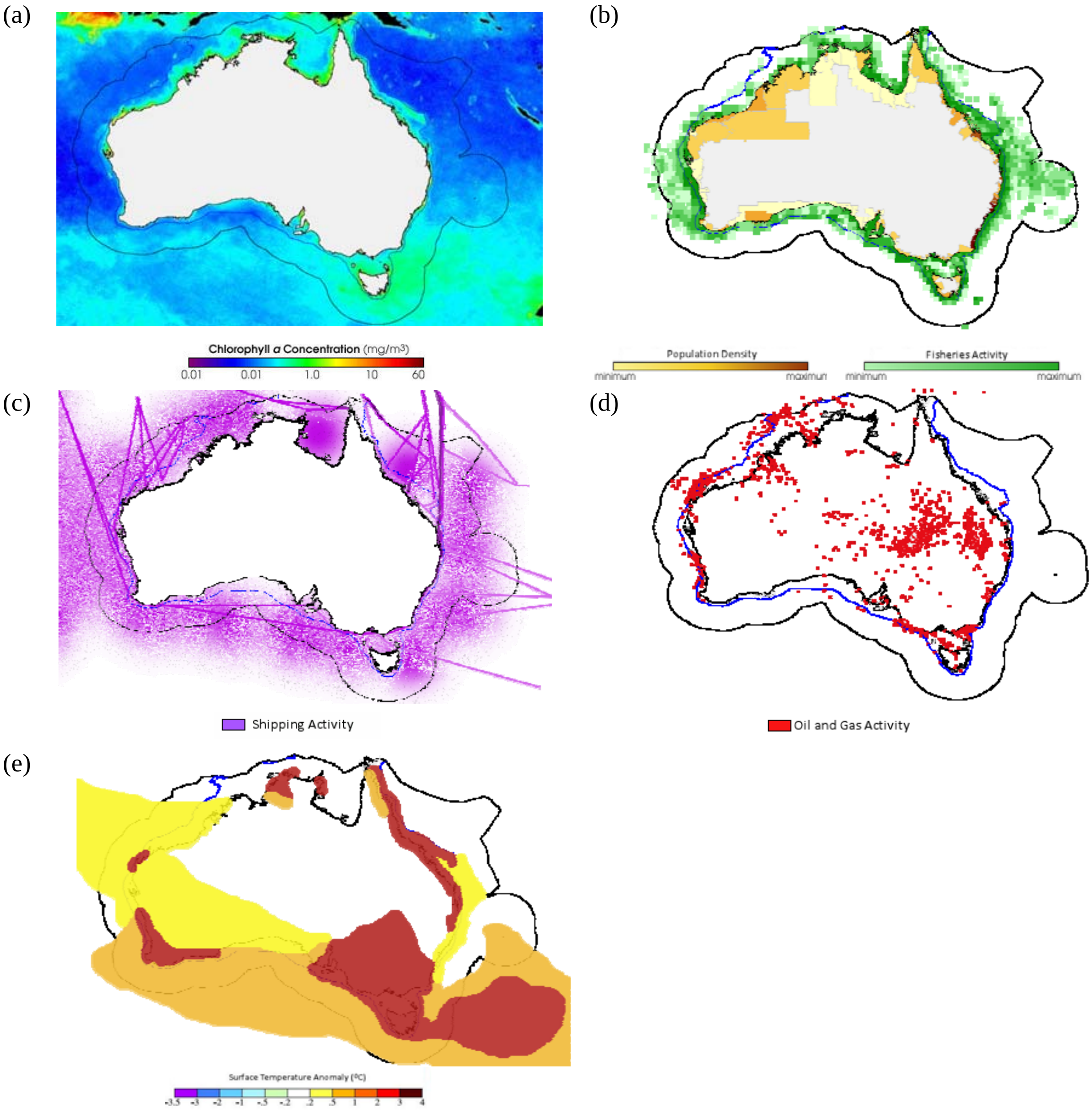

Figure 1. Maps of indices for (a) the concentration of ecological activity (in the form of primary production) in Australia's coastal fringe and the distribution of some of the strongest pressures on the system: (b) fishing and population density, (c) shipping, (d) oil and gas extraction and (e) predicted temperature increases in the next 50 years due to global climate change.

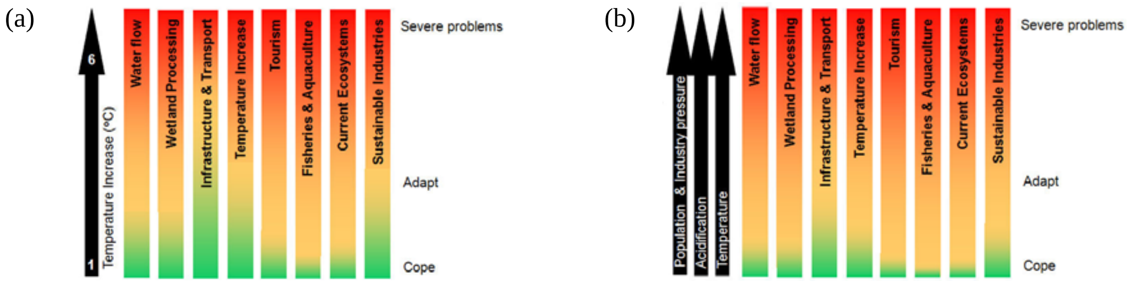

Figure 2. A schematic representation of how cumulative impacts can more rapidly degrade responses of natural systems and the profitability and sustainability of industries exploiting them; (a) represents the shift from coping with a pressure to adaptation or the prospect of severe problems (modified from Figure 11.4. in Hennessy et al 2007); (b) represents the same shift under cumulative and compounding pressures.

Whole-of-system (or end-to-end) models are one way to explore the implications for environmental, social and economic outcomes of the activities associated with, and management of, fisheries, tourism and recreation, ports, oil and gas extraction and transport, mining, local economies, agriculture, urban development, roads and conservation. As ecological, economic and social processes associated with these activities occur at a range of spatial and temporal scales, it is a significant modelling challenge to seamlessly incorporate them into a single modelling platform. End-to-end models of different types tackle the challenge of scale in a range of different ways. In some (e.g. Ecospace, Walters et al 1999) a regular grid is used for the majority of the processes (e.g. ecological and industry) with global processes (e.g. economic markets and chains) represented in one dimension (i.e. through time, but with no spatial component). Another approach is to simply avoid putting all model components on a universal scale (and so avoid the issue of determining exactly which scale to use to avoid the loss of functionality) and to represent each component at the scales that best capture its dynamics. This concept can be taken still further, rather than just using the scale best suited to each component (but still trying to represent them in a common mathematical framework) as inspiration can be drawn from the field of model coupling to create hybrid models. Hybrid end-to-end models not only represent processes at their native scales, but also use whatever mathematical or algorithmic representation is best suited to do this. For instance, differential equations are typically the best means of representing the dynamics of large groups (e.g. patches of phytoplankton production) or large (e.g. regional scale) areas; while IBMs are adept at the representation of fine scales (their computation load excluding them from the feasible representation at very large scales). Translating between the native scales of these different model types is non-trivial, but has been accomplished in modelling frameworks like *InVitro* (Gray et al 2006), where each ecosystem component is represented by the model type that best captures its dynamics and then a central kernel (or framework backbone) handles any requisite spatial or temporal translations, removing the need for the individual sub-models to know of any scales but the ones they function on. This has the added bonus of allowing the model to effectively act in a continuous 3-dimensional spatial field and to allow for the asynchronous handling of time. The handling of time is particularly important. Put simply, the kernel maintains a queue of agents (instances of different sub-models) and shuffles that queue depending on what is happening in the model at any one time. This allows the sub-models to act on their own (semi-independent) time steps and for the IBM sub-models to change their time-step based on their current behaviour (e.g. the animal agent may have relatively large time-steps while sleeping, but very fine time-steps if in the midst of a hunting event).

By handling such a disparate range of processes and scales in a single modelling framework, it creates a potential environment for simulating potential futures. While the uncertainties involved mean these predictions could not be used for making detailed operational-level management decisions, the model trajectories can provide significant insight into the benefits and pitfalls associated with different anthropogenic activities and different management strategies.

2. NINGALOO-INVITRO

One example of an end-to-end model being used to look at regional scale management questions is Ningaloo-InVitro. This implementation of InVitro covers the Ningaloo Reef and Exmouth region of Western Australia (Figure 3). It includes a large number of components (Figure 4), from substrates and environmental variables through 40 different ecological groups (some at the species level), 23 components of the human activities in the region (including extractive industries, tourism, economies, infrastructure and transport), governance of each industry and external drivers (e.g. storms, advertising and global events like fuel prices fluctuations or terrorist attacks that could influence tourism markets).Typically the physical processes and biomass pools of lower trophic levels are represented by differential equations; habitats by gridded and layered metapopulations (sensu Fulton et al 2006); mid trophic layers by age-structured population models; higher trophic levels and many human activities by IBMs (either at the individual or small group level); and the economic components by a modified form (including dynamic feedback) form of computable general equilibrium models.

3. NINGALOO-EXMOUTH REGION – LESSONS LEARNT

Figure 3. Map of the Ningaloo-InVitro model domain.

Ningaloo reef and the Exmouth region is an area of exceptional beauty and productivity that attracts national and international tourists as well as supporting a diverse range of local activities (e.g. farming, fishing and oil and gas exploration). The proximity of Ningaloo reef to the coastline and the presence of Cape Range National Park in the same area mean that any development or growth of industries (including tourism) needs to be done with a careful eye toward sustainability and unintended effects.

One of the greatest hurdles for modelling the area is that it is a system where the extremes of scale are very important – from the finest of reef scale interactions and nutrient impacts up to regional current patterns and global influences on the tourism market. One of the clearest examples of this is that ecologically, species assemblages show a clear break on the northern tip of North West Cape (north of Exmouth), while the resident human population considers the area as an integrated hole (reef associated industries to one side, activities in the Gulf on the other, with agriculture and other land-based activities in between).

The benefits of considering all sectors in a unified framework is clear once the interconnected nature of the main influences in the system are considered. For example, Figure 5 is a simplified diagram of all the interacting aspects and drivers of tourism and associated planning and development in the Ningaloo-Exmouth region. Even in this simplified version of reality it is clear that if asking the question “how many people could Ningaloo support?”, information is required on a diverse range of topics, including the state of the natural resources, capacity of different locations, pressures associated with different activities, tradeoffs between activities, tourist (and local) preferences, access and infrastructure, water, waste, labour, housing, supplies, as well as cross sector social and economic competition and interaction. Managers at different levels and in different departments or jurisdictions will focus on specific aspects that will influence the potential performance of decisions made by managers in other departments. For instance, a fisheries or conservation manager may decide that keeping stocks of large ‘trophy’ fish at high levels might be the best way to sustainably manage the stock and make the area attractive to tourists (who want to see big fish). Consequently, fisheries regulations may be tightened and commercial fishing access reduced. Unfortunately, that action could actually negatively impact tourism via restricting flow of product to local restaurateurs (who can’t easily access a supply of fresh fish due to the isolated position of settlements like Coral Bay) and by leading to dissatisfaction among tourists who want to eat sustainably caught local fish. Similarly, the web of indirect pathways that link the many ecological, economic and social components of the Ningaloo region mean many well intentioned decisions regarding the timing and location of new infrastructure construction, licensing schemes and land release**,** can lead to unintended consequences that are opposite to the desired outcome.

The issue of unintended consequences is particularly important when it comes to cumulative impacts and the implications for pressure on water resources in such an arid area. The new set of environmental conditions created by changed weather patterns and oceanic water column properties (e.g. temperature and pH) is likely to impact the availability of water in the region and may also affect the resilience of the reef to pressure. This means that any management decision that may also affect water or the reef**,** needs careful attention. However, there will be tradeoffs between sectors and system components and potentially even between generations when addressing questions regarding: whether open or restricted access (by area or activity) is the most

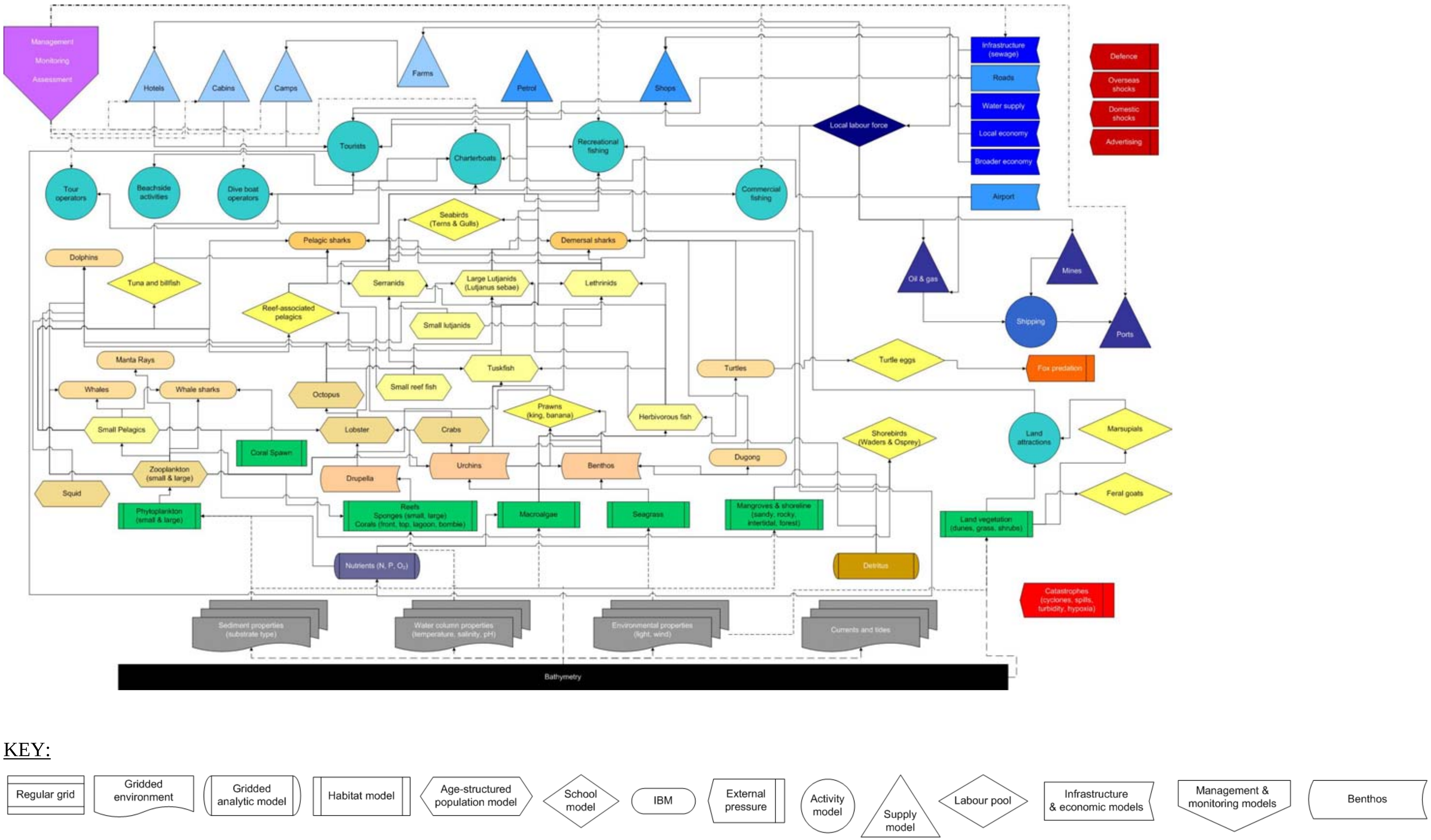

Figure 4 Schematic drawing of agents and model types in Ningaloo-InVitro.

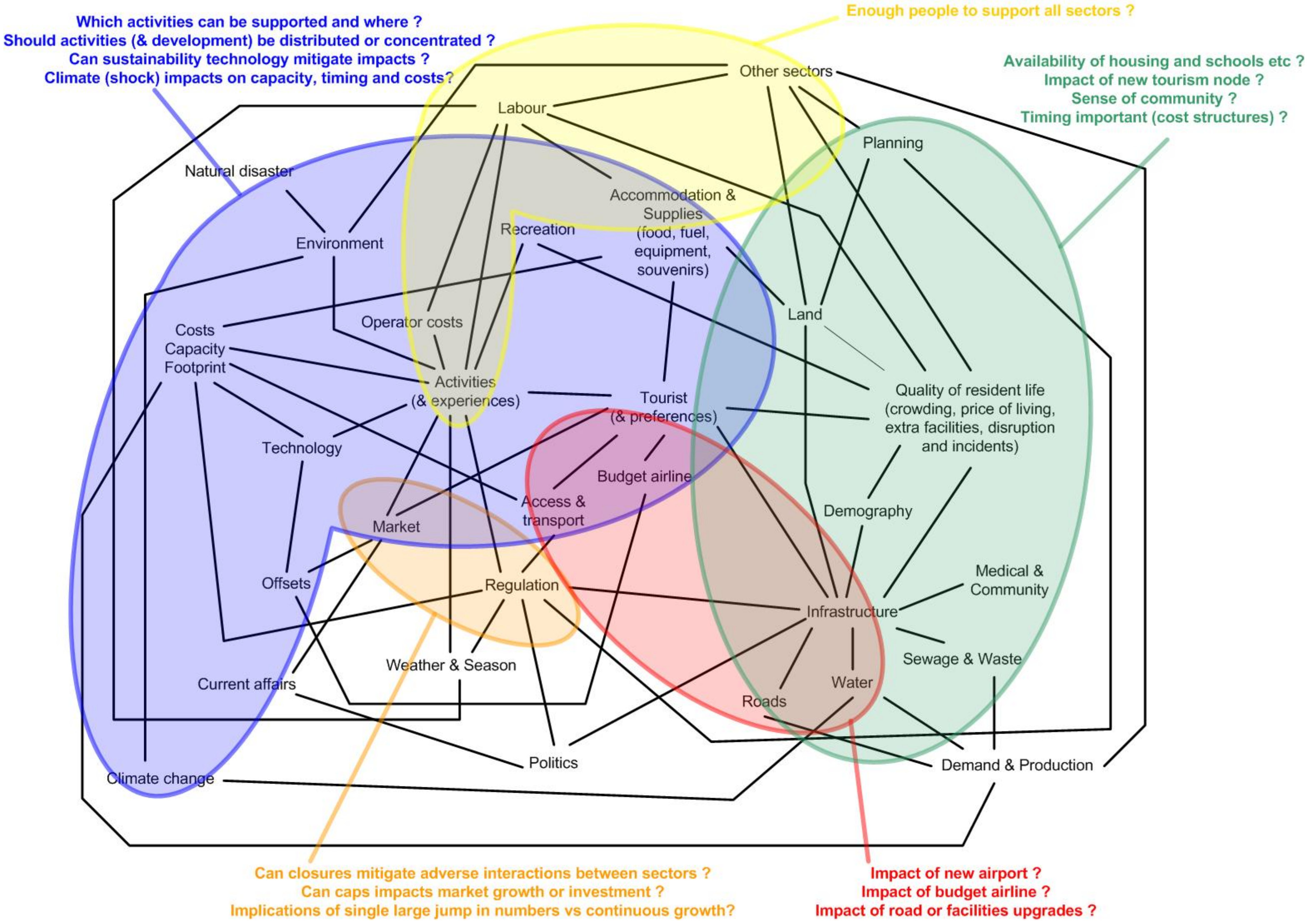

Figure 5 Diagram of drivers and processes associated with tourism, planning and development in the Ningaloo-Exmouth region. Pertinent management questions are also given in the coloured bubbles for reference.

effective means of meeting management objectives across the system; whether development in the region should happen slowly or in a pulse (to get all developments to a high standard quickly); or whether reducing environmental load (via use of more eco-efficient practices and technology) can increase the sustainability of regional development (and allow for an expansion of human activities in the area). Preliminary results show that the restricted size of the local aquifer, the isolated nature of the region and the close proximity of the reef and terrestrial parks means that in every one of these cases just a few decisions separate a possible future where governance and development encourages economic growth and sustainable industries, and a possible future where (even for a short period) the capacity of the system is exceeded leading to environmental impacts and social feedbacks that ultimately lead to a contraction of tourism and service industries and a poorer overall system state.

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