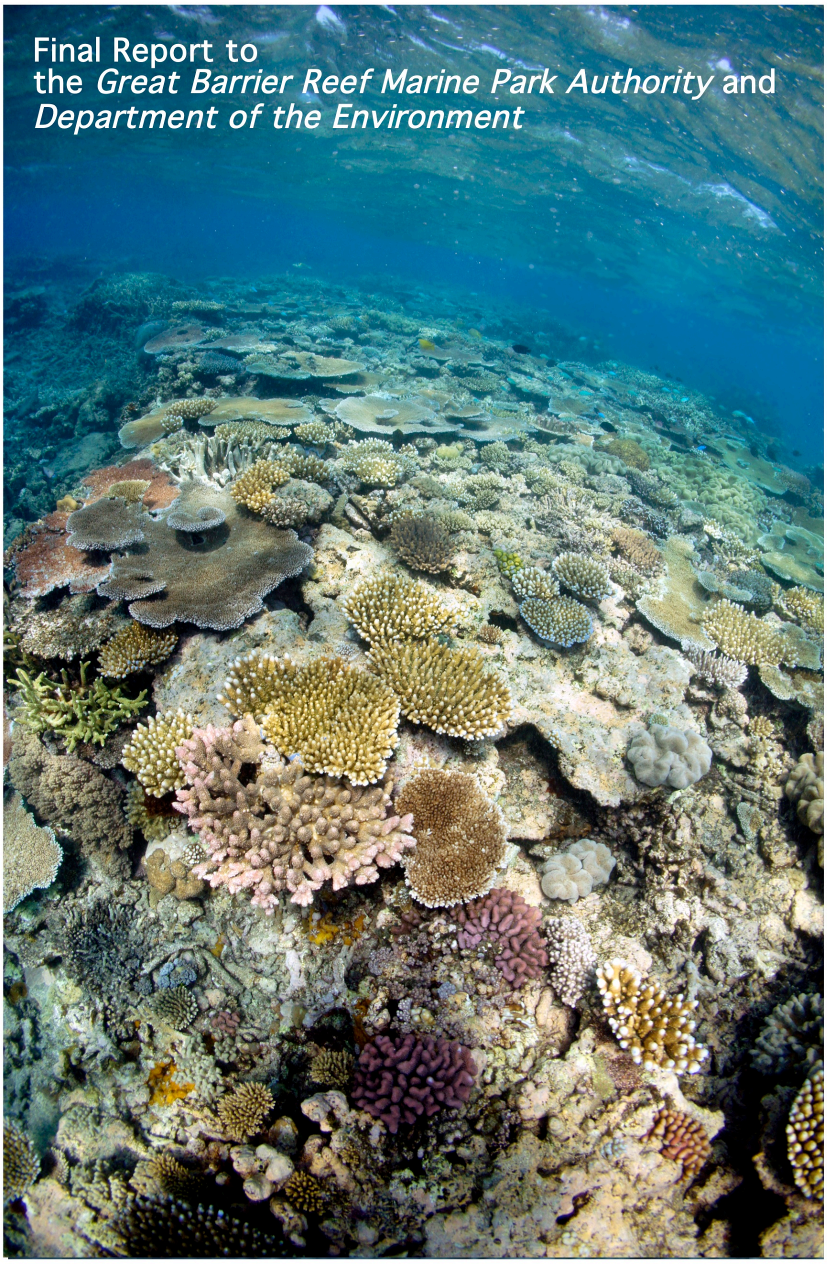
A FRAMEWORK FOR UNDERSTANDING CUMULATIVE IMPACTS, SUPPORTING ENVIRONMENTAL DECISIONS AND INFORMING RESILIENCE-BASED MANAGEMENT OF THE GREAT BARRIER REEF WORLD HERITAGE AREA

Kenneth R.N. Anthony, Australian Institute of Marine Science, PMB3, Townsville Q4810
Jeffrey M. Dambacher, CSIRO, Hobart, Tasmania, 7000
Terry Walshe, NERP Decisions Hub, University of Melbourne
Roger Beeden, Great Barrier Reef Marine Park Authority, Townsville Q4810



Final Report to
the *Great Barrier Reef Marine Park Authority* and
Department of the Environment

Australian Government

Australian Institute of Marine Science

CSIRO

The University of Melbourne

Australian Government
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Great Barrier Reef Marine Park Authority
2-68 Flinders Street (PO Box 1379)
Townsville QLD 4810, Australia

Phone: (07) 4750 0700
Fax: (07) 4772 6093
Email: info@gbrmpa.gov.au

www.gbrmpa.gov.au

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Executive summary

The Great Barrier Reef is facing unprecedented pressures, and supporting the resilience of the Reef has become a central focus in its management. A key challenge for managers is to understand the cumulative impacts of multiple stressors and incorporating this knowledge into management decisions.

The Cumulative Impact and Structured Decision-Making (*CISDM*) framework represented in this report is designed to assist Great Barrier Reef Marine Park managers and stakeholders in this challenge. The framework uses qualitative and probabilistic modeling to provide a systems-level understanding of how cumulative stressors affect coral reefs and seagrass ecosystems in the GBRWHA. These ecosystems underpin matters of national environmental significance (MNES), including the outstanding universal value (OUV) of the GBRWHA. The modeling approach enables managers to identify precautionary spatial and temporal boundaries for the assessment of development proposals. These 'Zones of Influence' are integrated with a structured decision-making process that is designed to help managers and stakeholders use the results of the models to make informed choices between a range of possible intervention scenarios to achieve management objectives (Fig. ES1).

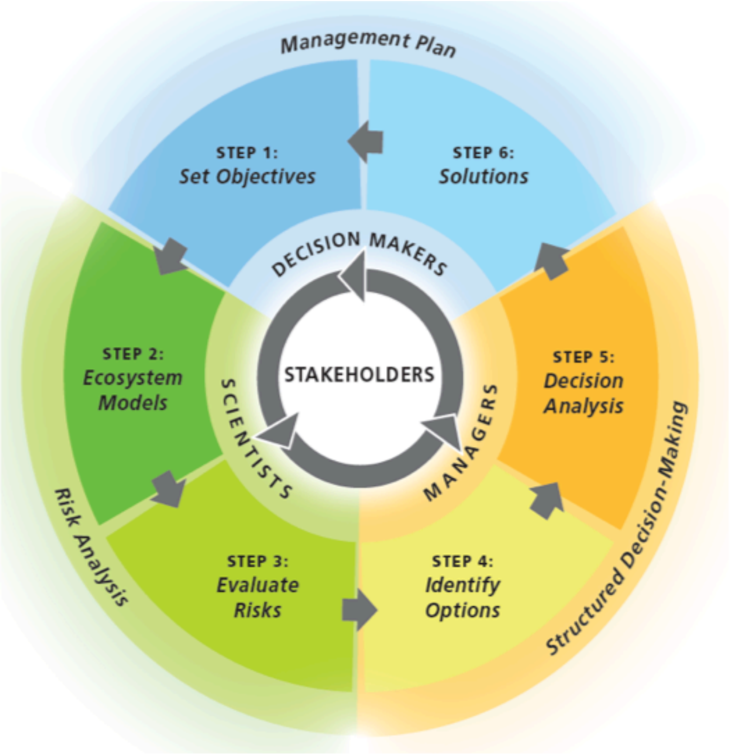


Figure ES1: Visual representation of the *CISDM* framework, illustrating the integrated and staged approach that all revolve around stakeholders, guided to varying degrees by scientists, managers and decision makers.

This report provides:

- An explanation of the methodology behind the CISDM framework
- User-guidance on how to approach the environmental problem, including setting objectives, modelling, estimating risks, exploring development and management alternatives, and informing the decision-making process
- Hypothetical examples demonstrating and testing the application of the CISDM framework (Info Box 1)

This report focuses on coral reefs and seagrass ecosystems, and is spatially scalable so that it can be applied to specific areas (e.g. Cape York, the Wet Tropics, the Central Section and different regions of the Southern Section) as well as GBRWHA-wide. Key linkages between environmental exposure and values underpinning ecosystem values have been preliminarily assessed through a series of expert workshops, and incorporated into the component qualitative models. Several scenarios are presented based upon provisional management objectives to explore the sensitivities of ecosystem values to key impacts, activities and drivers.

The report demonstrates the utility of the CISDM framework for these two ecosystem types across the wider GBRWHA. It presents qualitative and probabilistic models (Bayes nets) for each ecosystem type, and analyses relationships between a subset of cumulative stressors: nutrients, turbidity and sedimentation, habitat erosion, and climate change and their impacts on ecosystem values. To demonstrate how to apply the framework, the models are used to analyse and compare potential impacts of these stressors on ecosystem values in four geographic areas in the GBRWHA: Cape York, the Wet Tropics, the Central Section, and Southern Section. Hypothetical land-use and port development scenarios are then explored and used to inform a structured decision-making process. The decision-making process involves exploration of hypothetical management interventions, consequences and trade-offs. Preliminary findings from application of the framework to hypothetical scenarios, combining agricultural run-off with port developments and climate change, demonstrate how a qualitative systems understanding of cumulative impacts, and the risks that they pose to ecosystem values, can be used to estimate risks to ecosystem values and inform decision-making and effective management responses.

This report describes the logical development of a prototype framework, using hypothetical examples to test its utility. Operational use of the framework will be dependent upon clear definition of management objectives, refinement of the qualitative models, the availability of key datasets and integration with current decision-making processes.

Info Box ES1: Testing the CISDM framework with hypothetical scenarios

The CISDM framework is a prototype that has been developed to assist the Australian Government in protecting and managing the Great Barrier Reef World Heritage Area. This report describes the development of the prototype framework and the anticipated benefits of its use. The development process has used a series of hypothetical scenarios to evaluate the capacity and utility of the framework. It is important to note that while these scenarios include real spatial references, the datasets that have been used are not real. The current status of many MNES in the World Heritage Area would preclude consideration of the development and mitigation scenarios used to demonstrate the utility of the framework.

Operational use of the CISDM:

1) Would be governed by the primary objective to achieve net benefits for matters of national environmental significance in the Great Barrier Reef World Heritage Area.
2) Would require further work to refine the qualitative models and analyse the available quantitative datasets to inform the Structured Decision Making components of the framework.

Acknowledgements

This project was commissioned by and developed with the Department of the Environment and the Great Barrier Reef Marine Park Authority (GBRMPA). It is one of several projects being funded under the Sustainable Regional Development Program to support the Strategic Assessment of the Great Barrier Reef World Heritage Area (GBRWHA). This report and other deliverables under the project is the result of close collaboration between the Australian Institute of Marine Science (AIMS), GBRMPA, Department of the Environment, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the University of Melbourne.

Project collaborators and extended team members include: Ryan Black, Stephanie Cooper, Annie Keys and Leah McKenzie (Department of the Environment), Josh Gibson, Peter McGinnity, Mark Read, Bronwyn Houlden, Hayley Gorsuch, Margaret Gooch, Donna Audas, Cherie Malone, Rachel Pears and Jen Dryden and Laurence McCook (GBRMPA), Mike Ronan (Qld Gov, EHP), Russell Kelley, Jon Brodie (JCU), Morgan Pratchett (JCU, ARC CoE), Nick Graham (JCU, ARC CoE), Julia Playford (DSITIA), John Bennett (Qld Gov, EHP), and Richard Kenchington (Uni of Wollongong).

The project was guided by a steering committee comprised of: Ryan Black, Stephanie Cooper, Annie Keys, Peter McGinnity, Mark Read and Fergus Molloy.

A project reference group was also formed to seek feedback on the framework as it was developed. This group was comprised of: Julia Playford, Richard Kenchington, John Bennett, Hugh Yorkston, Laurence McCook and Mike Ronan.

Expert panel members contributing to the development of qualitative models

Dr Rob Coles, Seagrass Watch, Qld Gov/James Cook University (JCU)
Dr Len McKenzie, Seagrass Watch, Qld Gov/ JCU
Dr Michael Rasheed, DAFF
Dr Alana Grech, ARC CoE, JCU
Prof Michelle Waycott, DEWNR, SA
Jon Brodie, Tropical Biology, JCU
Stephen Ban, ARC Coe, JCU
Dr Mark Read, GBRMPA Manager, Species Conservation
Hugh Yorkston, GBRMPA
Dr Katherine Martin, GBRMPA
Donna Audas, GBRMPA
Dr Bronwyn Houlden, GBRMPA
Cherie Malone, GBRMPA Spatial Data Centre
Carol Honchin, GBRMPA
Dr Scott Wooldridge, AIMS
Prof Morgan Pratchett, ARC CoE, JCU
Prof Bette Willi, ARC CoE, JCU
Dr Ashley Frisch, ARC CoE, JCU
Dr Katharina Fabricius, AIMS
Dr Nick Graham, ARC CoE, JCU
Dr Aaron MacNeil, AIMS
Dr Stuart Kininmonth, GBRMPA
Dr Angus Thompson, AIMS
Dr Laurence McCook, GBRMPA

Part 1 – Introduction and Methodology

1.1 Purpose of the CISDM Framework

The overarching purpose of this framework is to provide a tool that can assist managers and policy-makers understand the risk that cumulative impacts pose to coral reef and seagrass ecosystems in the GBRWHA and identify management levers in a rigorous, defensible and transparent way. The specific objectives are three-fold:

1. To produce a framework that enables GBRWHA managers and stakeholders to understand the complexity associated with multiple drivers, pressures and impacts of environmental and human-use scenarios and the responses of ecosystems and the species they support.

2. To help identify and prioritise points of intervention (i.e., management 'levers') in the ecosystems where policy and management decisions can make the largest difference to the resilience and sustainability of ecosystem values in the GBRWHA.

3. To provide a transparent process that enables managers, researchers, stakeholders and delegates to make informed management decisions in complex situations. For example, coastal development and land-use management under a changing climate.

The *CISDM* framework has broad scope with respect to the types of decisions it can help support, ranging from decisions associated with regional and strategic land-use planning to decisions around individual development projects.

1.2 Who can use this framework?

The *CISDM* tool can be used by planners, regulators and other decision-makers wanting to understand impacts of cumulative stressors on complex ecosystems. The framework is designed in the first instance for marine park managers, policy makers, conservation practitioners and other managers interested in making informed decisions about activities and policies in the GBRWHA. The tool can help these users explore cumulative impact scenarios, the efficacy of management options and decisions that minimise stress on key ecosystem functions and values, and maintain net benefits to the Great Barrier Reef Region.

1.3 How to use this document

This document has been structured as a guide with clearly outlined steps through the *CISDM* framework. Worked examples are provided throughout, illustrating how the framework can be applied. More detailed background information and the scientific basis for the different framework steps are supplied as appendices at the back of the report.

Sections 2-5 of the document provide the user with direction on the exploration of, and where possible interaction with, ecosystem models and the structured decision-making framework. To help the user explore models, generate their own examples, and run structured decision-making examples, practical user information is provided in blue boxes. These boxes provide information on models and step-by-step guidance on how to run and explore models, set up environmental scenarios and explore management options, and calculate entries into tables used in the cumulative impact assessment and structured decision-making. The models that underpin the framework need to be run in the program Netica. A demonstration version of the Netica software, which can be downloaded from http://www.norsys.com/netica.html

Where further background information is needed for the user to understand or appreciate the workings of principles or concepts, but without the need to consult the technical chapters (appendices), such information is provided in boxes throughout the document.

1.4 Framework Structure, Approach and Methodology

The Cumulative Impacts and Structured Decision-Making (*CISDM*) framework is built around insights from modelling of complex systems and the decision sciences. The framework uses a qualitative modelling approach (Levins 1966, 1998) to understand and predict cumulative impacts on ecosystems underpinning Matters of National Environmental Significance (MNES) including the outstanding universal value of the GBRWHA. These predictions are then used to inform a process of Structured Decision-Making (SDM).

The framework, however, also allows for Cumulative Impacts analyses to be separated from the SDM process outlined here, enabling the user to employ other decision-making tools or systems. SDM as used in the CISDM framework is a process that deals effectively with complex science information as well as value judgements in an organized, inclusive and transparent approach (Gregory et al. 2012). SDM is designed to engage stakeholders, technical experts and decision makers in a deliberative process, using best practices in decision-making. Its goal is to both inform and actively aid decision makers.

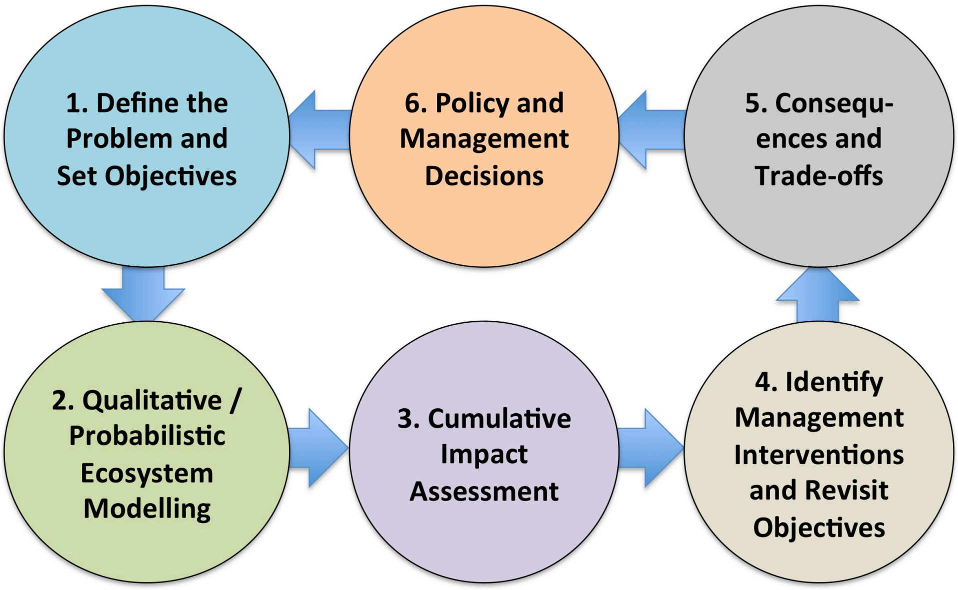


Figure. 1.1. Staged approach of the CISDM framework. Stages link logically and form the bases for different functional elements of the framework. Each step involves participation and consultation with marine park managers, scientists, decision makers and other stakeholders. The framework is cyclical, enabling the solution outcomes and dynamic processes to be considered and integrated into future decisions for continuous improvement. Stages 4 and 5 can be adapted to the current decision processes employed by the user. In an adaptive management cycle, new data, for example from an integrated monitoring program is incorporated into step 2. See also Fig. ES1.

Taken together, the qualitative modelling and SDM approaches are implemented in the CISDM framework through six logical steps linked in an adaptive cycle (Fig. 1.1). The entry point is the formulation of the environmental problem and the definition of the management objectives. The end point is the management or policy solution, and resulting recommendations based on a structured decision-making process. All steps in the cycle require significant engagement with three stakeholder groups: (1) GBRWHA natural resource managers, (2) decision makers, and (3) scientists with a systems understanding of environmental, ecological and biological processes in the GBRWHA.

The following outlines the six steps of the CISDM framework, how they are linked logically and functionally, and what roles different GBRWHA stakeholders play at every step.

1. *Defining the problem and objectives*

Defining the environmental problem and the fundamental management objectives for ecosystem values, and the Matters of National Environmental Significance (MNES) they underpin, is the first step of the framework. The decision problem typically involves judgements around whether environmental or development scenarios present an acceptable risk to environmental values. Depending on context, the notion of 'acceptability' may or may not be conditioned by consideration of anticipated social and economic outcomes. The details will vary according to the regulatory setting.

For example, the *Environment Protection and Biodiversity Conservation Act* (*1999*) (EPBC Act) places primary emphasis on the protection of Matters of National Environmental Significance (MNES). There is also a requirement to consider social and economic outcomes when making decisions on whether to approve a proposal and what conditions to impose. Under the *Great Barrier Reef Marine Park Act* 1975 (GBRMP Act) the protection and conservation of the environment, biodiversity and heritage values of the Great Barrier Reef Region takes primacy over social and economic activities. Consequently the decision framework in the GBRWHA is governed by the requirement to first protect the environment and MNES and second to support sustainable use. Very coarsely, the fundamental objectives are:

- Minimise impacts or improve condition of MNES, and
- Generate positive social and economic benefits

Consistent with the emphasis on protection of MNES in the EPBC and GBRMPA Acts, the CISDM framework takes the position that trade-offs among these objectives can only be considered following efforts to avoid and mitigate.

The CISDM framework therefore formulates the decision problem according to the logic shown in Figures ES1 and 1.1. In steps 1 – 3 an assessment of cumulative environmental impact is made based on defined scenarios that do not at first include the effects of management interventions. To facilitate the identification of optimal management solutions that minimise risks to ecosystem values (primary objectives), while considering other societal benefits (secondary objectives), the CISDM framework recommends that substantial decision analyses, either using the SDM approach outlined here or alternative decision tools, are always undertaken. Part of the SDM analysis is the specification of alternatives for risk mitigation (step 4). Assuming a subset of those alternatives may plausibly lead to broadly acceptable impacts on MNES (Appendix 3), the analysis then progresses to characterisation of the expected consequences against a wider set of fundamental objectives, including consideration of social and economic outcomes (step 5). After articulating trade-offs, a decision is made to inform solutions (step 6). The sections below provide a brief outline of each of these steps.

It is important to emphasize that the examples presented in this report do not attempt to comprehensively capture social, economic and environmental impacts, but provides hypothetical examples and placeholders to allow the user to extend the framework to consider and include those relevant elements. Management actions will be reviewed adaptively as conditions change (Fig. 1.1).

2. *Qualitative and probabilistic ecosystem models*

The CISDM framework uses qualitative models to capture causal linkages between global, regional and local-scale environmental drivers, human activities, and resulting pressures and impacts on key environmental values in the GBRWHA. Qualitative models are useful tools for rapidly capturing the complexity of ecosystems and highlighting key linkages between drivers, activities, impacts and effects on ecosystem values. Qualitative models in this framework were developed during workshops with the help of more than 30 scientists and marine park managers. The qualitative models were transformed to probabilistic models (Bayes nets), allowing the user to explore relationships between a likelihood of increase in one or more pressures and the resulting likelihood of change in ecosystem values. The probabilistic models can be used to make predictions about changes under varying impacts or intervention scenarios, diagnose the cause(s) of change, run sensitivity analyses to identify key indicators of change, and validate models. Results of integrated monitoring programs informing causal linkages between drivers, activities, pressures and values in the qualitative and probabilistic models are key components of this step.

3. *Cumulative Impact assessment*

Traditional approaches to determine environmental risks usually pertain to a quantum or magnitude of change in a value of concern. The CISDM framework instead employs qualitative methods to assess only the directions of change in drivers, activities, pressures and/or values. The assessment of cumulative impacts result from analyses of the qualitative models, as represented within the Bayes nets. Such analyses can directly inform existing policy and management decision processes using varying decision tools or criteria. Where decisions involve complex tradeoffs, steps 4 and 5 should be implemented as a formal and rigorous Structured Decision-Making process (Figures ES1 and 1.1).

For cumulative impact assessments, probabilistic models are used in combination with *Zones of Influence* to calculate a measure of *estimated risk*. Here *estimated risk* is calculated as the product of probability (likelihood) of the change in ecosystem values and the consequence of that change, the latter represented by the area of the ecosystem value affected. Estimated risk is presented as an index. For these analyses the concept of *Zones of Influence* (*ZOIs*) was developed. *ZOIs* are areas within which drivers or activities can be expected to exert significant and observable pressures on ecosystem processes and values. In essence, *ZOIs* are a set of geospatial exposure layers of environmental or anthropogenic pressures (*e.g*., are exposed to nutrients, turbidity and sedimentation, storms etc) resulting from drivers and/or activities. *ZOIs* represent acute (pulse-type) as well as chronic (press-type) exposures integrated over extended timeframes. Multiple *ZOIs* for different scenarios of land-use developments and climate change are combined with the distribution of ecosystem habitats (coral reefs and seagrass meadows) in the framework to estimate cumulative risks.

4. ***Identify management interventions and revisit fundamental objectives***

   Once cumulative impacts to ecosystem values have been assessed based on potential future scenarios, the next step in the CISDM framework is to identify options for management interventions and mitigation that could reduce environmental risks. This invokes a broader set of objectives, including identification of the key drivers and/or activities responsible for the environmental impacts (or risks), the identification and assessment of potential management levers to minimise impacts, evaluation of the current policy and legislative basis for actions and estimation of the costs of mitigation actions. Also, in addition to environmental impacts, social and economic outcomes of decisions can also be taken into account in this step. This can be framed as an optimisation problem if the amount of environmental risk-reduction associated with varying levels of investment into management interventions could be quantified. In the absence of this knowledge, a broad set of alternatives should be identified and their expected consequences estimated.

5. ***Consequences and trade-offs***

   Identifying alternatives (representing scenarios and options) and analysing consequences and trade-offs are the end-points of the structured decision making process. Here, the consequences of environmental scenarios and management interventions for ecosystem values, and potentially social and economic values, are examined. Lastly, tradeoffs are explored between spatial areas, and potentially between ecosystem values.

6. ***Policy and management decisions***

   Examples used in this framework focus on protection of ecosystem values as a key fundamental objective. Effective policy and management decisions therefore mean decisions that represent mitigation options or management actions that effectively alleviate cumulative environmental impacts on values, as assessed through the analysis of the qualitative and probabilistic models and the structured decision-making process. This final step in the CISDM framework is one of communicating results to decision-makers and to implement programs that test and monitor the effectiveness of decisions to enable an adaptive management approach.

Each step of the CISDM framework informs the next and builds upon those before it. The result is an adaptive management cycle that is both transparent and responsive to change. These attributes are critical to management and policy decisions, which must inevitably adjust to the differences between model predictions and reality. This is all the more important for the effective management of vulnerable natural resources under the broad range of climate scenarios and potential outcomes forecast for the coming decades (Raupach et al. 2007).

1.5 Stakeholder roles

The CISDM framework is designed to engage three key groups of stakeholders: (1) GBRWHA managers, (2) decision makers, and (3) scientists (Figs. ES1 and 1.2). Decision makers include the subset of GBRWHA managers who are the delegates for decisions. These groups engage to different extents at different steps in the cycle. For example, managers and decision makers collaborate on the formulation of the problem and in the setting of fundamental and adaptive management objectives. Scientists lead the development and elicitation of models in close collaboration with managers and stakeholders with systems knowledge. The structured decision-making can involve not only managers and decision makers, but also the broader group of stakeholders including industry and community representatives. This report and the examples used in the presentation of this framework have used this strategy for engagement through four stakeholder workshops, with 15-30 people in each workshop.

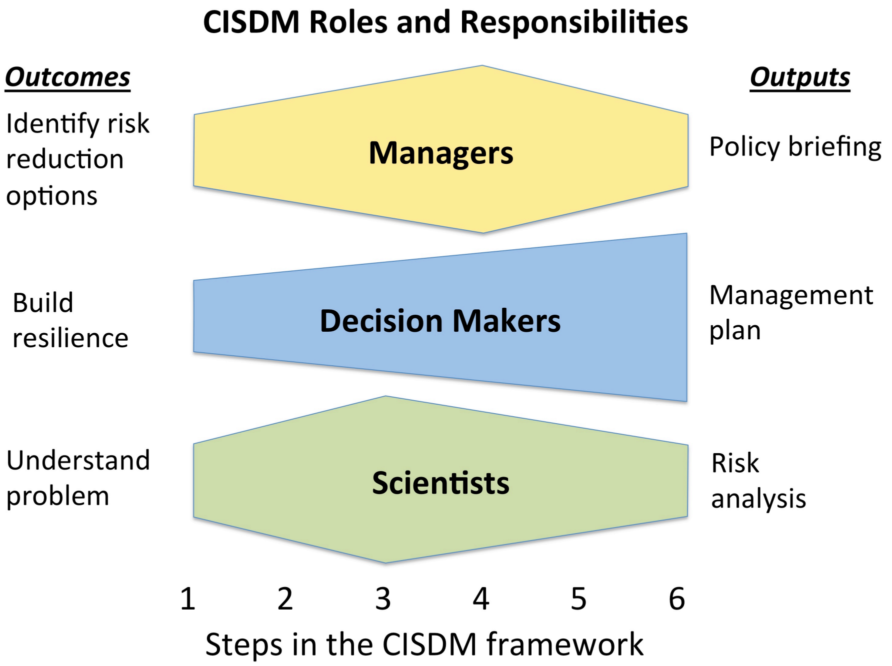


Figure 1.2. Outcomes, outputs, roles and responsibilities of the CISDM framework and its users. The width of each wedge illustrates the degree of leadership responsibility and engagement of each stakeholder group in each step of the CISDM framework cycle. For example; Managers will lead steps 4 and 5; review of the scientific risk analyses against the Step 1 objectives and current policies, in order to identify relevant management options, Scientists lead and are responsible for Steps 2 and 3; the development and maintenance of relevant ecosystem models and risk analyses. Decision makers 'close the cycle' by approving step 6; Policy and Management Solutions, and setting and refining management objectives. Importantly, the needs of other stakeholders can be considered at each step and will play an important role in shaping the fundamental objectives. The framework provides a transparent process where the complexity of each decision is made apparent and can be considered by all parties. A description of the types of milestone outcomes and outputs generated through the implementation of the CISDM framework is indicated on the left and right of the figure respectively. See also Fig. ES1.

1.6 Vulnerability and Resilience Thinking

Qualitative and probabilistic models in this framework do not explicitly model resilience. Rather, the concept of resilience is embedded in the thinking around how drivers, activities and pressures impact on different processes that underpin the dynamics of the system. More specifically, the cumulative impact assessments (Section 2.3), building on qualitative and probabilistic models (Section 2.2), provide insight into the vulnerability of key ecosystem values and MNES. Vulnerability is defined as the outcome of exposures (pressures), sensitivity and adaptive capacity (Info Box 1.1). Resilience represents the composite of sensitivity and adaptive capacity, and is broadly defined as the capacity of a system to absorb disturbance and reorganise while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks (Holling 1973, Holling 1996, Gunderson 2000, Nyström et al. 2008).

Managing for resilience is a novel way to integrate and manage the interactions and feedbacks between people and nature, i.e. social-ecological systems, and helps provide a path to sustainability (Berkes and Folke 1998, Folke et al. 2011). Resilience thinking provides a focus on what can be done to enhance the system's intrinsic ability to cope with exposure and to recover (or reorganise) faster between disturbances (high adaptive capacity), thereby reducing the vulnerability of the ecosystem and dependent societies.

Info Box 1.1: Vulnerability and Resilience – definitions

Vulnerability: Generally the potential for net loss over time (Dow 1992). In social settings the inability of people, organizations, and societies to withstand adverse *impacts* from multiple stressors to which they are exposed (Cutter et al. 2003). Outcome of *exposures*, *sensitivity* and *adaptive capacity* (Füssel and Klein 2006).

Resilience (ecological): The ability of a system to absorb shocks and recover from *impacts* (Holling 2001). Combined capacity to withstand *exposures* and to recover or reorganise – essentially the *sensitivity* and *adaptive capacity* components of vulnerability (Nyström et al. 2008, Anthony and Mumby in review).

The CISDM framework considers both vulnerability and resilience by focusing on understanding exposures (via drivers and activities leading to cumulative stressors) and the identification of processes and management actions that build resilience. Figure 1.3 illustrates the roles of managing exposures as well as resilience in minimising vulnerability.

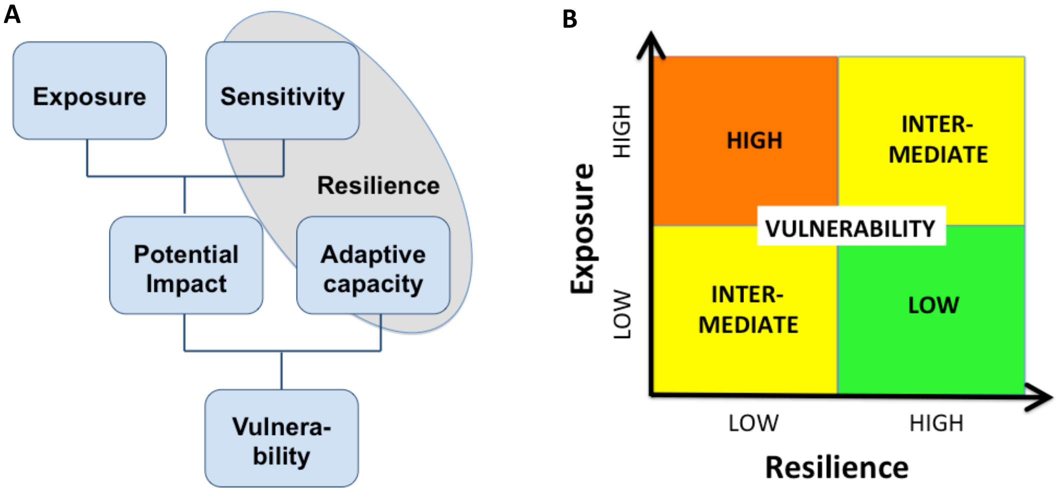


Figure 1.3. A: Vulnerability framework adopted from the IPCC (Fussel & Klein 2006). **B**: Relationship between level of exposure (intensity and/or frequency), level of resilience and resulting vulnerability (see also Info Box 1.1). Source: Anthony and Mumby (in review).

Part 2 – Framework Steps, User-Guidance and Hypothetical Examples

2.1 Define the Problem and Set Objectives

The environmental context for the CISDM framework is: cumulative pressures on ecosystem values within the Great Barrier Reef World Heritage Area (GBRWHA). The problem can be summarised as a four-point challenge:

1. Ecosystem values in the GBRWHA are at risk,
2. There are several sources of cumulative stressors, i.e. environmental and anthropogenic drivers and activities,
3. There are a range of potential environmental and/or developmental scenarios, and
4. There are several fundamental objectives to be achieved.

To address point 1 (ecosystem values at risk) the framework focuses on two principal ecosystem types in the GBRWHA: coral reefs and seagrass meadows and the key species they support.

To address point 2 (sources of cumulative stressors), the framework is set up to allow the user to manipulate key pressures separately or in combination. For the purpose of user tractability, only a key subset of all possible stressors is included in the Bayes nets.

Point 3 is in essence the environmental problem. Here, the user first needs to identify the spatial and ecological scale of the problem. The examples of environmental scenarios used in this report and described below are partly hypothetical.

Given the size and ecological complexity of the GBRWHA, the CISDM framework is spatially scalable, i.e. it allows users to address issues at the scale of the entire GBR, as well as regions and specific locations (e.g. an individual bay) within the larger system. In this report, the problem is divided into four geographic demonstration cases, comprising the four GBR management areas (Fig. 2.1):

1. The Far Northern (Cape York) Section;
2. Wet Tropics;
3. Central Section; and
4. Southern Section.

Point 4 involves defining the fundamental objectives, which are critical to enable a comparative assessment of the different environmental and/or developmental scenarios and potential management options.

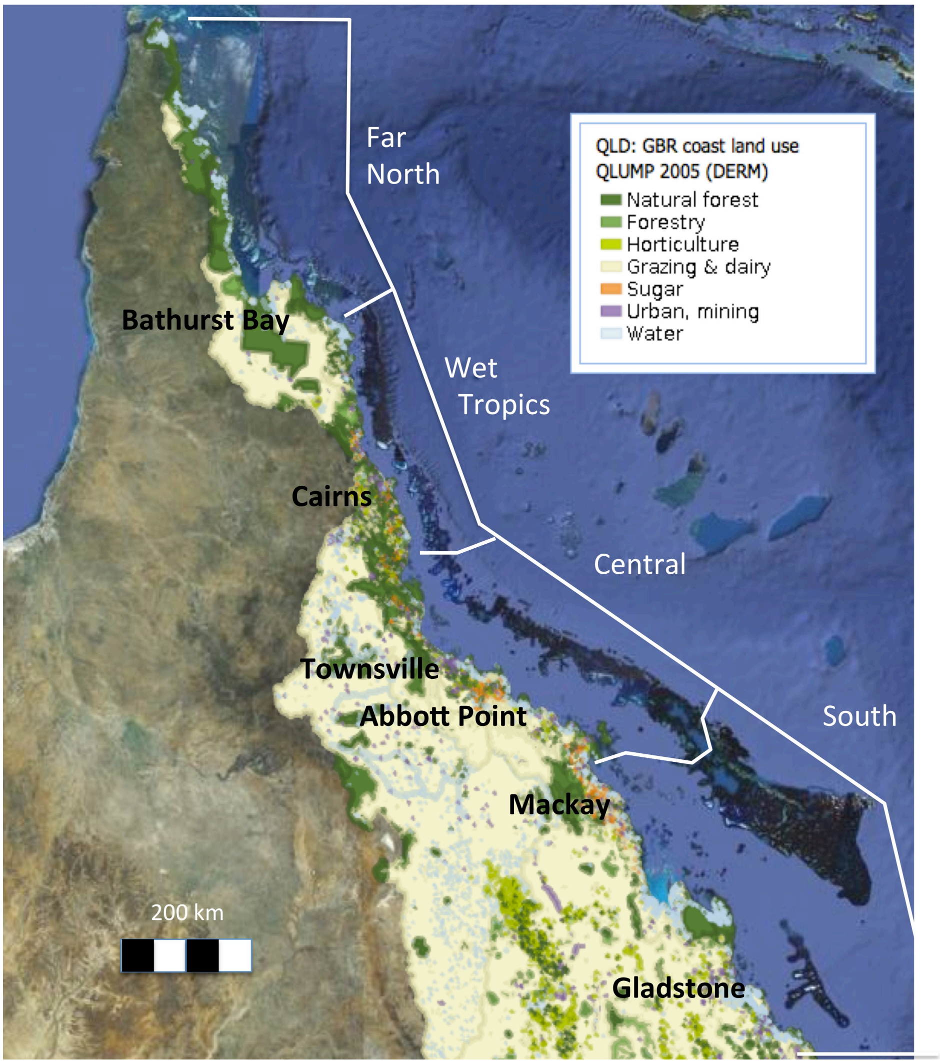


Figure 2.1. Coastal and catchment land-use of the GBR upland area. White lines indicate the GBRMPA outer boundary and the four management areas used as demonstration cases in this report.

2.1.1 Values at risk: ecosystem-level demonstration cases

The Great Barrier Reef World Heritage Area (GBRWHA) encompasses the largest coral reef ecosystem in the world; the Great Barrier Reef (GBR) has over 2900 reefs and 348,000 km^2 of marine and coastal habitat. The GBRWHA is home to more than 1500 species of fish, around 400 species of hard coral, more than 10,000 species of other marine macro invertebrates, breeding populations of 22 species of seabirds, more than 30 species of marine mammals and over 20 species of reptiles. A conservative assessment of the economic value of direct uses that rely on the Great Barrier Reef is $5.7 billion in ecosystem goods and services per annum (Bohensky et al. 2011, Stoeckl et al. 2011, DeloitteAccessEconomics 2013).

The CISDM framework takes a systems approach to the environmental and ecological value of biodiversity using coral reefs and seagrass ecosystems as key systems underpinning MNES. Coral reefs and seagrass ecosystems, and their key dependent species, are used as *ecological demonstration cases* to illustrate the use of the CISDM framework. Coral reefs and seagrass meadows are two of the most critical ecosystems underpinning Matters of National Environmental Significance (MNES) including the Outstanding Universal Value (OUV) of the

GBRWHA. By taking an ecosystem-level, rather than a species-by-species, approach the framework accounts for ecosystem processes and thereby provides a practical context for management.

Coral reefs

On coral reefs, branching and plating corals, in particular those of the genus *Acropora*, provide key habitats and resources for fish and invertebrates (Jones et al. 2004, Pratchett et al. 2004, Cole et al. 2008), not unlike trees providing habitats for species in the rainforest. Structural corals are therefore used as a principal ecosystem value underpinning MNES in the GBRWHA, and provides an understanding of how other ecosystem components and processes promote or hamper the growth and survival of structural corals and the species they support, including fish and invertebrates. For the purpose of keeping the modelling accessible to most users, this version of the CISDM framework does not include explicit linkages to the broader fish community and fishing pressures, as these foodweb models are highly complex (Bascompte et al. 2005). Herbivorous fish are incorporated as a key functional group that provides important reef services via their control of macroalgae (Bellwood et al. 2004, Nyström et al. 2008, Anthony et al. 2011, McClanahan et al. 2012). Also, crustose coralline algae provide substrate for coral and invertebrate recruitment (Harrington et al. 2004). Herbivores and crustose coralline algae are hence key indicators of coral reef resilience.

Seagrass ecosystems

Seagrass meadows provide critical habitat for a range of marine species and serve an array of functional roles in the GBRWHA. Seagrass meadows support dugong and green turtle populations as their primary food source, are important nursery grounds for fish and prawns, and transient homes to a diverse set of species that use seagrass meadows as stepping-stones between coastal ecosystems and coral reefs (Meynecke et al. 2007, Hori et al. 2009). At least 20 species of prawns and over 130 species of fish use seagrass meadows, with many of these fishes being part of marine food chains that support commercial fisheries (DERM 2003). Lastly, seagrasses are effective primary producers and play a role in nutrient uptake and cycling in coastal waters and help to consolidate sediments (Mellors et al. 2002). To make the CISDM framework tangible for users to explore how seagrass meadows support MNES, models include links to dugongs and green turtles, but have not been implemented for the complex foodwebs represented by fish communities.

Dugongs, a listed migratory and marine species protected under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act), feed primarily on seagrasses (Aragones and Marsh 2000) and are therefore highly sensitive to seagrass loss (Lawler et al. 2007). Although dugongs move between foraging grounds, large-scale losses of seagrasses can contribute to population decline (Preen and Marsh 1995, Sheppard et al. 2006, Sheppard et al. 2007).

Green turtles *Chelonia mydas*, a vulnerable species under the EPBC Act and on IUCN's list of endangered species (IUCN 2013), are also reliant on seagrass and are sensitive to losses of seagrass meadows, as they are relatively stationary in their foraging grounds (André et al. 2005). The dependence of dugong and green turtle population on seagrass distribution and abundance was evidenced by increased dugong and green turtle deaths in 2011 following several tropical cyclones, which devastated seagrass habitats in the GBRWHA over most of the Wet Tropics and Central region (GBRMPA 2011a) and major river floods which devastated seagrass meadows in the southern GBR (Devlin et al. 2012).

2.1.2 Sources of cumulative stress

Stressors on the GBRWHA are increasing (GBRMPA 2009). Recent evidence indicates a more than 50% decline in coral cover on mid and outer shelf reefs over the past three decades, with the majority of this loss occurring during the past decade (De'ath et al. 2012). The decline was highest in the central and southern GBR with no decline on Cape York reefs. Cape York is the one area of the GBR not subject to extensive agricultural development and has a low human population. In addition coral cover on inner shelf reefs in the central and southern GBR has been in decline (Thompson et al. 2012). Stressors to corals have been attributed mainly to combinations of acute (pulse-type) stressors such as tropical cyclones, crown-of-thorns starfish (COTS), coral disease and coral bleaching (Osborne et al. 2011). Other more chronic (press-type) stressors such as declining water quality (i.e. increased turbidity, sedimentation, nutrients and other pollutants) in the Wet Tropics and the Central Section have increased in pace with intensified agricultural activities in river basins (catchments) draining into GBR waters (Brodie et al. 2012). Water quality pressures have manifested themselves through increased algal cover (Wismer et al. 2009), low cover of crustose coralline algae (Fabricius and De'ath 2001), reduced coral recruitment on inshore reefs (Thompson et al. 2012) and shifts in coral community types towards more hardy species (Roff et al. 2012). While coral decline on the GBR has been attributed mostly to acute stresses from cyclones, COTS and coral bleaching (De'ath et al. 2012), water quality is a key stressor leading to coral decline in inner shelf reefs and reduces ecosystem resilience (Fabricius and De'ath 2004, Anthony et al. 2011).

Seagrass ecosystems, which support endangered and EPBC listed species including dugong and green turtles are in decline in most areas of the GBRWHA except in the Cape York section (Grech et al. 2011). In recent years the decline in seagrasses has been driven mainly by a series of severe tropical cyclones (TC), in particular TC Larry in 2006, TC Hamish in 2009 and TC Yasi in 2011 (GBRMPA 2011b) and major river floods in the southern GBR in 2011 associated with intense rainfall following Cyclone Tasha and in 2013 following Cyclone Oswald. More generally, seagrass meadows are threatened by sedimentation, habitat erosion and herbicides, and in the longer-term, sea level rise and ocean warming (Waycott et al. 2007, Waycott et al. 2009).

Globally, climate change is expected to increase the vulnerability of marine and terrestrial ecosystems (Walther et al. 2002, Füssel and Klein 2006). The role of climate change and ocean acidification as cumulative stressors on the GBRWHA is expected to increase this century (Anthony and Marshall 2012). Five severe cyclones have impacted the GBRWHA within the past seven years, and two severe bleaching events have occurred in the GBR in 1998 and 2002 (Berkelmans et al. 2004), with localised bleaching in the south in 2006 (Weeks et al. 2008). If the trend of the past decades is a harbinger of what is to come, then the ecosystems of the GBRWHA will be increasingly challenged under multiple stressors that will increase the need for innovative management strategies based on assessments of cumulative impacts.

2.1.3 Hypothetical environmental and/or development scenarios

There are a plethora of possible configurations of activities and environmental factors representing cumulative stressors on values in the GBRWHA. Current and historical scenarios and trends in stressors to the GBRWHA are summarised above (section 2.1.2). In addition, altered environmental scenarios under new developments can combine with current land-use and climate change scenarios influencing outcomes for ecosystem values. This report does not provide an exhaustive treatment of all the scenarios and alternatives. Importantly, the purpose is not a search for the definitive ‘optimal’ solution. Rather, it is to illuminate key consequences and trade-offs using a handful of alternatives.

In section 2.3 (*Assessment of Cumulative Impacts*), examples are provided on how different combinations of agriculture, port developments and climate change impact on ecosystem values in hypothetical case studies. The purpose of the hypothetical case studies is to illustrate to the user how cumulative risks are estimated in the framework under complex scenarios and how they can inform environmental decision-making.

The report then demonstrates the spatial scalability of the framework by applying it to four geographic demonstration cases within the GBRWHA (described below). Users of the framework could define alternative spatial scales at which to apply the framework depending on the problem/scenario to be examined (for example, catchment or local scales).

Seven hypothetical development and/or management intervention alternatives are used in this report. Here, the status quo and a scenario that is focused on limiting development and investing in the protection and restoration of ecosystem values are also included. Importantly, the alternatives do not reflect any formal (or informal) short-listing of candidate options. Also, they do not include any potential management interventions. At an SDM workshop, participants were asked to consider what might be a hypothetical package of risk mitigation actions for each of the alternatives, and who might appropriately be required to bear the costs of those actions. Implementation of the CISDM framework would require substantial additional work under step 4 to identify and critically evaluate the merits, feasibility and potential costs of management actions. Such an assessment would also need to clarify the policy and legal basis for actions, any impediments to actions, and the capacity to ensure compliance.

Geographic demonstration cases

The Cape York section of the GBR catchment has the lowest level of land use (Fig. 2.1). There are no major urban areas except Cooktown, and three small ports (Cooktown, Cape Flattery and Quintell Beach, Lochart River). Approximately 50% of the Cape York region is grazed but largely in unmodified natural areas. As a result, coral reefs and seagrass habitats in the Cape York Section are in relatively good condition. Specifically, coral cover in the region has fluctuated between 20 and 30% in the past three decades (De’ath et al. 2012) and seagrass habitats in the north have low vulnerability scores from current anthropogenic stressors based on modelling studies (Grech et al. 2011). The majority of coral reef areas, and nearly all seagrass resources, in the Cape York section are within 30km from the coastline and are hence vulnerable to changed land use. A small-scale port development is being proposed for Bathurst Bay and amendments to the *Vegetation Management Act 1999* are being proposed in part to expand agriculture in Cape York.

The Wet Tropics region is an area of intensive agriculture and high rainfall. Coral reefs are closer to the coast here than in the Central and Southern sections, with flood plumes extending episodically to all reefs. The Wet Tropics has seen five severe cyclones in the past decade. There is some evidence that reefs in the Wet Tropics may be a source area for primary COTS outbreaks, triggered by major floods and elevated nutrients, leading to enhanced primary productivity in the water column (indicated by chlorophyll concentrations), which enhances larval COTS survival and recruitment (Fabricius et al. 2010). Coral cover in the Wet Tropics (and Central, see below) is currently at a record low based on observations over the past three decades (De'ath et al. 2012) on mid and outer shelf reefs and has declined, albeit minimally, on inner shelf reefs (Thompson et al. 2012) over the last eight years. Recruitment and juvenile densities of corals are declining (Thompson et al. 2012) indicating reduced resilience. Similarly, seagrass resources are low, in part due to recent cyclones (see also below for Central). Cairns is the key urban centre in the Wet Tropics and a hub for tourism in North Queensland. There are only two small industrial ports in the Wet Tropics at Mourilyan and Lucinda associated with sugar export as well as the moderately sized Port of Cairns which handles cruise ships, sugar export and general cargo. Expansion of the Port of Cairns shipping channel in Trinity Inlet is proposed to accommodate larger cruise ships.

The Central Section has a large catchment area (Burdekin) with grazing in the upper catchment and predominantly sugar cane on the flood plains. Episodic floods following periods of drought lead to large amounts of sediment and nutrients and pesticides delivered by flood plumes, mainly via the Burdekin River and its flood plain, to the inshore GBR lagoon (Devlin and Brodie 2005, Devlin et al. 2012). Coral reefs in the central section are increasing in distance from north to south and most coral reef areas are outside the reach of most flood plumes (Schroeder et al. 2012)(See also Appendix 3). Similar to the Wet Tropics, coral cover, coral recruitment and seagrasses are at a record low on both mid, outer and inner shelf reefs attributed to a combination of recent cyclones, COTS and land-use management. Townsville is the major urban centre in the central section. Port of Townsville is proposing to expand to handle a trebling in trade volume by 2040. Adjacent to Townsville Port is a Ramsar wetland of international importance (Cape Bowling Green Bay), which supports local dugong populations. Significant expansion of a coal port at Abbott Point (near Bowen) is under consideration.

The Southern Section also has a large catchment area (including Fitzroy), with cattle grazing sugarcane, grains cropping and cotton being the predominant land use. Analogous to the Burdekin, Fitzroy River sends large amounts of sediments, nutrients and pesticides into the GBR lagoon during floods (Devlin and Brodie 2005, Packett et al. 2009, Devlin et al. 2012). Most reef areas in the Southern Section are further from the coast than in any other region, and hence outside the reach of flood plumes. Coral cover on midshelf reefs in the southern section has declined to a record low within the past decade attributed mainly to a combination of cyclones and COTS (De'ath et al. 2012) and also on inner shelf reefs associated with repeated floods. Mackay, Rockhampton and Gladstone are major urban centres with Mackay and Gladstone also having industrial ports. Significant expansions are being proposed for Mackay (Hay Point) and Gladstone Ports, and possibly expansion of minor port facilities at Port Alma (Rockhampton) in the Fitzroy River delta.

2.1.4 Setting fundamental objectives

The process for setting of objectives under the CISDM framework is consistent with operational management objectives used in the Integrated Monitoring Framework (e.g. Table 2.2, Hedges et al. 2013), and used generally in GBRMPA's Strategic Assessment of the GBRWHA.

In summary, objectives should reflect what stakeholders value (i.e. care about) in the system (Gregory et al. 2012) and should not be confounded with the activities (means) used to achieve these objectives (Info Box 2.1). Fundamental objectives form the basis for value-based trade-offs.

The specific fundamental objectives used in this report were formulated in meetings with the project's Steering Committee and the Reference Group, and during an SDM workshop involving 30 Australian Government and industry stakeholders (Appendix 3).

The CISDM framework applies fundamental objectives to the likelihoods of change in ecosystem values (e.g. corals, seagrass meadows, dugongs and green turtles). However, the framework has the capacity to also consider social, economic and cultural objectives, although these were only considered tentatively as they require broader stakeholder consultation and canvassing of potential management options than was possible within the scope of this project.

Info Box 2.1: Types of objectives

Fundamental Objectives
- Maintain values underpinning ecosystem values
- Minimise cost

Strategic objectives
- Maximise sustainability
- Maximise public trust

Means objectives
- Minimise COTS
- Comply with regulations

Process objectives
- Maximise public involvement
- Ensure effective communication

Adapted from Gregory et al. (2012) and Keeney (2007)

Table 2.1 lists examples of objectives in three categories: ecosystem values, economics and social. The list is by no means exhaustive but illustrates the diversity of objectives that can be used. Note, however that some MNES objectives are potentially "means" as opposed to "ends" or fundamental objectives. The abundance of COTS, for example, is not strictly a fundamental objective (most people regard COTS to be a pest); instead COTS is a pressure on corals and thus a means objective. Because corals and seagrasses are effective indicators of biodiversity and represent conservation values for multiple other species, as well as contributing to the OUV of the GBRWHA, they are here regarded fundamental objectives.

The SDM steps in the framework (steps 4 and 5, Figs. ES1 and 1.1) do not specify targets or thresholds for objectives. That is, the SDM process does not draw a line in the sand for what might represent a tolerable risk of decline. It is possible for the user, however, to apply decision rules directly to the outcomes of the cumulative impact analyses (section 3). What is required in SDM is to state that 'more (or less) is better' for each objective. The inclusion of targets is inappropriate in SDM because the level of aspiration specified for any objective implies a trade-off against other values within the constraints shaped by current legislation and policy. Trade-offs that underpin targets cannot be meaningfully made until the consequences of candidate alternatives have been estimated (see Section 2.5).

Table 2.1. Examples of environmental, economic and social objectives, their metrics (attributes), and the preferred direction of the attributes. Note that different objectives may be required for different areas depending on the spatial and environmental context of the problem. For example, if ecosystem values in a given region are in good condition, "more is better" could be substituted with "maintain values". The specific fundamental (5-year) objectives under the GBRMPA Strategic Assessment are given in brackets and *italics*.

Category	**Primary Objectives**	**Attribute**	**Preferred direction**
Ecosystem values	Corals (habitats for a rich reef fauna)	Protect	More is better (*trend in coral reef condition, community composition and coral recruitment is increasing*)
	Reef fish and invertebrates (goods, services and biodiversity)	Protect	More is better (*maintain and enhance*)
	Seagrass meadows	Protect	More is better (*extent and condition maintained in the north and improved in central and south*)
	Dugongs (endangered under EPBC Act)	Protect	More is better (*reverse the decline and enhance the condition of populations*)
	Turtles (vulnerable under EPBC Act)	Protect	More is better (*showing signs of recovery in the short term and increasing in the long term*)
	COTS (a pressure on corals)	Risk of increase	Less is better
Category	**Secondary Objectives**	**Attribute**	**Preferred direction**
Economics	Total port capacity	Millions of tonnes per annum	More is better
	Agricultural production	Farm gate value ($M)	More is better
	Tourism	Number of visitors or contribution to GDP	More is better
	Cost of risk mitigation borne by Government	$M	Less is better
	Cost of risk mitigation borne by industry	$M	Less is better
Social	Livelihoods	Number of jobs	More is better
	Cultural values	Risk of decline	Less is better

2.2 Qualitative and Probabilistic Models

The *CISDM* framework uses qualitative models in combination with probabilistic network models (Bayesian Belief Networks or Bayes nets) to describe linkages between environmental drivers, human activities, resulting pressures and potential impacts on ecosystem values and their likely responses. The models have been directly informed by the individual and collective judgements of experts in these domains (Appendix 1).

The following is a brief overview of the framework's modelling approach to allow the user enough insight to appreciate and understand the model's capability, limitations and assumptions. As a basis for the development of qualitative models, the framework uses a hierarchy of *Drivers, Pressures, State, Impacts and Responses* (DPSIR) modified by GBRMPA for linking causes and effects (Fig. 2.2). The probabilistic models (Bayes nets) are derived from qualitative models and allow the user to explore the potential impact of development and environmental scenarios and activities on the likelihood of change in values in coral reef and seagrass ecosystems. A more detailed description of the modelling components is given in Appendix 1.

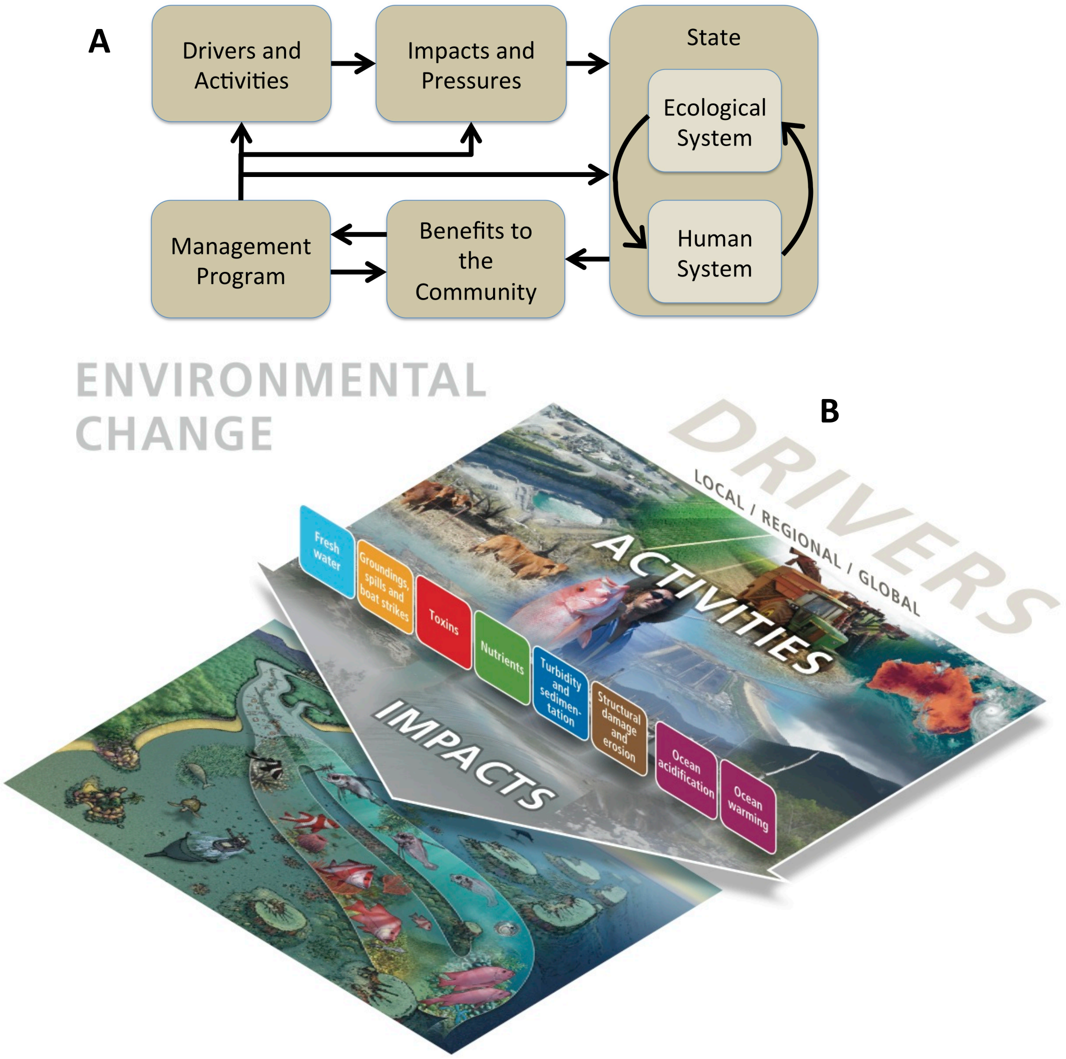


Figure 2.2. Schematic representations of the hierarchy of causal links between Drivers, Activities, Pressures and Impacts, system state and management responses (DPSIR structure) used as a basis for constructing qualitative models.

2.2.1 Qualitative modelling – background and methodology

Qualitative modelling is a powerful tool to analyse linkage pathways in complex systems (Puccia and Levins 1985, Petschel-Held et al. 1999, Coyle 2000, Dambacher et al. 2003, Dambacher et al. 2009). Qualitative models are networks of linkages describing causal relationships between elements of a system, for example within an ecosystem. They differ from quantitative models by only describing positive or negative causal linkages, not the strengths or shape of those linkages.

The CISDM framework uses qualitative models to understand how exposure to multiple stressors that result from human-related activities, or environmental or societal drivers, cumulatively impact on ecosystem values in the GBRWHA. A basic feature of qualitative modelling is the development and analysis of signed digraphs (Info Box 2.1), which are used to describe the main interacting variables within a system.

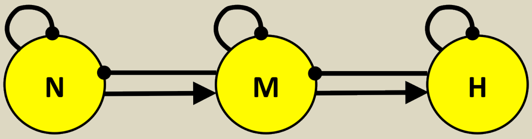
Importantly, beyond the technical aspects of signed digraphs, this work is guided by Levins' (1966) approach to model building, which ultimately seeks a unification of different modelling approaches to better understand, predict and intervene in complex ecological and socioeconomic systems (Appendix 1). The rationale for using qualitative models in this framework is three-fold.

- Firstly, qualitative models can be developed in consultation with mixed groups of scientists, managers and stakeholders and provide a platform for discussing the structure and key elements of the system of interest.
- Secondly, qualitative models have conceptual appeal, are intuitive and are good communication tools. The essential details of highly complex systems can be captured relatively quickly through mixed-group consultation where everyone has equal opportunity to contribute.
- Thirdly, the development and analysis of qualitative models is rapid relative to quantitative models, as their objective is realism and generality rather than precision (Appendix 1) (Levins 1966, 1998).

Lastly, a key benefit of qualitative models is that (in combination with a probabilistic representation in Bayes nets, see below) they can rigorously inform risk-based management decisions. It can be argued that explicit quantification is often too onerous a task for many of the judgments required in assessing cumulative impacts over a large geographic area. If deployed carelessly, detailed quantitative modelling can lead to decisions that suffer from myopia and overconfidence (Hammond et al. 2006). In any case, much of the variability and uncertainty in expert judgment stems from qualitative differences in perspectives on which variables drive system dynamics and in which direction, rather than the details of the magnitude of one or more drivers (Hosack et al. 2008). Quantitative approaches will still play an important role, however, but are best applied where there are sufficient resources for data collection, and where they can be focused to resolve key uncertainties or address critical management questions requiring precision.

INFO BOX 2.2: Qualitative models and their analysis

Qualitative modelling proceeds from the construction and analysis of sign-directed graphs, or signed digraphs, which are depictions of the variables and interactions of a system. Qualitative models are only concerned with the sign (+, -, 0) of the direct effects that link variables. The below signed digraph is a straight-chain system with a pressure such as nutrients (N) resulting from land-use run-off, an impact on Macroalgae (M) and a resulting increase in grazing by herbivorous fish (H). There are two Nutrient-Herbivory relationships, where the herbivorous fish receive a positive direct effect (i.e., grazing, shown as link ending in an arrow (→)), and the macroalgae receive a negative direct effect (i.e., mortality, shown as link ending in a filled circle (●—)). Included also are self-effects, such as density dependent growth.



Stability. Based only on this qualitative structure, it can be determined that this model is stable, which is a result, in part, of it having only negative feedback cycles. The paths leading from the herbivores to the macroalgae and back to the herbivores are negative feedback cycles of length two, and there are no positive (destabilizing) cycles. Thus, if this system were to experience a sudden disturbance it would be expected to return relatively quickly to its previous state or equilibrium.

Prediction of perturbation response. One can predict the direction of change in each variable (i.e., increase, decrease, no change) due to a sustained input or pressure to the system. Consider a pressure on the system in the way of food supplementation to the herbivore that increases its reproductive capacity. The predicted response of M is determined by the sign of the link leading from H to M, which is negative (denoted H —● M). The predicted response of N will be positive because there are two negative links in the path from H to N (H —● M —● N), and their sign product is positive (i.e., − x − = +). In this system there is complete sign determinacy for all response predictions, as there are not multiple pathways between variables with opposite signs, but in more complex systems there can be responses that are governed by multiple direct and indirect effects that have different signs, thus leading to ambiguous predictions of response sign.

2.2.2. Qualitative model development in expert workshops

Two expert and stakeholder workshops were conducted to develop qualitative models for two key ecosystem values: coral reefs, seagrass meadows and their dependent species. The names and affiliations of participants are listed in the Appendix 1. A third workshop was held to develop qualitative models for coastal ecosystems and to further explore the connectivity between land-use and pressures in receiving waters. Results of the third workshop are not reported here as analyses are contingent on further development of quantitative modelling of water and pollutant flow through catchments and coastal ecosystems.

Coral reefs

In the coral reef workshop, a group of 12 scientists with broad expertise in coral reef ecology collaborated with the team in eliciting qualitative models that best represent the functional causal linkages between drivers, activities, pressures and impact on, and responses of, key ecosystem values in the system. Experts were asked to only include processes that are well documented by the scientific literature, and involve ecosystem components that are considered to underpin MNES and OUV. Four alternative models were generated based on differences of opinions around specific causal linkages and processes involved. Two examples of uncertain linkages were (1) the link between major nutrient run-off events during floods and the probability of primary outbreaks of Crown-of-thorns starfish (COTS) and (2) the negative relationship between turbidity and the abundance of herbivorous fish. Rather than dismissing the least popular or likely linkages in the two examples, all possibilities were embraced formally giving rise to four alternative models. These alternative models are presented in Appendix 1. Also, information on how the user can switch between alternative models is presented in the next section (*Probabilistic models*). The alternative model used predominantly in examples in this report (model 2) is shown in Fig. 2.2.

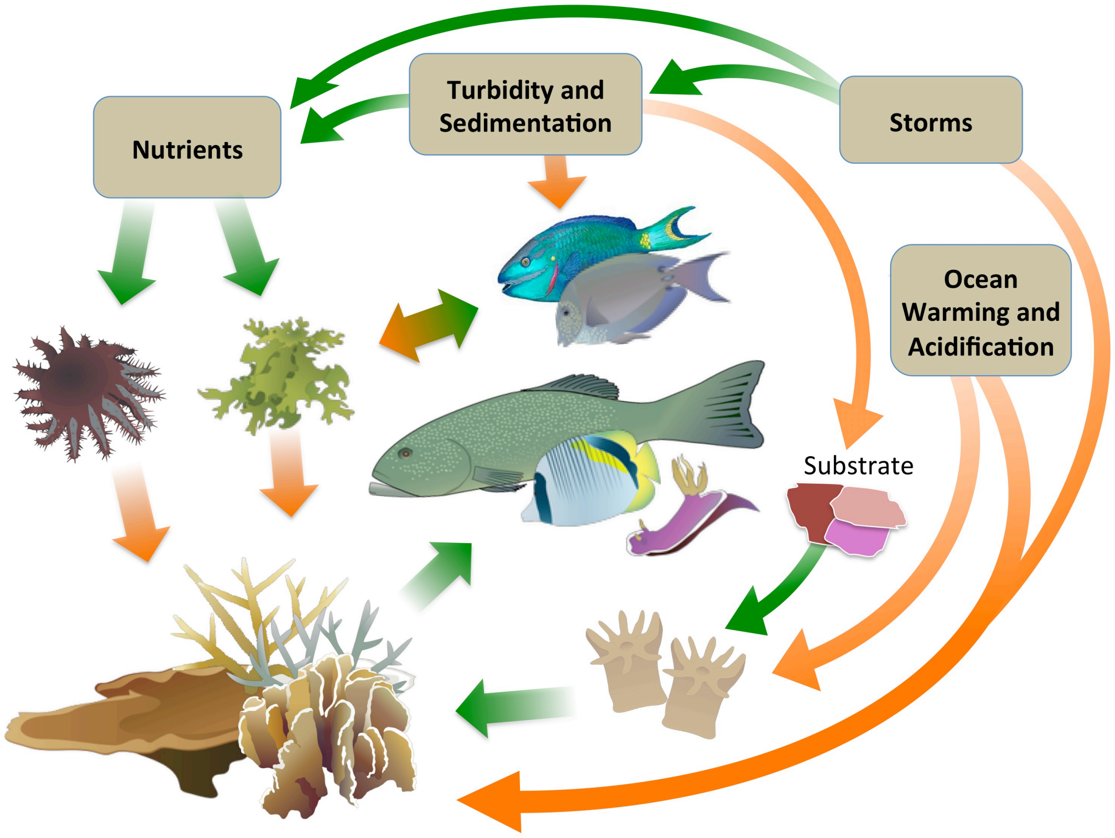


Figure 2.3. Conceptual representation of simplified qualitative model developed for the coral reef system. Blue arrows are positive and orange arrows are negative linkages. Here, only four pressure nodes (nutrients, turbidity and sedimentation, storms and ocean warming and acidification) are represented without showing their multiple, possible linkages to drivers and activities (see also Fig. 2.4). For tractability, complex food web linkages between all functional fish groups are not included in the model. Source of graphics: IAN Image Library.

Figure 2.4 below shows an influence diagram for coral reefs, including drivers and activities. Here, dashed lines represent uncertain links, which gave rise to alternative representations. While nodes represent drivers, activities, pressures and values, arrows represent impacts and processes. Some individual arrows include chains of processes. For example, the link between ocean acidification and coral cover includes impacts on a suite of cellular, biogeochemical and ecological processes, of which several underpin reef resilience (Anthony et al. 2011).

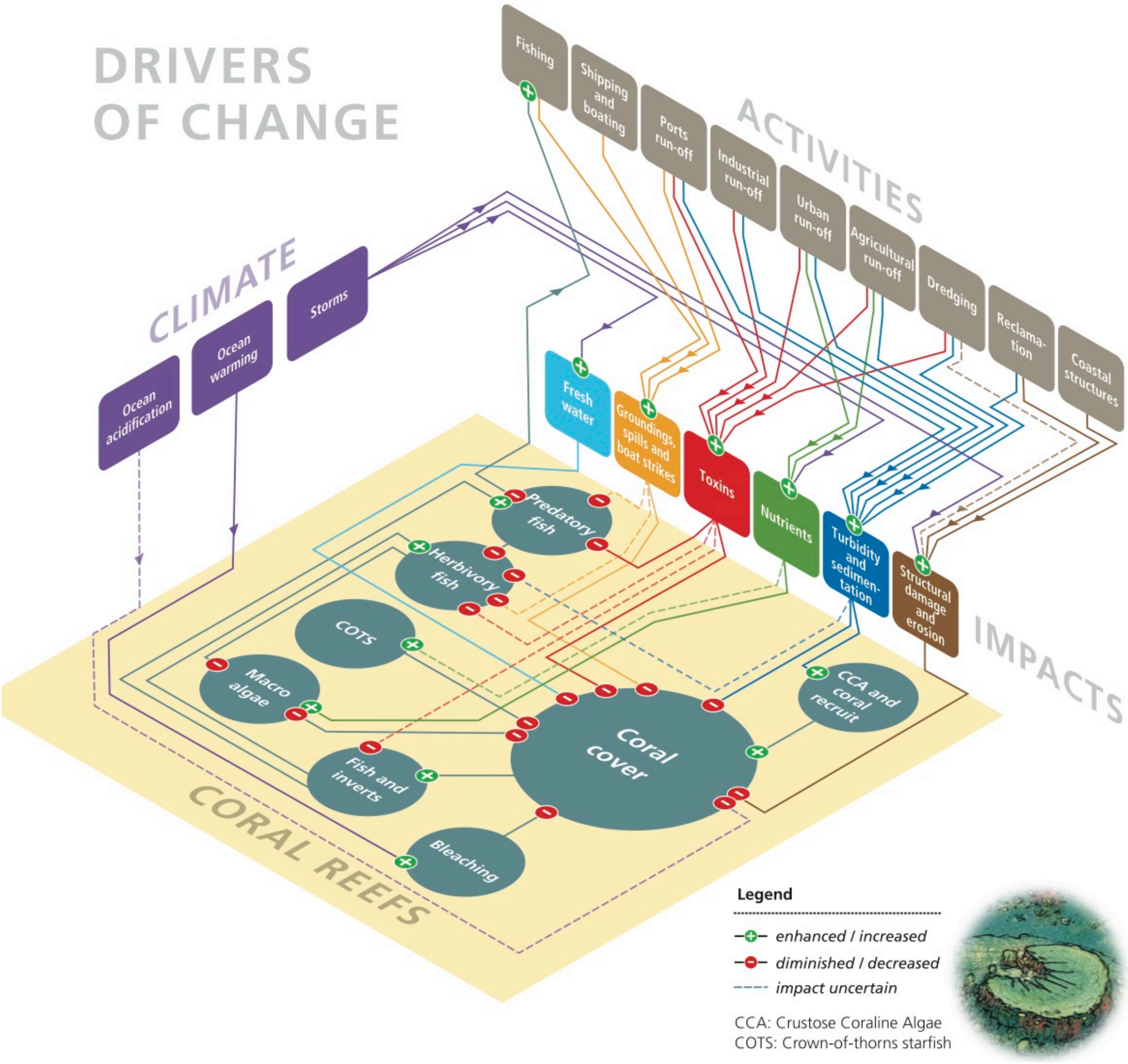


Figure 2.4. Influence diagram of how coral reef ecosystem links to activities and exposures. Dashed lines are uncertain linkages of which two gave rise to alternative representations (links between turbidity and herbivorous fish, and between nutrients and COTS).

Seagrass systems and dependent species

In the seagrass workshop, eight leading experts in seagrass systems ecology and dugong and turtle biology collaborated with the team to elicit qualitative models that capture the causal chain of linkages between drivers, activities, pressures, impacts and responses in seagrasses and their dependent species. Similar to coral reefs, sets of alternative models were developed where experts could not agree on the inclusion or exclusion of specific links, or where there were feasible alternative hypotheses. Uncertain links were (1) whether dugongs are regulated solely by seagrass abundance or whether for example density-dependence is relevant, and (2) whether epiphytes impact negatively on seagrasses. The four alternative models resulting from these uncertainties are given in Appendix 1. Also, information on how the user switches between alternative models is presented in the next section (*Probabilistic models*).

In the seagrass system, three key value nodes were identified: distribution and abundance of climax seagrass communities, dugongs and green turtles (Fig. 2.5). In addition, seagrasses are nursery habitats for many species of fish and prawns (Fig. 2.6). However, the nursery habitat function was omitted from the Bayesian Belief Network constructed for this ecosystem, as habitats are represented by seagrass distribution and abundance *per se*, similar to structurally complex corals providing habitats for fish and invertebrates.

Five variables were identified as key impacts on seagrass systems and their associated fauna: background dugong mortality, ocean warming, nutrients, sedimentation and turbidity, and structural damage and erosion. Background dugong mortality (i.e. in addition to resource dependence) includes boat strike, incidental drowning in mesh nets and traditional hunting (Grech et al. 2008b). Ocean warming is included as seagrass growth is stimulated by warming up to a threshold (Waycott et al. 2007) and turtles are negatively impacted by warming as high temperatures skew the gender ratio in hatchlings towards females (Fuentes et al. 2011). Structural damage and erosion includes impacts resulting from cyclones, dredging, trawling, anchoring and reclamation.

In the qualitative model for seagrass, turbidity and sedimentation are combined into one pressure as they are strongly correlated. Ideally, however, turbidity and sedimentation should be separated as they affect seagrasses differently. Turbidity causes a negative impact on seagrasses in deep water (Collier et al. 2008), whereas sedimentation causes both positive and negative impacts. Some seagrasses are robust to relatively high sediment supply (Manzanera et al. 1998) and sediment is a requirement for the establishment of seagrass meadows (Hugh Yorkston, GBRMPA pers comm). Therefore, the model makes the assumption that background sediment loads in near-shore habitats do not cause an observable response, but sedimentation levels exceeding the baseline will lead to negative effects on seagrasses.

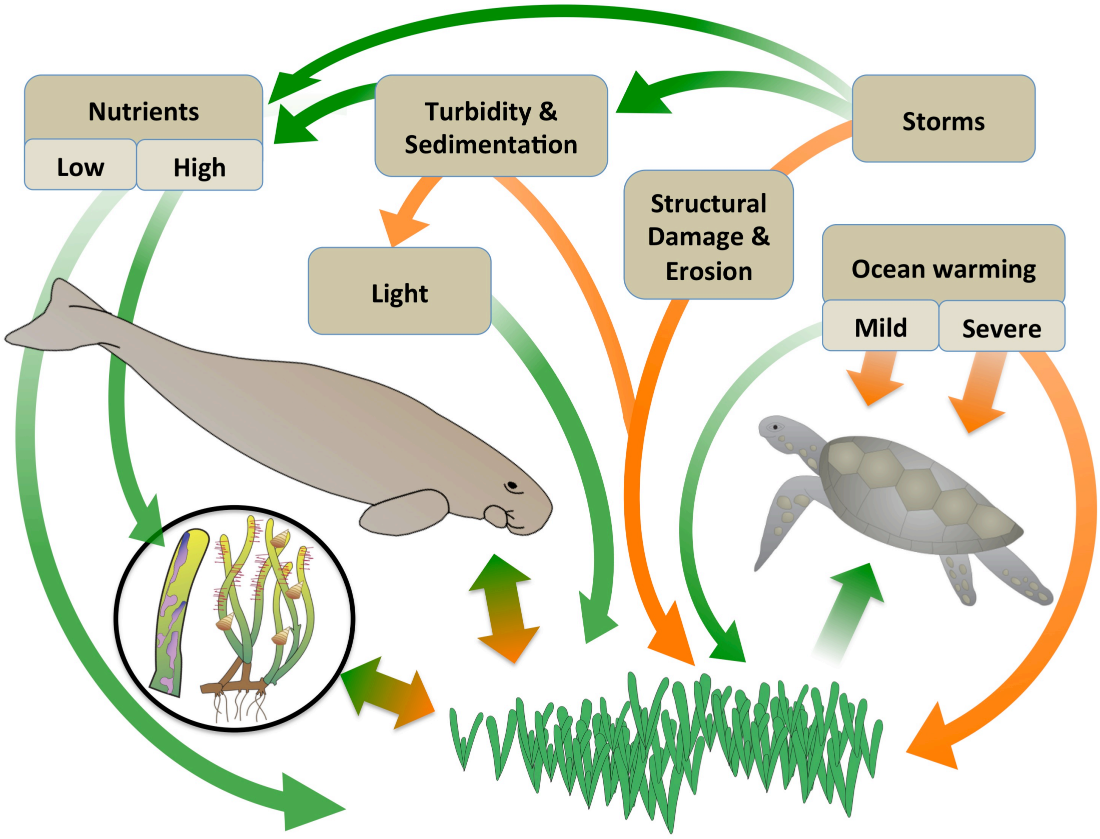


Figure 2.5. Conceptual representation of qualitative model for seagrass and key dependent species. Blue arrows are positive and orange arrows are negative linkages. Similar to coral reefs, four pressure nodes (nutrients, turbidity and sedimentation, storms and ocean warming) are represented without their linkages to drivers and activities (see also Fig. 2.6). Ocean acidification is not included here as acidification effects are unlikely to cause as severe an impact on seagrasses as on coral reefs. Note that low and high bands are used for nutrients and for ocean warming. This is to account for the non-linear responses of seagrasses to these pressures. Effects of sedimentation are only assumed to be significant where background levels are exceeded (see text). An increase in nutrients at low concentration ranges stimulates growth in seagrasses (Powell et al. 1989, Udy and Dennison 1997), but high nutrients lead to increased competition with epiphytes for light (Fong et al. 1997). Similarly, warming below the optimal temperature for seagrasses stimulates growth rates, whereas higher than optimal temperature is likely to lead to suppressed growth (Collier et al. 2011). Source of graphics: IAN Image Library.

Similar to Fig. 2.4, Fig. 2.6 below shows an influence diagram for seagrass ecosystems. Again, dashed lines represent uncertain links, which give rise to alternative representations. Arrows also represent impacts and processes, of which some include chains of processes such as seagrass growth, succession between early and late colonisers, and competition with epiphytes (Fong et al. 1997).

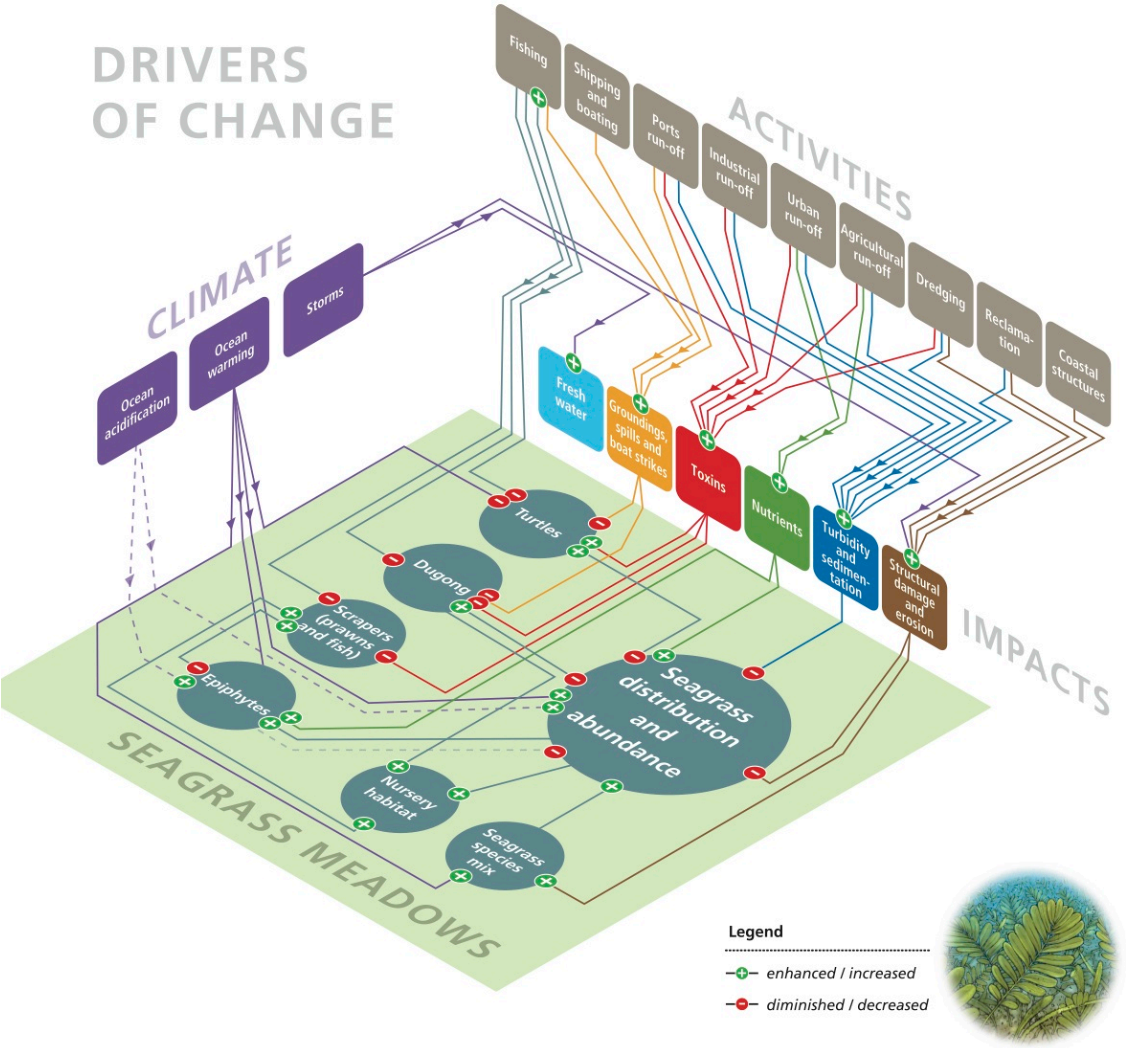


Figure 2.6. Influence diagram of how a seagrass ecosystem links to activities, exposure and impacts. Here, the direct drivers are separated from activities as they are outside the control of local management. Dashed lines are uncertain or disputable/contentious causal links and gave rise to alternative representations.

2.2.3 Probabilistic models: Bayesian Belief Networks (Bayes nets)

In this framework Bayesian Belief Networks, or Bayes nets, are used to represent the predictions from qualitative models in networks of probabilities of change for both pressures and values. More specifically, Bayes nets are networks of causal linkages with information on three conditional probabilities at each node: likelihoods of (1) *increase*, (2) *no change*, and (3) *decrease*. Importantly, in the CISDM application of Bayes nets, they are not used to inform about magnitudes of change, only the probability that a change will occur or not, and if it does occur, in which direction. Moreover, there is no scaling for time within the Bayes nets; the time scales over which pressures and responses occur are addressed in the context of the qualitative models. For this work the Strategic Assessment planning horizon of 25 years into the future was used in qualitative modelling workshops with respect to the net changes in key drivers, activities and ecosystem values. Lastly, conditional probabilities do not take account of the current status of the ecosystem value, for example the current abundance of corals, fish or dugongs. The current status of ecosystem values can, however, be considered when exploring

Bayes nets in the diagnostics mode (Fig. 2.7). See also Appendix 1 for more detailed information.

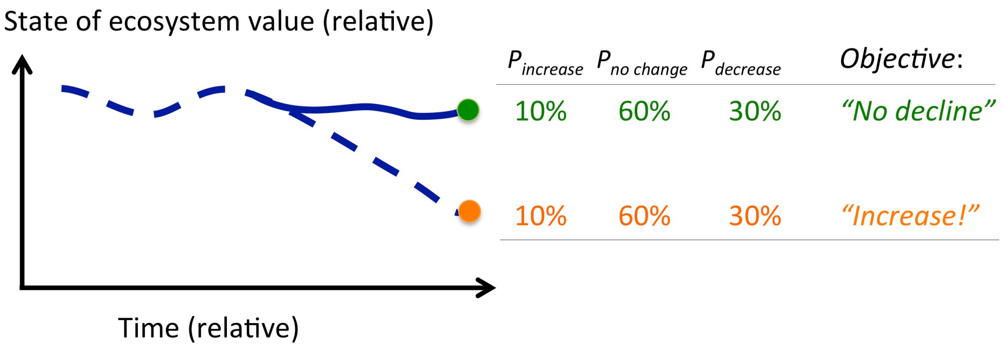
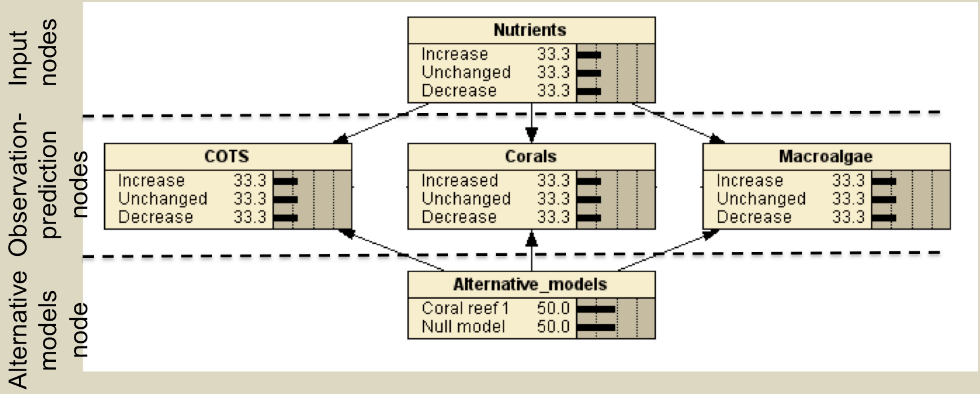


Figure 2.7. Example of how two contrasting system states (e.g. coral cover) could be explored diagnostically using Bayes nets. Where system state is high, the fundamental objective would be "No decline"; where system state is low, the fundamental objective would be "increase". Where there is information to support that probabilities of change vary with system state, the user can account for this in the Bayes net.

The Bayes nets mostly represent the same variables that are in the qualitative model and also include an "alternative model" node, which allows the user to select from the four alternative models outlined in Appendix 1 (as discussed above, Model 2 has been used for the purposes of this report). Activity nodes (e.g. land-use, port developments, dredging and spoil dumping etc) have been removed so that the user interacts directly with the pressures acting on the model system. The role of activities and how they influence ecosystem values spatially under different scenarios (alternatives) is dealt with in Section 2.3 where the concept of *Zones of Influence* is introduced.

INFO BOX 2.3: Structure of Bayes nets representing and analysing predictions from qualitative models

Bayes nets can be used to represent and analyse the predictions of qualitative models in a probabilistic framework (Hosack et al. 2008). The below Bayes net represents the qualitative model described in Info. Box 2.2, and has three types of nodes. An *alternative models node* represents the likelihood for the model(s) under consideration (here Model A), and also includes a null model, which has the function of making predictions for model variables with equal likelihood for increase, unchanged, or decrease. A middle tier of nodes (*observation-prediction nodes*) contains one node for each of the variables in the qualitative model, and is used to either record empirical observations or represent the likelihood of model predictions. The *input nodes* represent the likelihood of pressures that cause a perturbation to the system. While this example has only one input node, the Bayes net can include multiple input nodes, which allows for assessment of cumulative impacts from multiple pressures. Note that likelihoods within the *observation-prediction nodes* are dependent on the state of the *alternative models node* and the *input node(s)*, as such all of the arrows in the Bayes net lead towards, and never away from, them. The example follows a characteristic structure that is used for Bayes nets throughout this report; see Appendix 1 for a general description of the analysis and interpretation of Bayes nets within this report.



2.2.4. How to use and interpret the Bayes nets

In this framework Bayes nets are used primarily in combination with *Zones of Influence* (see the following section) to explore how different land-use and development scenarios lead to potential impacts on ecosystem values. In doing so, the framework takes advantage of the *predictive* capability of Bayes nets, which produces data to inform cumulative impact assessments and also the structured decision-making process.

Prediction: Bayes nets allow the user to predict the likelihoods for a direction of change (*increase*, *no change* and *decrease*) in a value node caused by the likelihoods of change in one or more pressure nodes linked directly or indirectly to the value node. Importantly, in the CISDM application of Bayes nets, only the direction of change, not its magnitude, is predicted. Nor is the time scale of the predicted response explicitly analysed within the Bayes net, rather, it is implicit within the context of the qualitative models, both with respect to the dynamics of system perturbations, but also to the dynamics of the system variables. For example, a sustained increase in the frequency or magnitude of nutrient inputs (say from flood events in fertilized catchments) might be expected to be observed within a few months in fast growing plant species, but would perhaps require a number of years to be observed in large bodied mammalian grazers. The CISDM framework uses this predictive function extensively for cumulative impact assessments and structured decision-making. An important caveat that must be stressed when considering the probabilities for the qualitative predictions is that they are based on a relatively crude measure of sign determinacy derived from analysis of the qualitative models (see Appendix 1). As such, the reported probabilities are contingent on the context and assumptions that are implicit within the signed digraph models, and also on the particular details of the numerical simulation studies used to generate the probability values (Hosack et al. 2008). Therefore, the use of Bayes nets for analysis of these probabilities is intended only to highlight large relative differences between model predictions, and the exact value of any given prediction, or small differences between multiple predictions, should not receive undue emphasis.

Diagnostics: In addition to the *predictive* function of a Bayes net, they can also be used for *diagnostics* in a planning context. For example, fundamental and operational objectives can be entered directly into one or more value nodes to allow the user to ask specific management and planning questions. Consider a situation where a manager wants to have some confidence (could be 100% or more than 50%) that a value will increase or stop declining in the focus area. By selecting a high probability value for "*increase*" (e.g. 100%) in the value node for corals, the manager can analyse (diagnose) what changes are required in the pressure nodes (e.g., nutrients, turbidity and sedimentation, and ocean warming) to meet that objective. Again, the language must be framed with respect to likelihood of change in the direction, and not magnitude, of change in the value or the pressure. To narrow down the diagnosis to include only a subset of pressure nodes, other pressure nodes can be forced to 100% probability of "*unchanged*", or to "*decreased*" where mitigation is already implemented.

The user boxes below provide examples of how Bayes nets can be used to explore (1) impacts of scenarios through predictions by manipulating probabilities in pressure nodes and recording changes in value nodes (User Box 2.1), and (2) what changes in pressure nodes are required to provide desired outcomes for ecosystem values (User Box 2.2). Examples of other uses of Bayes nets including *sensitivity analyses* (key tool for selecting indicators for monitoring programs), and *model validation* (comparing model performance against observations) are given in Appendix 1.

The models do not address the role of local adaptation and site-specific sensitivities of species to prolonged exposures to, for example, turbid water (see *Framework Limitations and Caveats*). However, the current status of value nodes (e.g. coral cover or seagrass abundance) can be used in the setting of fundamental objectives and thus partially account for local sensitivity (Fig. 2.7). Also, current trends in ecosystem values can be used to inform baseline probabilities used in the Bayes nets, e.g. the expected decline or increase under the business-as-usual scenarios with respect to water quality and climate change.

2.2.5 Probabilistic scenario modelling of coral reefs

In the following, examples are presented to demonstrate how different cumulative stress scenarios affect the probabilities of change in different value nodes in the coral reef system.

The Bayes nets are first analysed in *Prediction* mode by manipulating probabilities of change in pressure nodes and observing changes in value (response) nodes. The user can ask the question: how do combinations of reduced water quality, climate change and storms impact on ecosystem values?

To prepare the user for this exercise, the following points provide some preliminary notes on setting conditional probabilities in the Bayes nets. More detailed guidance is provided in the next section (*Assessment of Cumulative Impacts*).

- In the prediction mode the user only interacts with the input/pressure nodes and the alternative models node (see User Box 2.1). The alternative models node is a switch box that allows the user to choose a model of interest or considered most appropriate (see Appendix 1 for a description of each of the alternative models).

- Inputs to the pressure nodes represent the likelihood of a change that would be expected to exert a significant and observable effect on value nodes (e.g. a 30% likelihood of an increase in nutrients to a level that would be expected to exert a significant and observable effect on coral reefs). Ideally, determining probabilities of change in pressures should be based on expert scientific opinion or models relating activities or drivers to probabilities of change (see section 2.3). However, the user can explore impacts on response nodes (e.g. values) based on some first-order judgement of how, for examples, probabilities of change in nutrients are likely to be affected by a doubling in land-use run-off.

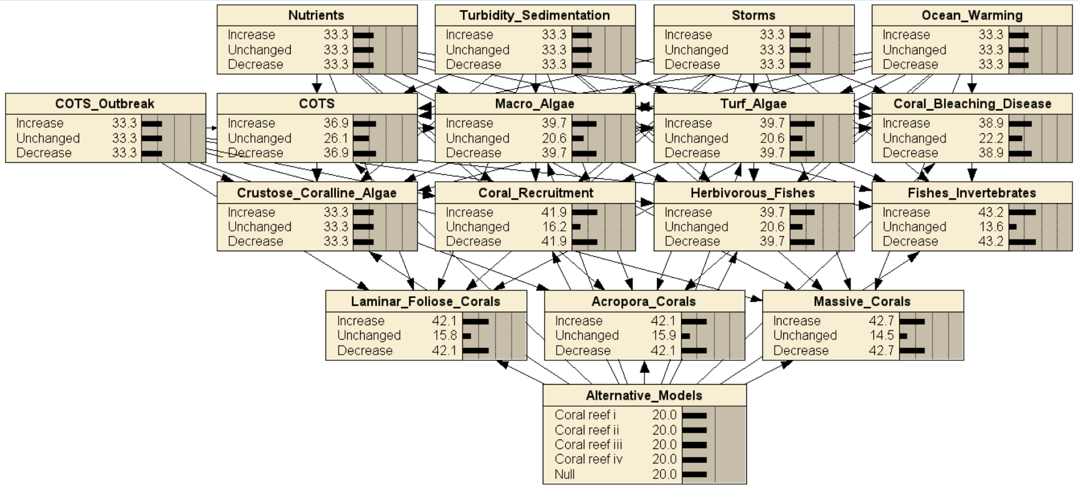
- A challenge for the user is interpret the probability distribution (*increase, unchanged, decrease*). As a rule of thumb, the narrower the distribution, the more confidence the user can have in a given change and the wider the distribution, the more uncertainty. For example, 100% *increase*, 0% *unchanged* and 0% *decrease* represent strong user confidence that there will be an increase in a pressure (e.g. in nutrients). The opposite extreme is 33.3% *increase*, 33.3% *unchanged* and 33.3% *decrease*, representing high uncertainty with respect to outcomes. The latter is often used as a status quo scenario with high uncertainty (see Info Box 2.4).

Building on the example in User Box 2.1, Fig. 2.8 shows an example of imposing an enhanced *Nutrients* and *Turbidity and Sedimentation* regime and recording probabilities in key value nodes. All three coral groups and the *Fishes and Invertebrates* have a more than 60% chance of decline determined by the probabilistic model. However, they also have a 27% chance of an increase, which means there is considerable *uncertainty* in these predictions (see Info Box 2.4). Part of this uncertainty is due to the fact that the nodes *Storms* and *Ocean Warming* are left untouched with equal chances of *increase*, *unchanged* and *decrease*.

User Box 2.1. Prediction using Probabilistic Models: Bayes nets

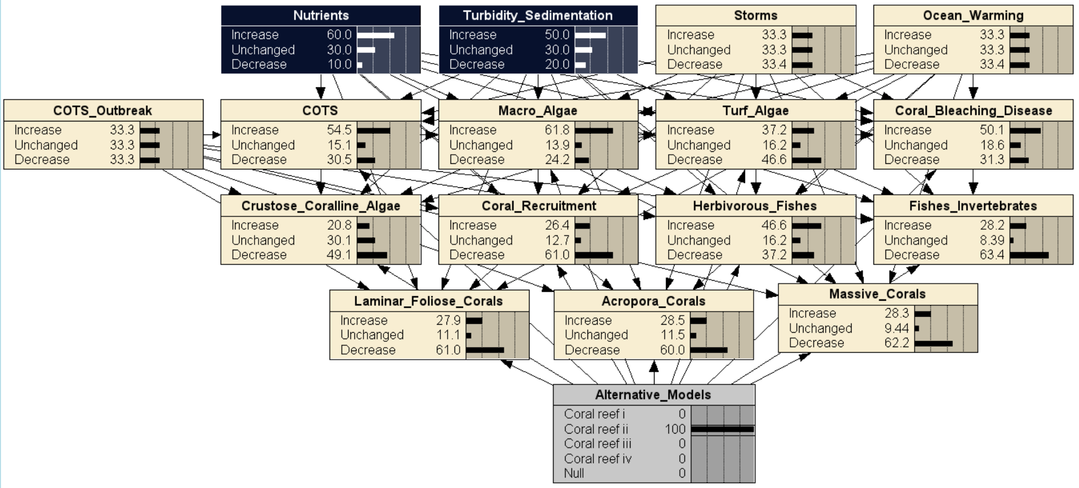
Two Netica files are available on the CD. These are Bayes Net models of the coral reef and seagrass ecosystems, respectively: *GBR_CoralReefs.neta*, and *GBR_Seagrass.neta*

Start by installing and opening the *Netica* program (can be downloaded from www.norsys.com.netica.html). The coral reef model should look like this:



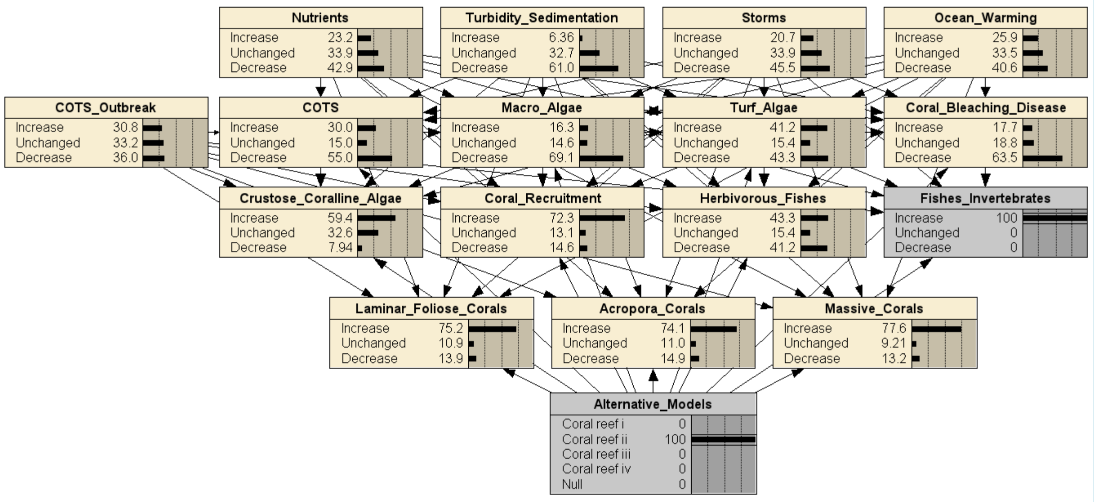
Note that likelihoods of change in all pressure nodes (top row) are 33.3% (all probabilities within boxes must sum to 100%), and similarly for the **COTS_Outbreak** node. The bottom box is a switch board for the different alternative models (see the *Qualitative Models* section), and can be interacted with by selecting the model directly. The box with then display "100" for the chosen model and "0" for the remaining models.

This example assumes focus on only one *Zone of Influence*, e.g. inside an area influenced by different activities all leading to significant pressures in that area (see section 3). Start by selecting a model, e.g. model 2: causal link between nutrients and COTS and between turbidity and herbivores (see Appendix 1). Note that the ***Alternative_Models*** node is a switchbox that allows the user to select a model of interest. Enter new probabilities of change for **Nutrients** and **Turbidity_ Sedimentation** to represent increased run-off from agriculture. Enter values by double clicking the pressure node, select *Table*, and then enter probabilities as percentages in the three boxes (sum = 100). Note how this changes the probabilities within all three coral nodes and for **Fishes_Invertebrates** (>60% likelihood of decrease). Also note elevated likelihoods of *increase* for **COTS** and **Macroalgae** and elevated likelihoods of *decrease* for **Coral_Recruitment**. Uncertainty in the value nodes is high because **Storms**, **Ocean_Warming** and **COTS_Outbreak** have been left untouched, i.e. completely uncertain. If the user has *a priori* understanding of COTS status then this can be entered. If the user wants to set one or more pressure nodes to 100% *unchanged*, this can be done by clicking on that row in the node.

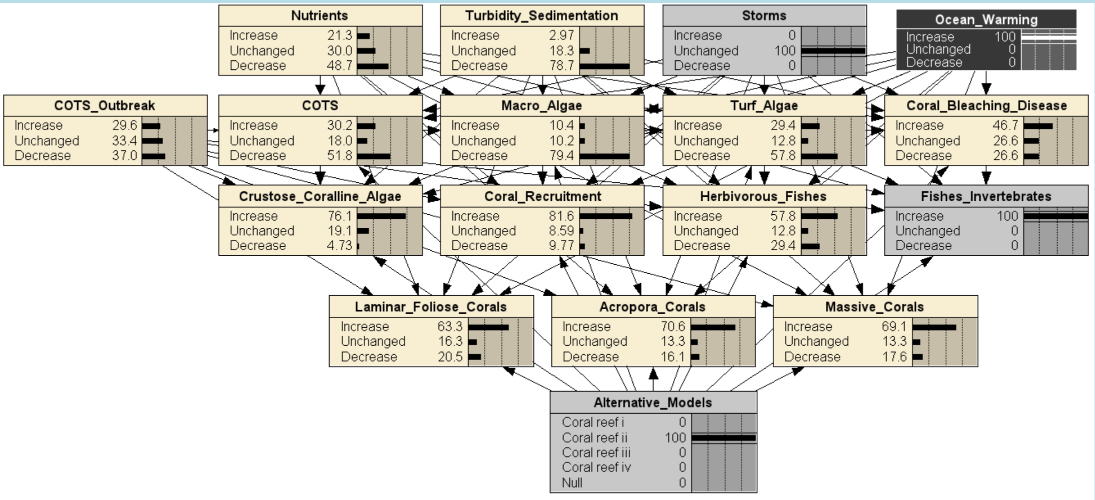


User Box 2.2. Diagnostics using Probabilistic Models: Bayes nets

To explore diagnostically how environmental variables (pressure nodes) need to change to fullfil fundamental objectives, e.g. as part of a planning strategy, probabilities are entered directly into value nodes. Start by entering 100 into the **Fish_Invertebrates** node**.** This means the fundamental objective is to be certain that fish and invertebrate abundance increase. As a result, values in all pressure nodes shift toward higher probabilities of *decrease*, necessary to achieve the objective. Also, because corals are important habitats for fish and invertebrates, all coral nodes shift to higher probabilities of *increase*.



If the user wants to focus on a subset of pressure nodes under local or regional management, setting realistic probabilities for **Storms** and **Ocean_Warming** can help constrain what management efforts are needed to fulfill objectives. As an example, set **Storms** to 100% likelihood of *unchanged* and **Ocean_Warming** to 100% likelihood of *increase.* Implementing a high likelihood of warming oceans (notwithstanding the effect of storms) increases the demand for management of water quality (see below).



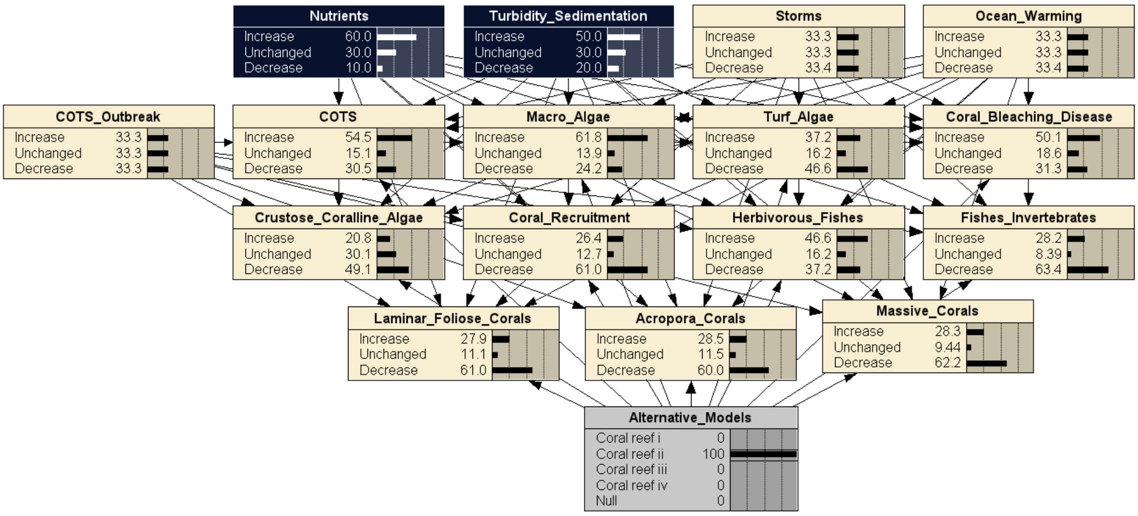
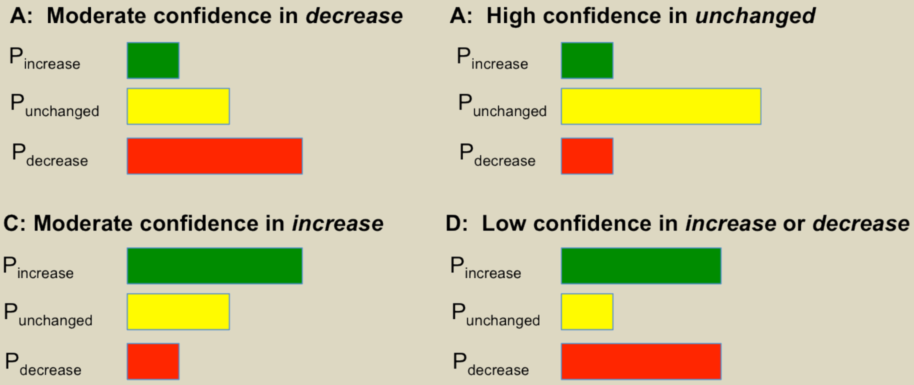


Figure 2.8. Bayes net results for imposed pressure scenarios for *Nutrients* and *Turbidity and Sedimentation* using *Alternative Model ii* (*Nutrients* affect *COTS* and *Turbidity and Sedimentation* affect *Herbivorous Fishes*).

Assigning increased probabilities of *Storms* and *Ocean Warming* as well as reduced water quality leads to a dramatic increase in the likelihood that all coral groups and the fish group will decline (Fig. 2.9). Because the Bayes net model is built on causal linkages in the qualitative model, patterns of probabilities in value nodes (including processes such as recruitment) reflect the underlying model, in this case *alternative model ii* which assumes a positive causal link between nutrients and COTS (Brodie et al. 2005, Fabricius et al. 2010) and a negative causal link between turbidity and the abundance of herbivorous fish (Wolanski et al. 2004, Cheal et al. 2012, Cheal et al. 2013).

Info Box 2.4. Bayes Net probabilities and uncertainty

The distribution of probabilities can be used to assign confidence versus uncertainty to result. For example, for analyses focusing on the probability of a *decrease,* the uncertainty is represented by the probability of *unchanged* (the neutral result) and in particular the probability of *increase* (the opposite result).


A: Moderate confidence in *decrease*

A: High confidence in *unchanged*

C: Moderate confidence in *increase*

D: Low confidence in *increase* or *decrease*

The results provide insight into how multiple pressures affect the whole system. For example, for an increase in nutrients and also turbidity and sedimentation, there is a high probability of an increase in the key stress indicators COTS, macroalgae and coral bleaching and disease, whereas coral recruitment, a resilience cornerstone, has a high probability of decrease. Note that the *COTS Outbreaks* node has been left untouched because it is a switchbox allowing the user to account for observations (e.g. 100% increase in the case of observed COTS outbreak) and does not form part of the prediction.

Interestingly, the three groups of corals and the fish and invertebrates also here have similar probability distributions as they are tightly linked in the qualitative model. Therefore, the scenario analyses in this report will only use results for corals generally (using *Acropora* as the coral representative) as a common indicator for coral reef values.

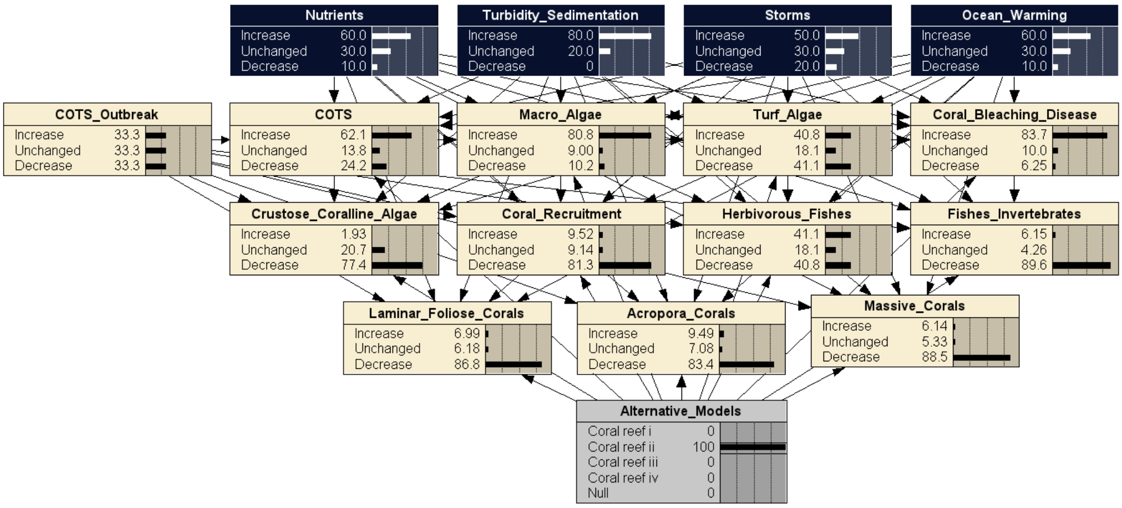


Figure 2.9. Bayes net results for cumulative pressure scenario for *Nutrients, Turbidity and Sedimentation, storms* and *Ocean Warming* using *Alternative Model ii* (*Nutrients* affect *COTS* and *Turbidity and Sedimentation* affect *Herbivorous Fishes*).

Lastly, building on the examples in User Box 2.2, the user can explore diagnostically how management of selected indicators will impact on key values, as well as provide guidance on which pressures and, by inference, which activities need to be managed as a priority. Below is an example in which a user has optimised probabilities in three nodes representing key resilience indicators: *reduced* macroalgae, *increased* coral recruitment and *no change* in herbivorous fishes (Fig. 2.10A). Herbivores are set to unchanged rather than increased, as herbivores are not fished commercially on the GBR. From a management perspective, three manageable pressures, *Nutrients*, *Turbidity_Sedimentation* and *COTS* all need to be decreased to meet this goal given *Alternative_Model_ii* (nutrients affect COTS and turbidity affect herbivores, Appendix 1). Note that, because coral recruitment is set to a maximum probability of increase, crustose coralline algae, another resilience indicator, are increased as a consequence.

If, however, the user has more confidence in *Alternative_Model i* (nutrients do not affect COTS and turbidity do not affect herbivores), then the need to reduce nutrients, turbidity and sedimentation and COTS are significantly reduced (Fig. 2.10B). Appendix 1 provides examples of how observations can be used to run *model validations* using Bayes nets to select the most appropriate alternative model.

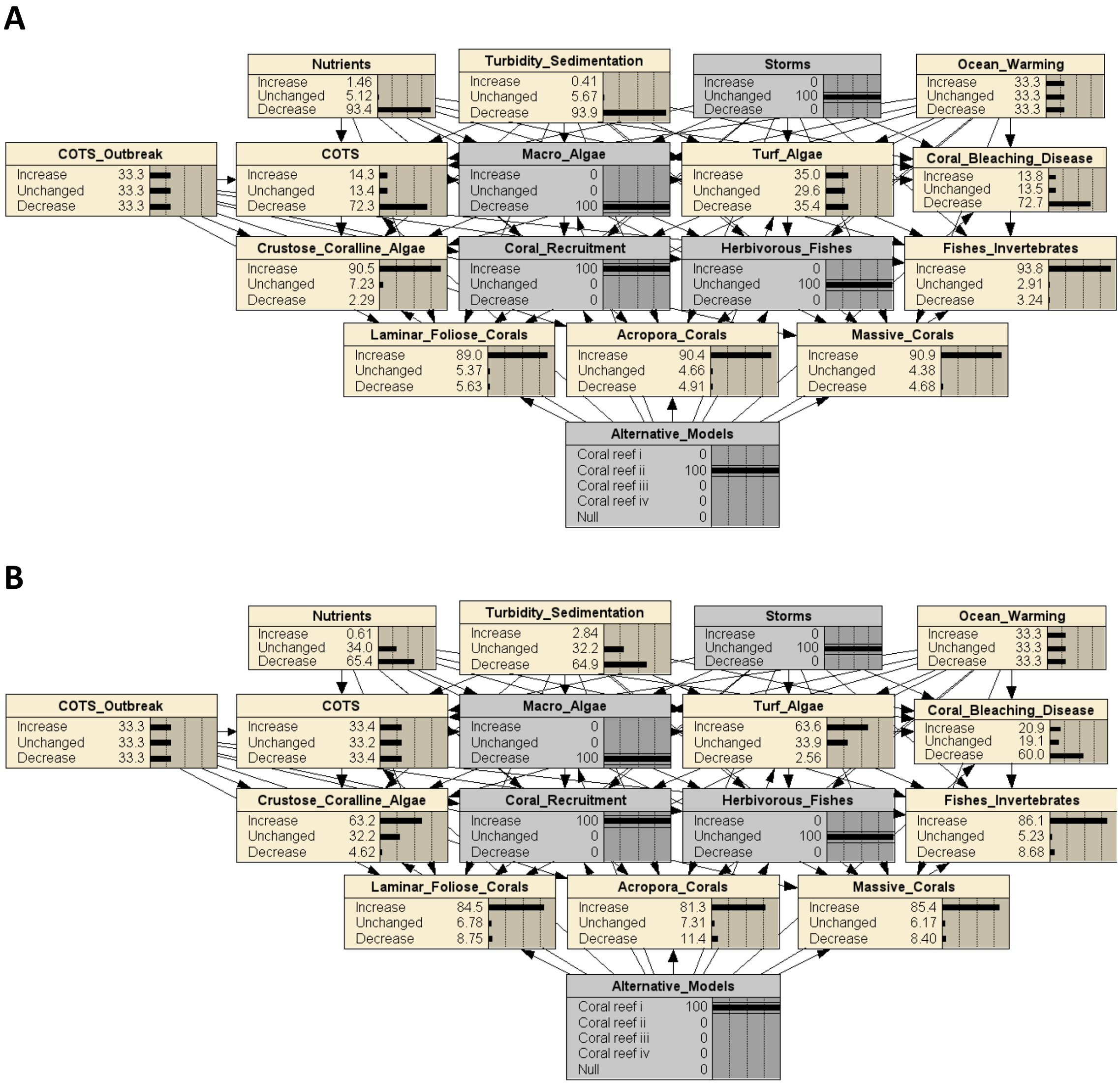


Figure 2.10. Example demonstrating how Bayes nets can be used to examine actions needed to meet management goals. **A:** example using *Alternative_Model_ii* (candidate model supported most strongly by the expert group), assuming that nutrients affect COTS and turbidity affect herbivores. **B:** Example using *Alternative_Model_i* (least supported model), assuming that nutrients do not affect COTS and turbidity does not affect herbivores (see also Appendix 1).

2.2.6. Probabilistic scenario modelling of seagrass systems

The Bayes net model for the seagrass meadows and key dependent species (dugong and green turtles) is built on principles identical to those of the coral reefs model, but with additional processes considered. Specifically, the nonlinear effects of nutrients and temperature on seagrasses (i.e. seagrass growth increases with nutrient and temperature up to a point, and then decreases) are carried through from the qualitative models to the Bayes nets. To run environmental scenarios for the seagrass ecosystem, the user needs to decide whether the scenario pertains to the low or high ends of the nutrient or temperature regimes, as it will produce different outcomes. In the following, examples are given to demonstrate effects of both nutrients and ocean warming.

First, a scenario is considered for an increase in nutrients in the low range. Observational and modelling studies for the GBR indicate that this range is represented by chlorophyll *a* concentrations in the range 0 – 45 ug/L (De'ath and Fabricius 2008) or particulate nitrogen and phosphorous of 20 and 2.8 ug/L respectively (GBRMPA 2010). For clarity, all other pressure nodes are set to *unchanged*. Note that this scenario predicts that *Seagrass Distribution and Abundance*, *Dugong*, and *Turtles*, will all increase and with similar likelihoods (Fig. 2.11). The increase is predicted because nutrients stimulate seagrass growth in the low range, and as a consequence provide more resources for dugongs and green turtles. This example uses *Alternative Model ii,* which assumes that epiphytes impede seagrass growth and dugongs are also regulated by intrinsic factors other than seagrass (Appendix 1).

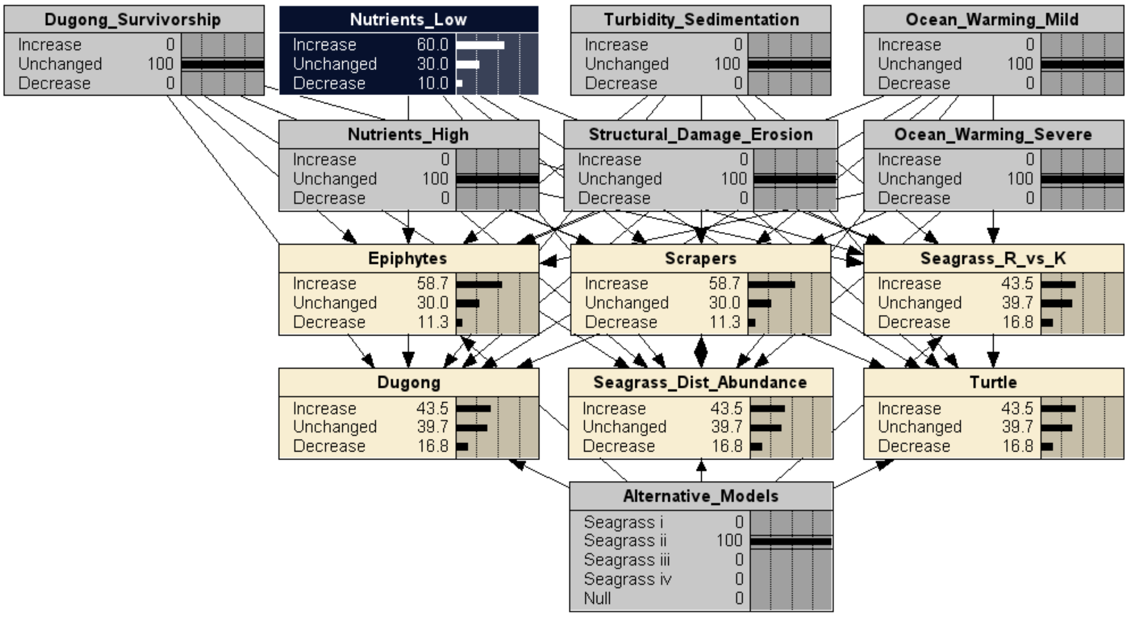


Figure 2.11. Bayes net results for pressure scenario for nutrient in the low range, while all other pressure nodes are set to unchanged. The scenario uses *Alternative Model ii*, which assumes that *Epiphytes* suppress seagrass growth, and that *Dugong* are regulated by intrinsic processes in addition to *Seagrass Distribution and Abundance*.

Secondly, a prediction is run for the high nutrient range (e.g. representative of chlorophyll *a* concentrations > 0.45 ug/L), by setting the *Nutrients Low* node to 100% unchanged and increasing probabilities of increase for the *Nutrients_High* node. Results are the opposite of those for the low nutrient range: dugongs, seagrasses and green turtles now have high and similar probabilities of decline (Fig. 2.12). Here, results are explained by a negative causal relationship between (high) nutrients and seagrass growth (Fong et al. 1997).

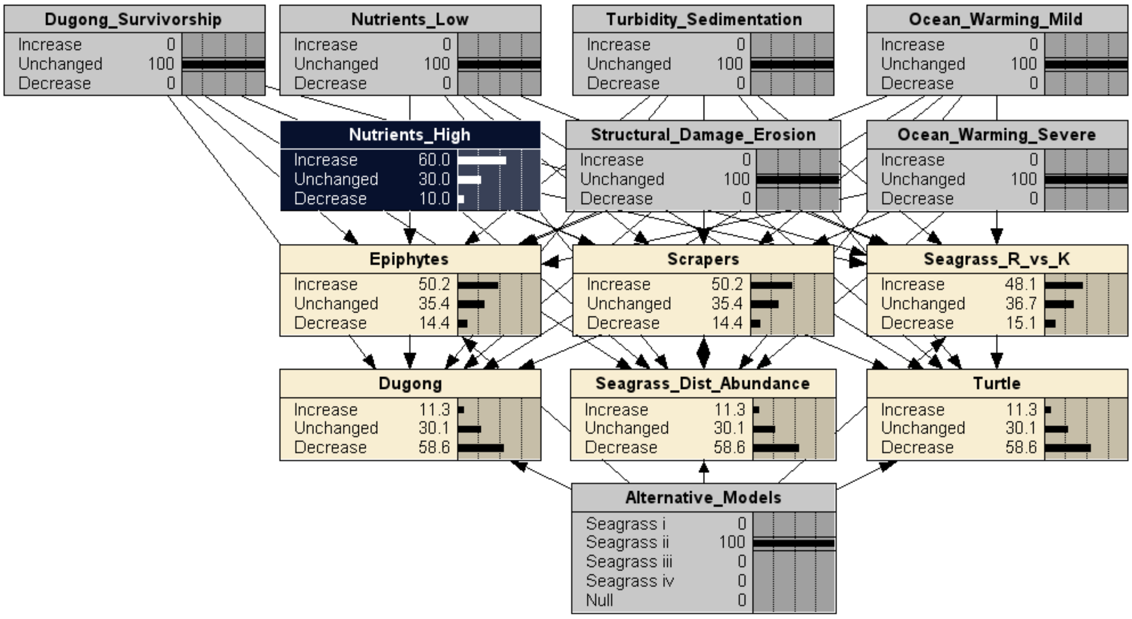


Figure 2.12. Bayes net results for pressure scenario for nutrient in the high range, while all other pressure nodes are set to unchanged. The scenario uses *Alternative Model ii*, which assumes that *Epiphytes* suppress seagrass growth, and that *Dugong* are regulated by intrinsic processes in addition to *Seagrass Distribution and Abundance*.

Thirdly, the high nutrient regime is combined with mild ocean warming to explore a climate change and enhanced agriculture scenario. This can be done simply by setting *Ocean Warming Mild* to 100% chance of an increase, tantamount to selecting a mild IPCC scenario (Moss et al. 2010). Results differ strongly from the previous scenarios: dugongs have a net likelihood of increase similar to that of seagrasses (their resource), but green turtles now have a high net likelihood of a decrease (Fig. 2.13). The result for green turtles is caused by their vulnerability to warming through a increase in the female to male ratio of hatchings (Fuentes et al. 2011). The increase in the probability of seagrass growth relative to the previous scenario is driven by the mild temperature increase, compensating for the negative effects of high nutrients as seagrasses now “grow through” the epiphytes stimulated by the temperature and nutrient increase (R. Coles and M. Waycott pers com, seagrass workshop). Note how the *uncertainty* of results for probabilities of *increase* or *decrease* are now increased as multiple pressures and processes are acting on *Dugong* and *Seagrass Distribution and Abundance* in opposite directions (see Info Box 2.2).

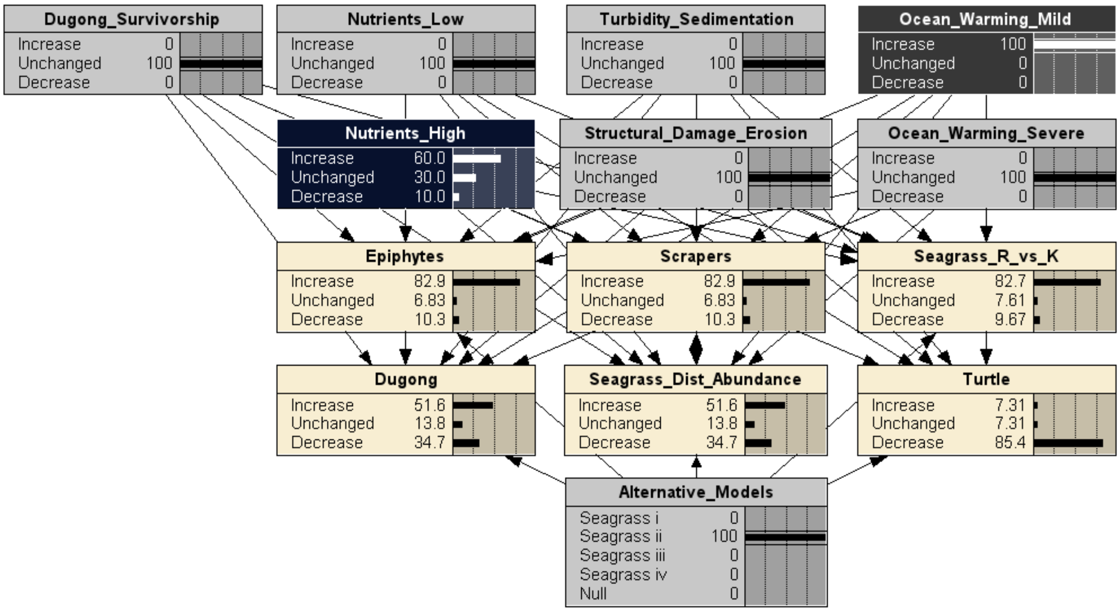


Figure 2.13. Bayes net results for pressure scenario for nutrient in the high range and *Mild Ocean Warming*. Other conditions are similar to Fig. 2.12.

Lastly, an example is used to demonstrate the impact of high nutrients, severe ocean warming and an increase in structural damage and erosion. The latter represents an increase in the likelihood of cyclone damage resulting from warmer oceans, but can also represent other activities such as dredging or anchoring (see section 2.3 and 2.5). To run this prediction scenario conservatively, mild and severe ocean warming are set to a 50% chance of increase and a 50% chance of unchanged, reflecting equal confidence in a business-as-usual and mitigated carbon futures (Moss et al. 2010). Also, the increase in cyclone strength (Knutson et al. 2010) and *Structural Damage and Erosion* are set to similar probabilities.

Results lead to high probabilities of decline for all three ecosystem values: *Dugong*, *Seagrass Distribution and Abundance* and *Turtles* (Fig. 2.14). Seagrass decline is expected here because temperatures above approximately 38°C lead to disruption of the photosynthetic pathways and a subsequent decline in growth and increase in mortality (Waycott et al. 2007). Results for this scenario have relatively low uncertainties, in particular for green turtles, as processes (e.g. population growth) linked to pressures predominantly acting in the same direction.

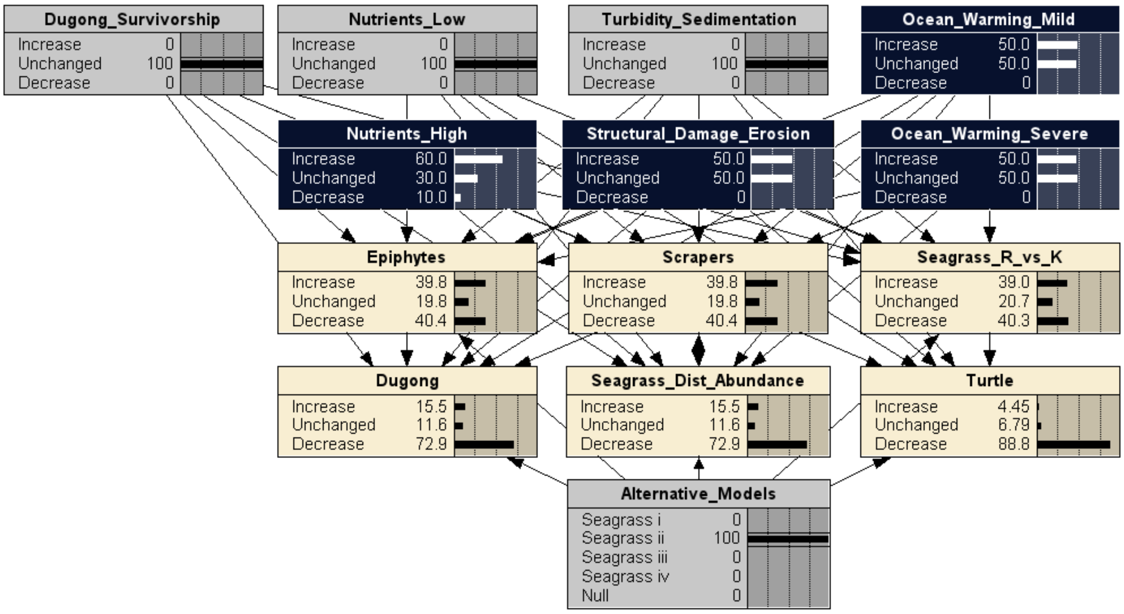


Figure 2.14. Bayes net results for pressure scenario involving high nutrients, mixed ocean warming predictions and cyclone regimes. Other conditions are similar to Fig. 2.13.

2.3 Assessment of Cumulative Impacts

The above scenarios and analyses provide examples of how qualitative and probabilistic (Bayes nets) models can be used to understand and predict probabilities of change in ecosystem values under different scenarios, and also to start exploring management needs through diagnostic analyses. The analyses taken thus far, however, cannot be fully implemented in a cumulative risk assessment and decision-making process, as model results are not embedded within a spatial context. The goal of this section is to outline a cumulative risk assessment approach that integrates Bayes net model outputs with the spatial distribution of pressures and values.

Different environmental drivers, human activities and resulting pressures will have different *Zones of Influence* (*ZOIs*) depending on the nature of the drivers and activities, and how they impact on the ecosystem values. In a qualitative analysis of cumulative impacts, an initial requirement is to identify, for a given pressure, a relative threshold value beyond which it is likely that a pressure will have an impact on the system that is large enough to be observable. The precise magnitude of the impact is of less concern; only that it is large enough to be significant and observable. This step requires consideration of expert judgement and the scientific literature. Areas that exceed threshold values can then be classified in a GIS to formally define a *ZOI*.

In mapping exercises, a *ZOI* can be defined by two categories of high and low, but can also include finer gradations (e.g., high-medium-low) where there is sufficient knowledge and justification for doing so (Fig. 2.15). Additionally, relative levels of a pressure, can, through expert judgement, be translated into a probability that is entered into the input node of the Bayes net (Fig. 2.16). Thus, a relatively high level of a pressure can be given a high probability of having a significant and observable impact on the system, while a lower level of a pressure can be given a lower probability.

Rigorous estimates of *ZOIs* as functions of pressures from drivers and activities require a detailed understanding of the physical oceanography of the receiving waters, which is beyond the scope of this project. For the purpose of illustrating the use of *ZOIs* in this framework, a coarser approach that builds on expert opinion and only 2 or 3 *ZOI* bands is used (Fig. 2.15). Specifically, boundaries of *ZOIs* are delineated as the thresholds where pressures are expected to exert significant and observable effects on value nodes. The spatial boundaries of the *ZOIs* represent ‘precautionary thresholds’, that can be used by managers as a first pass estimate of potential risk when considering proposals. *ZOIs* can be refined where necessary as information becomes available. For water quality pressures (*Nutrients* and *Turbidity and Sedimentation*) GBRMPA’s water quality guidelines and other underpinning analyses (De'ath and Fabricius 2008) are used to provide tentative boundaries and thresholds for *ZOIs.* For other pressures in the BBNs, such as climate change, storms and structural damage/erosion, ZOIs need to be informed by relevant regional-scale models of physical forcings.

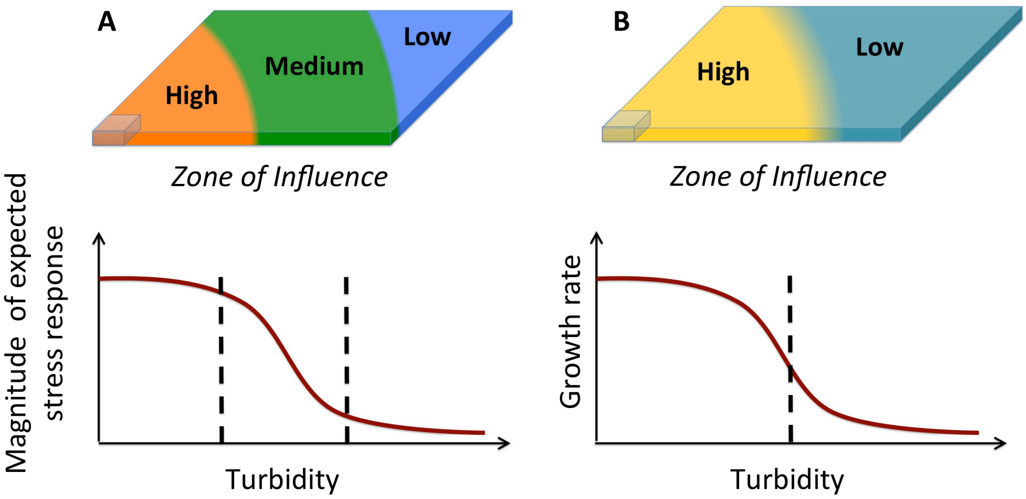


Figure 2.15. Diagram illustrating two resolutions of *Zones of Influence* to inform Bayes net probabilities based on predicted responses of ecosystem values to changes in pressures. Where only lower resolution information is available, precautionary (more conservative) thresholds will be used. Higher resolution threshold values, such as those provided for water quality based on GBRMPA's water quality guidelines (GBRMPA 2010) provide greater clarity and should be adopted where available.

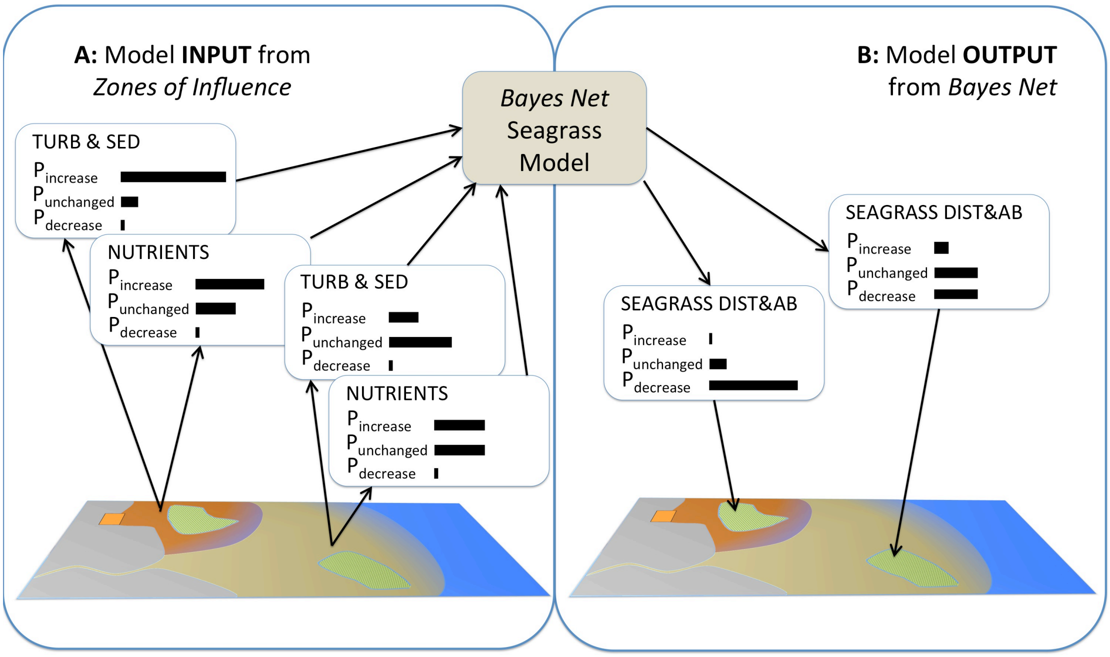


Figure 2.16. Example illustrating how probabilities of change in *Nutrients* and *Turbidity and Sedimentation* within zones of influence are used in the framework to predict probabilities for ecosystem values, here using seagrass *distribution and abundance*. **A:** Probabilities of increase, no change and decrease (Pincrease, Punchanged, Pdecrease) are derived from zone of influences (which in turn are derived from drivers and/or activities via expert opinion or for example from results of water transport models) and used as input into the Bayes net. **B:** Resulting output probabilities for ecosystem values by the Bayes net are recorded. These are then combined with the areas of ecosystem values to produce estimates of risk (see below).

2.3.1 Using zone of influence (ZOI) for spatially explicit pressure scenarios

In complex systems, such as GBRWHA ecosystems, any given activity may lead to multiple pressures that may vary in their effects at different points in time. Similarly, a given type of pressure (e.g., turbidity) may be driven by multiple activities (Fig. 2.17, see also section 2.2). To link different activities to exposure likelihoods in a demonstration area, and in turn to likelihoods of change in value nodes in a given area, two avenues are used.

- Firstly, causal linkages between activities and impacts are identified using the qualitative models and Bayes nets (see Fig. 2.3 and 2.5) resulting from expert workshops and model analyses.
- Secondly, spatial distributions in exposure likelihoods resulting from different activities are integrated across their *Zone of Influence* (Fig. 2.17). This allows the manager to account for different spatial distributions of exposures arising from, for example, coastal development activities with a relatively limited footprint compared to changed land-use practices in catchment areas. *Zones of Influence* also take account of the varying frequency of press- and pulse-type exposures by using a probabilistic approach.

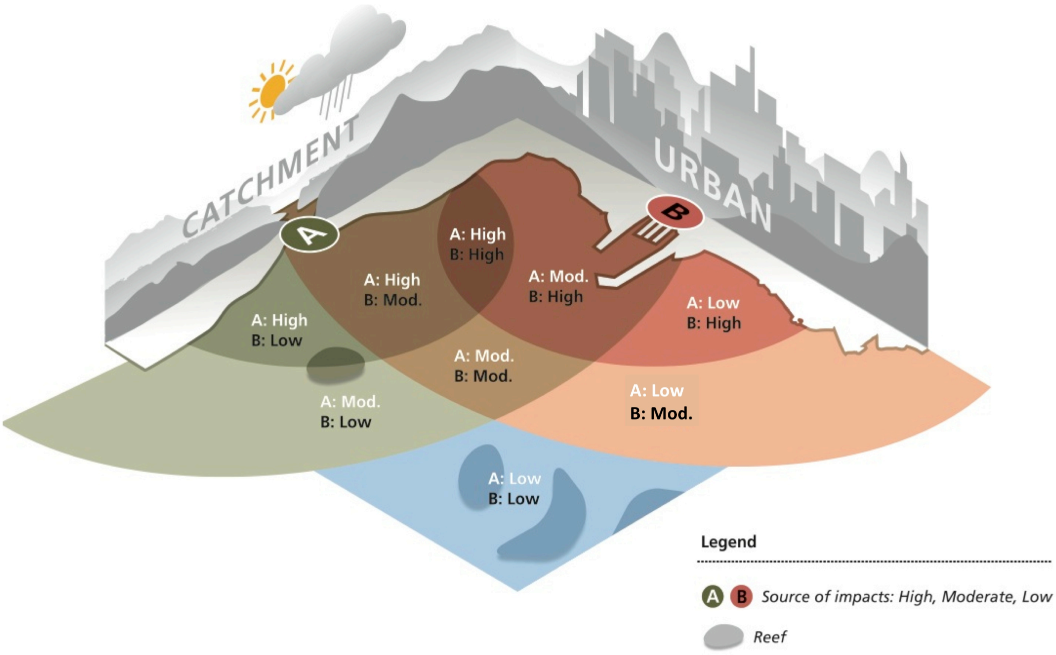


Figure 2.17. Conceptual model illustrating zones of influence (ZOI) for two examples of point sources: (A) river run-off from catchments and (B) urban or port development. The diagram uses three ZOI levels for each source: low, moderate and high.

The degree to which the user can assign probabilities from different activities depends on information from environmental impact assessments, spatial surveys and modelling studies of receiving waters (e.g. *eReefs* and *Source Catchments*). Also, observations of river plume behaviour (Devlin et al. 2012) and remote sensing (Schroeder et al. 2012) provides some basis for estimating probabilities of change under land-use activities and/or flood scenarios. In the following section results of pressure-likelihood scenarios are analysed without attribution to specific activities. Pressure likelihoods are estimated based on how large the areas of coral reefs or seagrass meadows are distributed within the zones of influence. This is the focus of the next section.

2.3.2 Estimating Cumulative Risk to Ecosystem Values

To produce tentative estimates of cumulative risk to ecosystem values under different scenarios or management alternatives, *Zones of Influence* (*ZOIs*) are combined with results of Bayes net outputs and the spatial distributions of key ecosystem values. Here, *ZOI*s for the different pressures (e.g. nutrients, sedimentation/turbidity and climate change) provide input data for the Bayes nets. The resulting output probabilities of the Bayes net for each ecosystem value (e.g. corals and seagrasses) are then integrated over the area they represent, and lastly summed across *ZOIs* to provide total estimates of risk within a geographic case area.

Once the user has constructed or compiled the environmental scenarios, risks are estimated following the following six steps:

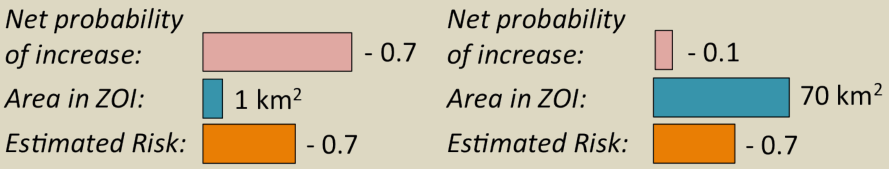
1. Estimate the *Zones of Influence* (*ZOIs*) for pressures for each scenario, for example based on water quality guidelines (e.g. Fig. 2.17).
2. Estimate probabilities of change for each pressure node within each ZOI based on expert knowledge or based on physical models.
3. Enter those probabilities into the Bayes net(s) to calculate the probabilities of change for each ecosystem value within each *ZOI.* Calculate and record the net probability of increase (**P**increase – **P**decrease) within each ZOI (Info Box 2.5, Fig. 2.18).
4. Estimate the amount of ecosystem value potentially impacted within each *ZOI*. The framework uses the area of coral reefs or seagrass meadows as proxies for ecosystem value underpinning MNES and OUV, but the numbers or distribution of dugongs or turtles or other species are similarly valid.
5. Multiply net probabilities of increase (**P**increase – **P**decrease) for ecosystem values by their extent (area, km^2) to calculate a value of *Estimated Risk (ER)* for each ZOI. NB: all such values are to be treated as crude and tentative estimates that should be reviewed and, where necessary adjusted, by domain experts (see *Caveats to the Use of Estimated Risk*, Info Box 2.5).
6. Integrate the reviewed values of estimated risk over all ecosystem areas (or groups of individuals) within ZOIs to estimate the *Total Estimated Risk* for a given area.

Note that risk estimates use *net increase* instead of net decrease. This is account for downside as well as upside risk. *Total Estimated Risk* may be positive (i.e. upside risk - net exposure to improved outcomes) or negative (downside risk - net exposure to adverse outcomes). To later allow for upside risk under mitigation scenarios, the user should present downside risk as negative and upside risk as positive.

The estimation of total risk within a larger case area (step 6) is built on two assumptions: Firstly, risks to individual areas are independent of risks to other areas. Secondly, a high probability of change for a small area is comparable to a low probability of change for a large area (see Info Box 2.5). The second assumption is only used tentatively here for the purpose of generality. To ensure full consideration of how spatial consequences influence risks (e.g. via impacts on connectivity), the user should elicit expert opinion for each case.

INFO BOX 2.5. Estimated Risk is calculated as net probability of increase (**P**increase – **P**decrease), multiplied by the area of ecosystem values within the given *Zone of Influence* (*ZOI*). The calculation follows from that of risk: *probability* x *consequence*. Note, however, that this framework focuses on the direction of change (i.e., positive or negative) as a measure of consequence, rather than the magnitude of change. Assuming that different areas of ecosystem values (e.g. coral reefs) are independent units across *ZOIs*, *Total Estimated Risk* is calculated as the sum of estimated risks for individual areas. Note that positive changes are used as the default to account for *upside* and *downside* risk, a distinction that becomes important when comparing management alternatives before and after interventions or risk mitigation.

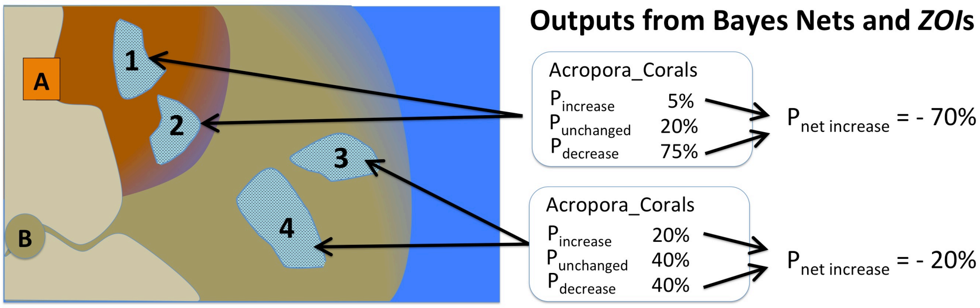
The example below builds on this assumption and illustrates that a high probability of decline for a small area bears the same risk as a low probability of decline for a large area. To avoid that the user interprets *Estimated Risk* as a measure of area, it is reported here as an index.



Caveats to the use of estimated risk

Values of estimated risk should be considered, at best, as only crude and tentative estimates, as they are based on the probabilistic output of the qualitative models. As such, they come with considerable levels of uncertainty and methodological assumptions (Hosack et al. 2008) that should be reviewed and considered, and, where necessary, revised by the domain experts for the underpinning values. In particular, the probabilities derived from the Bayes nets are intended to only highlight large relative differences between qualitative model predictions, and the exact probability for any given prediction, or small differences between multiple predictions, should not receive undue emphasis.

Figure 2.18 below demonstrates these six steps as a worked example for four coral reefs distributed over two ZOIs resulting from an urban point source (orange rectangle) and agricultural run-off from a nearby river. In addition to calculating the net probability of increase for each seagrass meadow, the residual probability of no change is also recorded in the table. This information is necessary to estimate the uncertainty associated with estimates of *Total Estimated Risk*.



Source	ID	$\frac{P_{net\ increase}}{100}$	*Area* (km²)	$P_{unchanged}$	***Estimated Risk*** $= \frac{P_{net\ increase}}{100}$ ***x Area***
A & B	1	- 0.70	25	20	- 17.5
A & B	2	- 0.70	20	20	- 14.0
B	3	- 0.20	30	40	- 6.0
B	4	- 0.20	50	40	- 10.0
	Total Estimated Risk =				**- 47.5**

Figure 2.18. Worked example of how *Estimated Risk* and *Total Estimated Risk* are calculated for four coral reefs in a geographic case area.

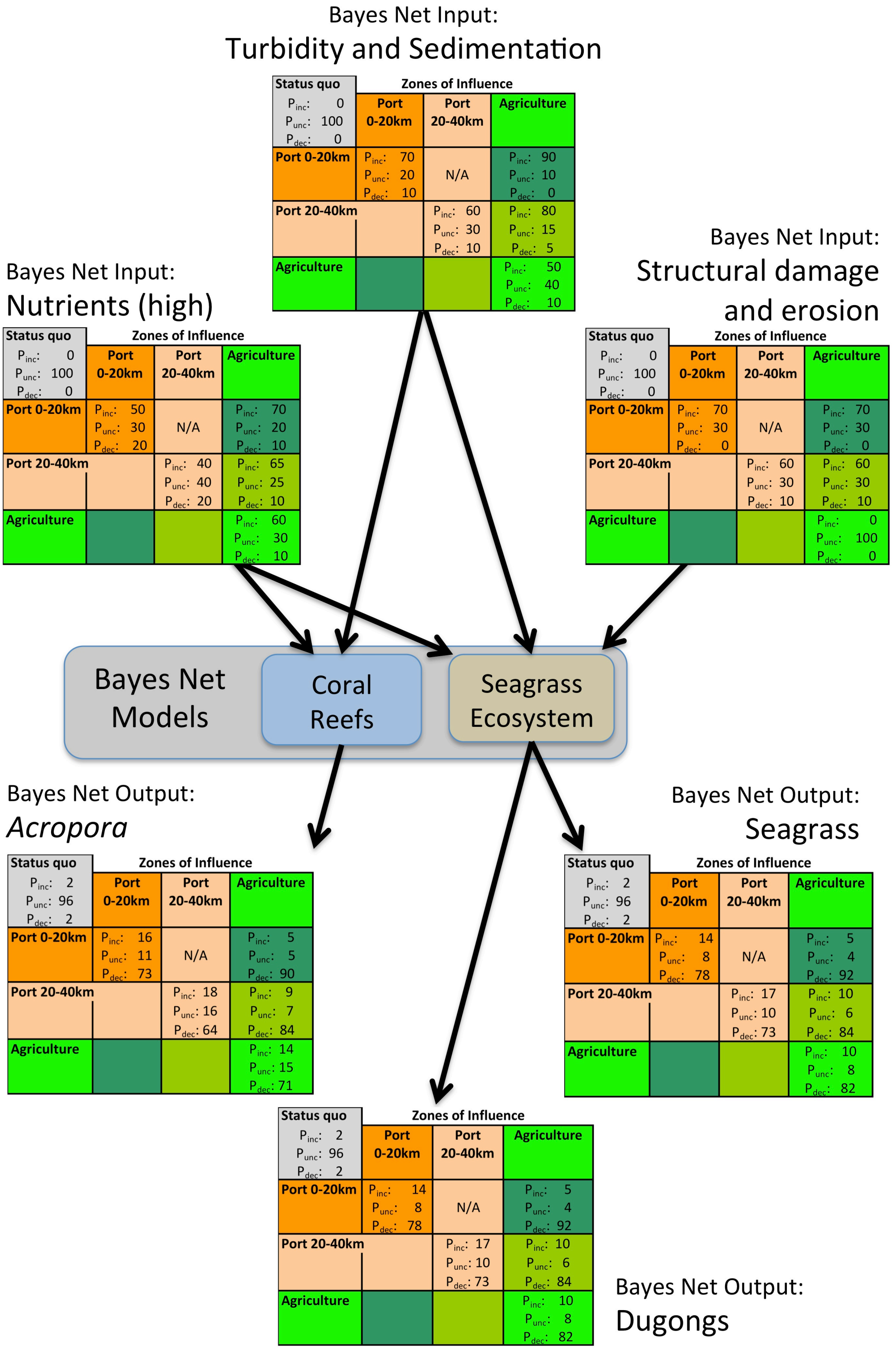
Total Estimated Risks are associated with four levels of uncertainty the user must consider.

1. Input values for the Bayes nets, i.e. the probabilities of change expected for the MNES in focus under the different environmental scenarios. The probabilities used in this example are approximations based on first-order expert elicitation within the team. Broader expert elicitation is required to reduce this source of uncertainty.
2. The location of boundaries for *Zones of Influence* for each activity and for each ecosystem value. These can be derived from a combination of observations and physical models (e.g. behaviours of river plumes or dredge plumes, 3-dimensional hydrodynamic models of the GBR lagoon, water quality guidelines for the GBR, etc) and expert elicitation.
3. The uncertainty associated with the distribution of conditional probabilities (*increase*, *unchanged*, *decrease*) in Bayes net outputs. Again, this uncertainty can be reduced by extracting probabilities from physical models (e.g. hydrodynamic and sediment-transport models).
4. The alternative model used in the Bayes net, and to what extent experts and the decision maker have confidence in a given model.

A simple uncertainty index is used in this report associated with Bayes net output probabilities. This uncertainty index is based on the relative variation in probabilities for the direction of change, calculated as **P**decreased + **P**unchanged. An absolute index value greater than 2/3 indicates high uncertainty associated with **P**increase. Absolute index values between 1/3 and 2/3 indicate intermediate uncertainty and values lower than 1/3 represent low uncertainty associated with **P**increase. See Table 2.3.

To estimate risks of activities and cumulative impacts on ecosystem values, a set of contingency tables (matrices) need to be constructed in which conditional probabilities for all *ZOIs* resulting from the combination of activities/drivers and pressures are listed. In the following examples pressures are limited to *Nutrients*, *Turbidity and Sedimentation* and *Structural Damage and Erosion*. As explained in Section 2.2, the seagrass model uses two categories of nutrients, low and high, to account for the non-linear response of seagrasses to nutrients. Only one broad nutrient category in the coral reefs model is used. Also, *Structural Damage and Erosion* (accounting for anchoring, dredging and storms) is a pressure variable in the seagrass model; in the coral reefs model, structural damage is accounted for by *Storms*.

An example of how input matrices and output matrices are used for different *ZOIs* is shown in Fig. 2.19 below. For simplicity, climate change (warming and storms) or dugong mortality (e.g. from boat strikes or bycatch) are not included in this example, i.e. default conditional probabilities as are left as 100% for *unchanged.* Where probabilities around an activity or a pressure are unknown for a region, the user should set the node's probabilities for each of *increase*, *unchanged* and *decrease* to 33.3%.



Bayes Net Input:
Turbidity and Sedimentation

Status quo	Zones of Influence		
P_{inc}: 0 P_{unc}: 100 P_{dec}: 0	Port 0-20km	Port 20-40km	Agriculture
Port 0-20km	P_{inc}: 70 P_{unc}: 20 P_{dec}: 10	N/A	P_{inc}: 90 P_{unc}: 10 P_{dec}: 0
Port 20-40km		P_{inc}: 60 P_{unc}: 30 P_{dec}: 10	P_{inc}: 80 P_{unc}: 15 P_{dec}: 5
Agriculture			P_{inc}: 50 P_{unc}: 40 P_{dec}: 10

Bayes Net Input:
Nutrients (high)

Status quo	Zones of Influence		
P_{inc}: 0 P_{unc}: 100 P_{dec}: 0	Port 0-20km	Port 20-40km	Agriculture
Port 0-20km	P_{inc}: 50 P_{unc}: 30 P_{dec}: 20	N/A	P_{inc}: 70 P_{unc}: 20 P_{dec}: 10
Port 20-40km		P_{inc}: 40 P_{unc}: 40 P_{dec}: 20	P_{inc}: 65 P_{unc}: 25 P_{dec}: 10
Agriculture			P_{inc}: 60 P_{unc}: 30 P_{dec}: 10

Bayes Net Input:
Structural damage and erosion

Status quo	Zones of Influence		
P_{inc}: 0 P_{unc}: 100 P_{dec}: 0	Port 0-20km	Port 20-40km	Agriculture
Port 0-20km	P_{inc}: 70 P_{unc}: 30 P_{dec}: 0	N/A	P_{inc}: 70 P_{unc}: 30 P_{dec}: 0
Port 20-40km		P_{inc}: 60 P_{unc}: 30 P_{dec}: 10	P_{inc}: 60 P_{unc}: 30 P_{dec}: 10
Agriculture			P_{inc}: 0 P_{unc}: 100 P_{dec}: 0

Bayes Net Output:
Acropora

Status quo	Zones of Influence		
P_{inc}: 2 P_{unc}: 96 P_{dec}: 2	Port 0-20km	Port 20-40km	Agriculture
Port 0-20km	P_{inc}: 16 P_{unc}: 11 P_{dec}: 73	N/A	P_{inc}: 5 P_{unc}: 5 P_{dec}: 90
Port 20-40km		P_{inc}: 18 P_{unc}: 16 P_{dec}: 64	P_{inc}: 9 P_{unc}: 7 P_{dec}: 84
Agriculture			P_{inc}: 14 P_{unc}: 15 P_{dec}: 71

Bayes Net Output:
Seagrass

Status quo	Zones of Influence		
P_{inc}: 2 P_{unc}: 96 P_{dec}: 2	Port 0-20km	Port 20-40km	Agriculture
Port 0-20km	P_{inc}: 14 P_{unc}: 8 P_{dec}: 78	N/A	P_{inc}: 5 P_{unc}: 4 P_{dec}: 92
Port 20-40km		P_{inc}: 17 P_{unc}: 10 P_{dec}: 73	P_{inc}: 10 P_{unc}: 6 P_{dec}: 84
Agriculture			P_{inc}: 10 P_{unc}: 8 P_{dec}: 82

Bayes Net Output:
Dugongs

Status quo	Zones of Influence		
P_{inc}: 2 P_{unc}: 96 P_{dec}: 2	Port 0-20km	Port 20-40km	Agriculture
Port 0-20km	P_{inc}: 14 P_{unc}: 8 P_{dec}: 78	N/A	P_{inc}: 5 P_{unc}: 4 P_{dec}: 92
Port 20-40km		P_{inc}: 17 P_{unc}: 10 P_{dec}: 73	P_{inc}: 10 P_{unc}: 6 P_{dec}: 84
Agriculture			P_{inc}: 10 P_{unc}: 8 P_{dec}: 82

Figure 2.19. Examples of input and output probability matrices for combinations of *ZOIs* resulting from ports and agriculture in a hypothetical case area. The top three matrices show examples of conditional probabilities for *Nutrients*, *Turbidity and Sedimentation* and *Structural Damage and Erosion* (on seagrasses), representing threats from anchoring, dredging and storms. In this case the Bayes net for corals, seagrass and dugongs assume no change under the status quo scenarios, but the user can modify this on a case-by-case basis where supporting information is available.

2.3.3 Zones of Consequence

While *Zones of Influence* provide information on the direct potential impacts of drivers, activities and pressures on ecosystem values, *Zones of Consequence* provide insight into up- and downstream effects within and potentially far beyond *ZOIs*. One example is agricultural and urban land-use runoff and the outbreak risk of crown of thorns starfish (COTS). The *Zone of Influence* of nutrients from river catchments in for example the Wet Tropics may directly affect around 1500 km2 of coral reefs (Fig. 2.20). However, assuming that the *alternative model ii* is correct (COTS outbreaks linked to nutrients), waves of COTS outbreaks following a high summer nutrient pulse in the Wet Tropics can then subsequently propagate down the GBR (http://www.aims.gov.au/docs/research/ biodiversity-ecology/threats/cots-animation.html), potentially reaching across a *Zone of Consequence* of around 15,000 km2 of coral reefs, an order of magnitude greater than the ZOI for nutrients.

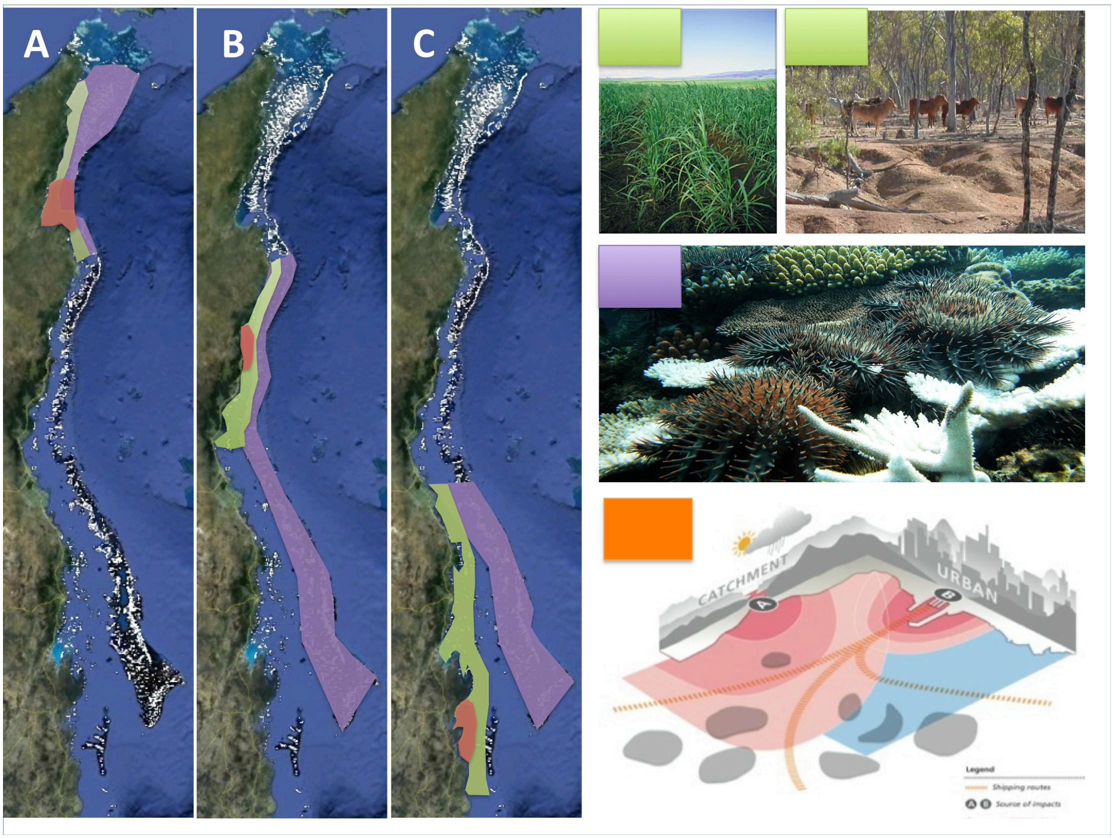


Figure 2.20. Example of how *Zones of Influence* can lead to *Zones of Consequence* for agricultural land run-off and urban/port developments. Green areas represent Zones of Influence directly impacted by changing water quality. Under the assumption that elevated nutrients during floods can trigger primary outbreaks of Crown of Thorns Starfish (COTS)(Fabricius et al. 2010), purple areas represent potential *Zones of Consequence* resulting from *Influences* in Cape York (A), Wet Tropics (B) and Central/South (C) driven by patterns of connectivity on the GBR (Hock et al. ms). Similarly, expansion of port areas (orange areas) and a consequent increase in trade volume potentially increases the risk from shipping-related accidents along shipping routes through the GBR (Ottesen et al. 1994). See also Fig. 2.22.

Similarly, while the port developments may have a relatively small footprint area of dredging operations and reclamation, the size and activity of anchoring areas, resuspension of bottom sediments from ship traffic, movement of dredge spoils from dumping grounds and the likelihood of shipping incidents all increase as a consequence of port size or trade volume well beyond immediate Zones of Influence (Fig. 2.21).

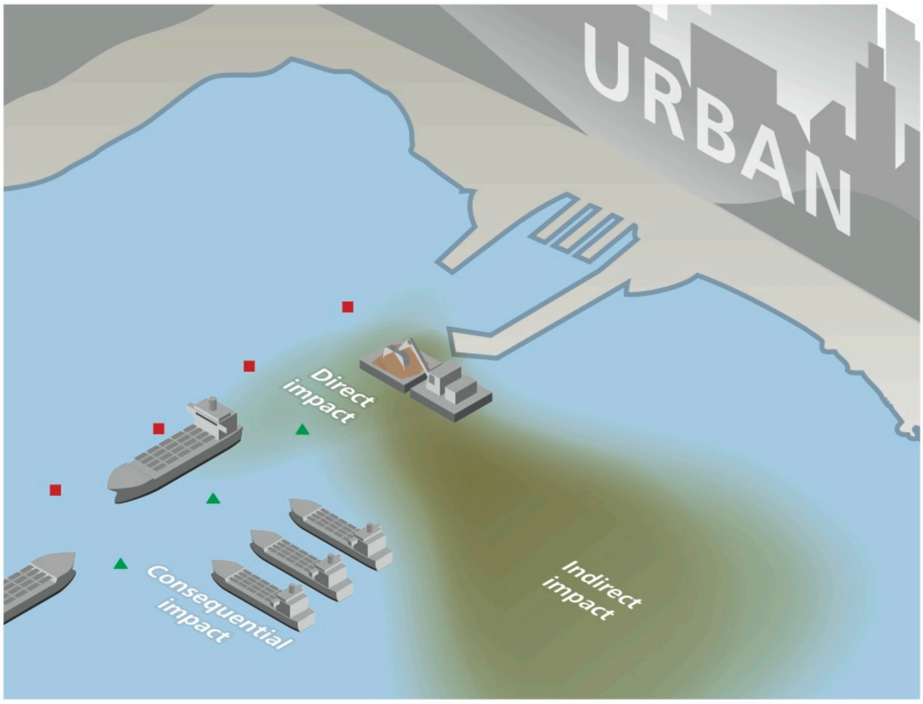


Figure 2.21. Schematic of likely indirect impacts of port operations as a consequence of port expansions or increase in trade volume: movement of dredge spoils, increase in anchoring areas, increase in sediment resuspension from ship traffic and potential increase in shipping incidents. Examples used in this report do not formally account for such risk, however the framework allows for such considerations in the cumulative risks assessment where probabilities and Zones of Consequence can be estimated.

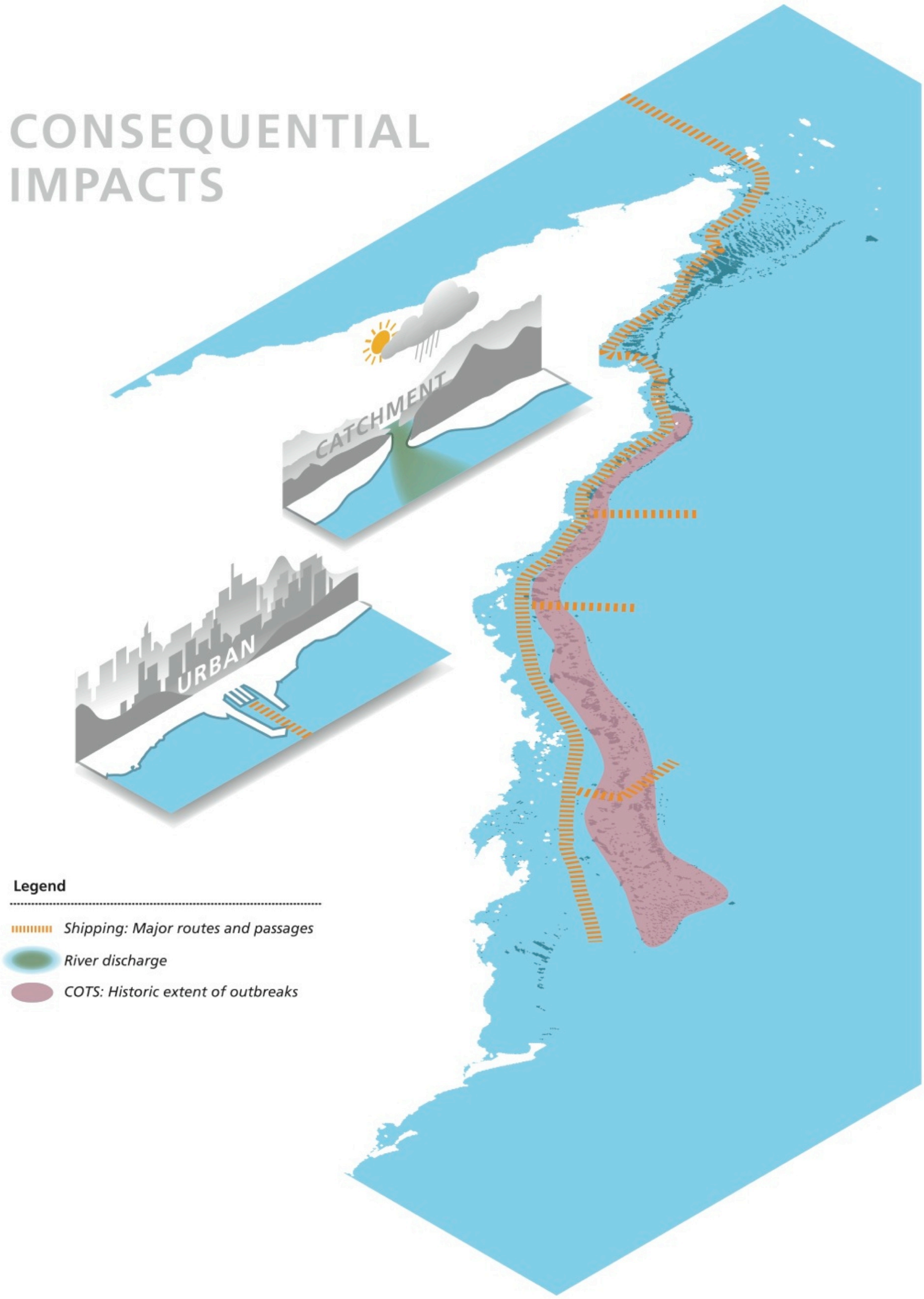


Figure 2.22. Schematic illustrating potential zones of consequence for ports and agriculture in the GBRWHA.

2.3.4. Example: estimating cumulative risk under complex scenarios

Examples in this section will not use extensive scenarios or alternatives, as these are dealt with in detail in sections 2.4 and 2.5. The purpose here is to illustrate how the user can estimate risk to key ecosystem values for an area under cumulative stress scenarios, and preliminarily assess which management actions might be effective in reducing those risks. However, the risk assessments developed at this step can be used as input data into the structured decision making process involving considerations of both environmental, social and economic consequences, trade-offs and management options (see Section 2.5).

This section works through a set of scenarios involving different combinations of pressures land-use activities and climate change. Port developments and agriculture are used as examples of land-use activities. The demonstration case is hypothetical, but resembles the situation for Cape York. Here, corals (genus *Acropora*) are used as the key MNES element under consideration only. Examples are later expanded to also include seagrasses and dugongs. The hypothetical example area has a total of 1000 km^2 of coral reefs (Fig. 2.23). Consistent with previous examples, three pressures impact on corals: nutrients, turbidity and sedimentation, and ocean warming.

All combinations of increased ports and agriculture land use and climate change give rise to eight scenarios (Fig. 2.23, Table 2.2), including what is referred to as *status quo*. Status quo means no change in current activities and can possibly lead to further decline if the system is on a downward trajectory (Fig. 2.7). Status quo is different from business as usual (BAU), however, which can include an increasing trend in activities. The status quo is adjusted in this example to a current downward trend by using marginally shifted Bayes net probabilities (**P**increase = 0.40, **P**unchanged = 0.30 , **P**decrease = 0.30) for all pressure nodes (*nutrients*, *turbidity and sedimentation* and *ocean warming*). Ideally, these status quo probabilities should be set via expert elicitation. Conservative assumptions are used for storms and ocean warming under climate change: 40% chance of increase in storm damage and 60% chance of warming (Hoegh-Guldberg 1999, Walsh and Ryan 2000, Donner et al. 2009, Knutson et al. 2010).

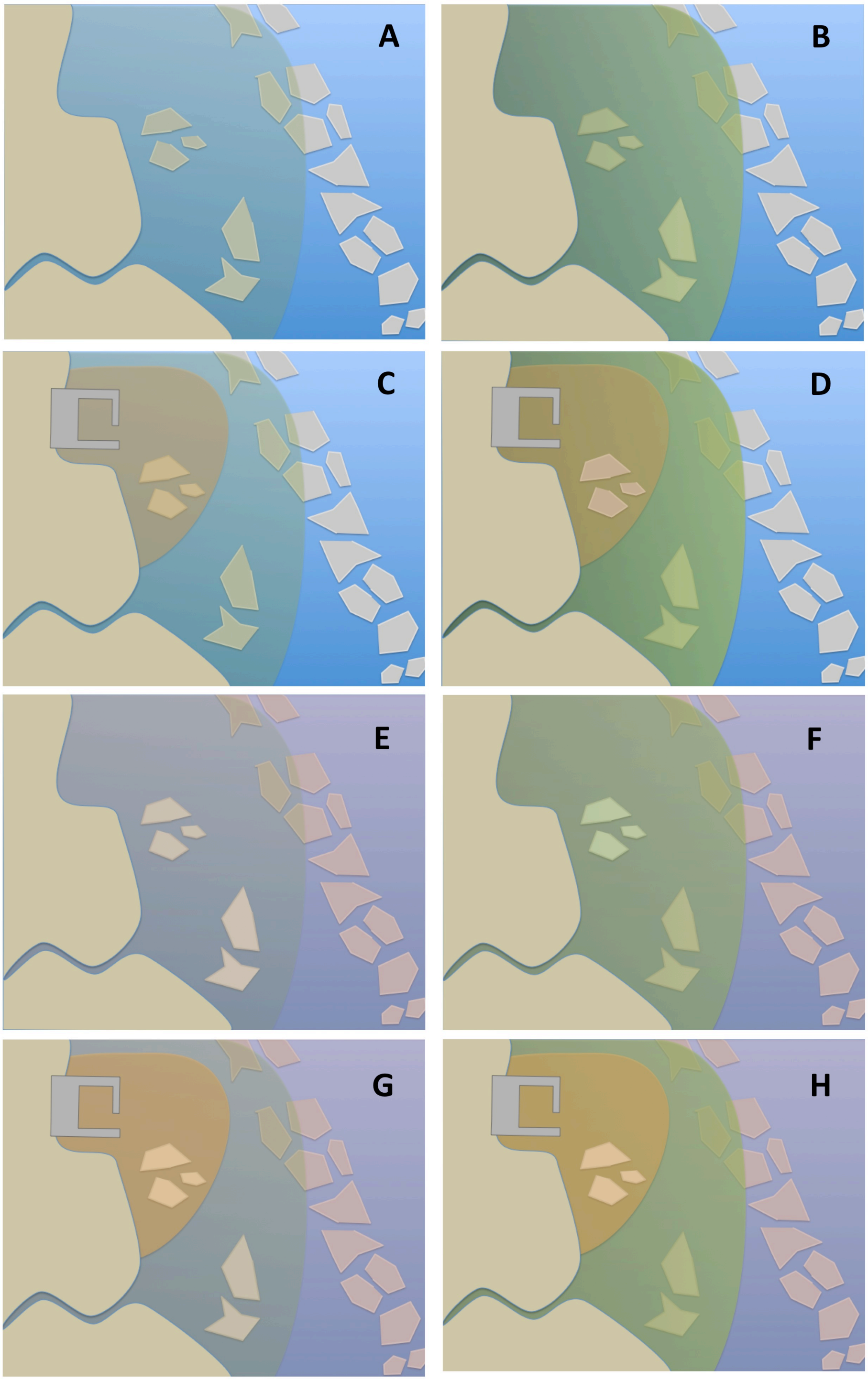


Fig. 2.23. Cumulative stress on coral reefs for hypothetical demonstration case under different scenarios of agriculture (B,D,F,H), port development (C,D,G,H) and climate change (E-H). Areas of corals reefs within each zone of influence and the associated conditional probabilities for nutrients, turbidity and sedimentation, storms and ocean warming are given in Table 3.1. Outputs of Bayes net model and estimated risks to corals are presented in Table 2.2.

Lastly, the uncertainty index is used based on the value of **P**decrease and **P**unchanged (see above). An uncertainty index value greater than 2/3 is indicated by a red symbol, between 1/3 and 2/3 by an amber symbol, and an index value lower than 1/3 by a green symbol (Table 2.3).

Table 2.2. Input probabilities for corals (*Acropora*) for the eight environmental and development scenarios in figure 3.7. Bayes net outputs and estimated risks are presented in Table 3.2

		Nutrients			*Turb and Sed*			*Storms*			*Ocean Warm*		
Scenario		P_{inc}	P_{unc}	P_{dec}	P_{inc}	P_{unc}	P_{dec}	P_{inc}	P_{unc}	P_{dec}	P_{inc}	P_{unc}	P_{dec}
A	Status quo	40	30	30	40	30	30	33	33	33	40	30	30
B	Agriculture↑ (Ag)	60	25	15	50	30	20	33	33	33	40	30	30
C	Port↑	40	30	30	70	20	10	33	33	33	40	30	30
D	Ag↑ and Port↑	60	25	15	80	15	5	33	33	33	40	30	30
E	Climate change (CC)	40	30	30	40	30	30	40	30	30	60	25	15
F	CC and Ag↑	60	25	15	50	30	20	40	30	30	60	25	15
G	CC and Port↑	40	30	30	70	20	10	40	30	30	60	25	15
H	CC and Ag ↑ and Port↑	60	25	15	80	15	5	40	30	30	60	25	15
B+	Ag↑ + COTS outbreak	60	25	15	50	30	20	33	33	33	40	30	30

Table 2.3. *Estimated Risk* (*ER = P net increase /100 x Area*) within *Zones of Influence* and *Total Estimated Risk* (*TER = sum of ER* within a scenario for the entire case area) to corals for the hypothetical case area in Fig. 2.23. Values in Table 2.2 are used as input values into the Bayes nets. Colour coding for *TER*: lowest risk is yellow, highest risk is orange. Negative values indicate downside risk. The *Uncertainty Index* is an indicator of the likelihood of a opposite (decrease) or neutral (unchanged) outcomes (green: < 33%, amber: 33-67%, red: > 67%).

		Bayes Net output probabilities					***Estimated Risks***		
Scenario		P_{inc}	P_{unc}	P_{dec}	$\frac{P_{net\ inc}}{100}$	**Area (km^2)**	***ER***	***TER***	**Uncertainty Index**
A	Status quo (little agriculture, no port)	39	12	49	-0.10	1000	-100	**-100**	🟡
B	Agriculture (Ag)	30	10	60	-0.30	200	-60	**-140**	🔴
	Remaining ZOI at status quo	39	12	49	-0.10	800	-80		🟡
C	Port	24	11	65	-0.41	100	-41	**-131**	🔴
	Remaining ZOI at status quo	39	12	49	-0.10	900	-90		🟡
D	Ag and Port	19	10	71	-0.52	100	-52	**-165**	🔴
	Remaining ZOI for Ag	28	11	61	-0.33	100	-33		🔴
	Remaining ZOI at status quo	39	12	49	-0.10	800	-80		🟡
E	Climate change (CC)	33	12	55	-0.22	1000	-220	**-220**	🔴
	Remaining ZOI at status quo	39	12	49	-0.10	0	0		🟡
F	CC and Ag	24	10	66	-0.42	200	-84	**-260**	🔴
	Remaining ZOI under CC only	33	12	55	-0.22	800	-176		🔴
	Remaining ZOI at status quo	39	12	49	-0.10	0	0		🟡
G	CC and Port	20	10	70	-0.50	100	-50	**-248**	🔴
	Remaining ZOI under CC only	33	12	55	-0.22	900	-198		🔴
	Remaining ZOI at status quo	39	12	49	-0.10	0	0		🟡
H	CC and Ag and Port	13	9	78	-0.65	100	-65	**-274**	🔴
	Remaining ZOI for Ag	28	11	61	-0.33	100	-33		🔴
	Remaining ZOI under CC only	33	12	55	-0.22	800	-176		🔴
	Remaining ZOI at status quo	39	12	49	-0.10	0	0		🟡
B+	Agriculture (Ag) +COTS outbreak	23	11	66	-0.43	100	-43	**-259**	🔴
	Remaining ZOI at status quo + COTS	32	12	56	-0.24	900	-216		🔴

The example demonstrates that increased land-use runoff from intensified agriculture and a port development both led to a significant increase in *Total Estimated Risk* (*TER*) for the area. Agriculture had the strongest impact due to its larger zone of influence (containing more reefs). Climate change represented the most severe stress, even assuming a modest increase in the probability of warming and storm damage, largely due to its large zone of influence (impacting the entire area). Combining climate change with agriculture and port development led to a 174% increase in *TER* above status quo. Simulating COTS outbreak as a consequence of nutrient enrichment in the agriculture (B+) scenario led to a *TER* similar to that of agriculture and climate change (scenario F). While agriculture or other sources of nutrients have a limited *Zone of Influence*, they may have an extensive *Zone of Consequence*. The concept of Zone of Consequence is illustrated briefly below.

Simulating a COTS outbreak as a consequence of nutrient enrichment in the agriculture scenario (B+) led to a *TER* similar to that of agriculture and climate change (scenario F). While agriculture or other sources of nutrients have a limited Zone of Influence, they may have an extensive Zone of Consequence (see section 2.3.3).

This example provides several points of guidance for managers and decision makers. Firstly, the systematic scenario structure enables the user to assess the relative importance of any given activity or driver by comparing *TER* across scenarios in Table 2.3. In this case, climate change was the strongest driver of coral decline change, and COTS was the second most important. From a management perspective, addressing COTS via reduced nutrient runoff from agriculture and/or via tactical programs to combat COTS are effective actions if feasible.

The example here used *Alternative model ii*, which assumes that nutrients drive COTS outbreaks (Fabricius et al. 2010) and turbidity affects herbivore density (Cheal et al. 2013). If the user had instead chosen *Alternative model i* (COTS not linked to nutrient land-use runoff and herbivore density independent of turbidity), *TER* for scenario B would have been 140 instead of 146, which is of negligible difference.

In conclusion results for this scenario are quite robust to the choice of model. However, the choice of model has implications for management decisions. If a COTS outbreak is simulated for scenario B (B+ in Table 2.3) using *Alternative model i*, then results are essentially similar to the results for *Alternative model ii* as a COTS outbreak is underway for reasons other than nutrient runoff from land-use. Therefore a decision to combat COTS via mitigation actions on agriculture would be ineffective, and tactical programs to combat COTS in situ would be a better alternative.

Section 2.3.4 below provides hypothetical examples of scenario development and cumulative impact analysis using zones of influence for four GBRWHA demonstration cases. The examples demonstrate how the framework can be spatially scaled to different regions.

2.3.4. Environmental and geographic demonstration cases (GBR management areas)

The following examples use corals (*Acropora*), potential/modelled seagrass meadows and dugong hotspots as examples of key values underpinning MNES. Results of Bayes net analyses in section 2.2 showed that the three coral groups and fish and invertebrates co-varied strongly, which provides justification for using a reduced number of fundamental objectives. Because seagrasses are highly dynamic systems, potential or modelled seagrass habitat is used rather than standing stock (Grech and Coles 2010). Potential seagrass habitats based on physical characteristics provides a better indicator of seagrass conservation zones than standing stock, as potential habitats include areas recently degraded but with the potential for seagrass recruitment and regeneration. In addition to seagrass habitats, dugong hotspots are an information-rich indicator of conservation values estimated from a combination of dugong population modelling, observations, and analyses of dugong frequency and distribution among different areas (Grech and Marsh 2007). The distribution of coral reefs, seagrass habitats and dugong hotspots across the four geographic demonstration cases are presented in Fig. 2.24.

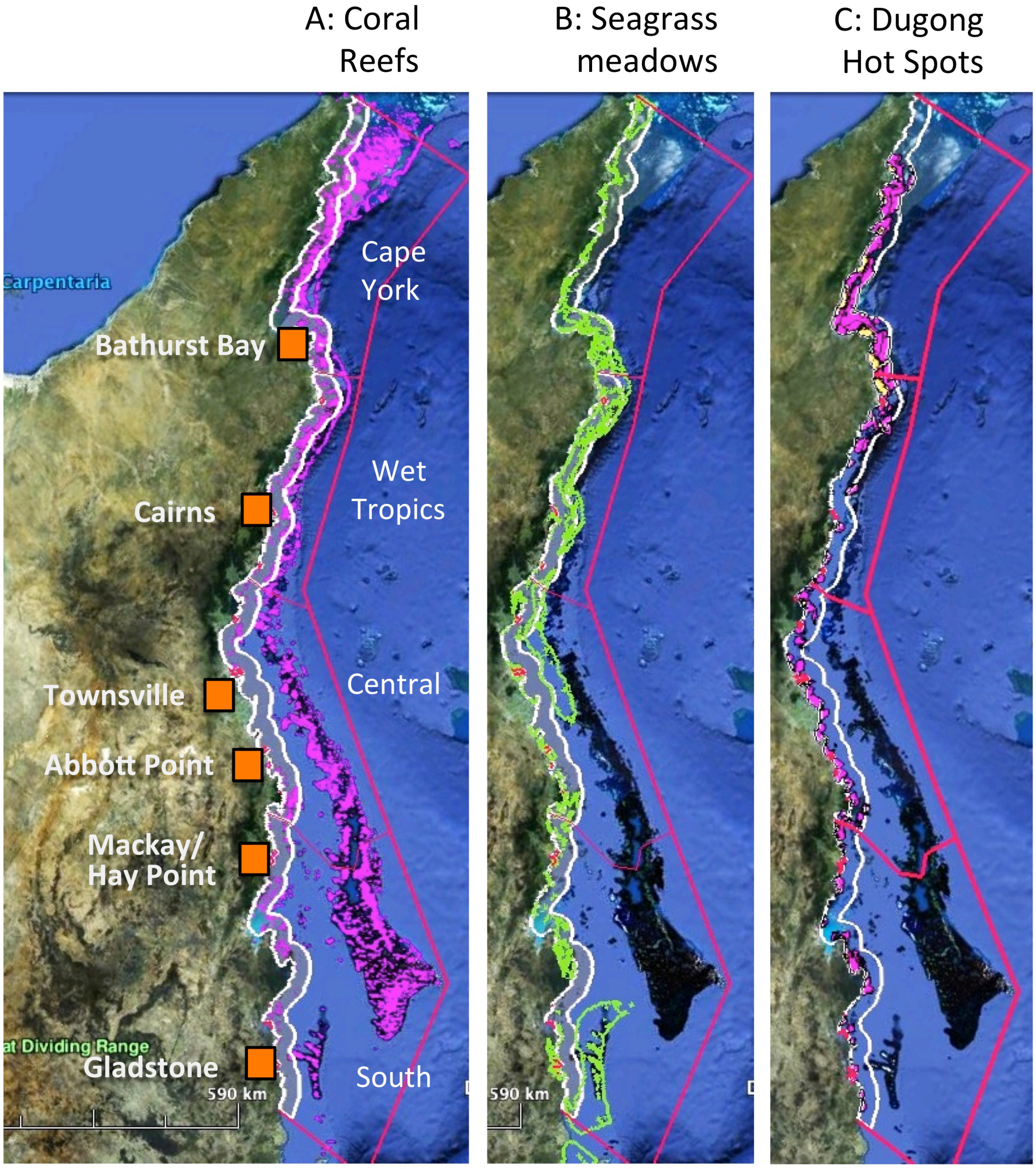


Figure 2.24. Distribution of *coral reefs* (A), *seagrasses* (potential seagrass habitats, B) and *dugong hot spots* (C). Orange markers in panel A are ports, including a proposed development in Cape York (Bathurst Bay). The white line indicates a 30 km buffer used as significant *Zone of Influence* for agricultural run-off of nutrients based on time series data for remotely sensed chlorophyll concentrations (>0.45ug/L). Red, yellow and purple areas in panel C indicate *dugong hot spots* with predicted densities of around 5, 0.5 and 0.125 animals per km^2 (Grech and Marsh 2007).

2.3.5. Exploring scenarios and alternatives

There are a plethora of possible configurations of activities and environmental factors representing cumulative stressors on values in the GBRWHA. The qualitative models in Section 2.2 illustrated some of those configurations, and the *Zones of Influence* presented examples of how scenarios can play out spatially. In addition, land-use and development scenarios can combine with different climate change scenarios and spatial (regional-scale) variation in environmental factors influencing outcomes for ecosystem values. This framework does not provide an exhaustive treatment of all the alternatives. The purpose here is to illuminate key consequences and trade-offs using a handful of alternatives, it is not a search for the definitive 'optimal' solution.

Figure 2.25 below provides a structured overview of possible scenarios for agriculture, port developments and climate change. To stay consistent with Bayes net configurations, the user should assign one of three possibilities for each driver or activity: *increase*, *unchanged* or *decrease*. It is not necessary to explore all possible combinations, which are in this case 3 x 3 x 3 = 27 scenarios. Note that two scenarios potentially represent trade-offs by design: (1) increased agriculture AND decreased port developments, and (2) reduced agriculture AND increased port developments. For the purpose of keeping the number of scenarios tractable in this framework demonstration, examples below pertain mainly to the front-most climate change layer of Fig. 2.25, representing the present-day climate conditions. However, the framework allows for the user to also explore the consequences of scenarios in the second or third climate change layer. In exploratory analyses of the impacts of multiple local, regional and global cumulative stressors, the user can use the Bayes nets to explore any scenario represented in Fig. 2.25.

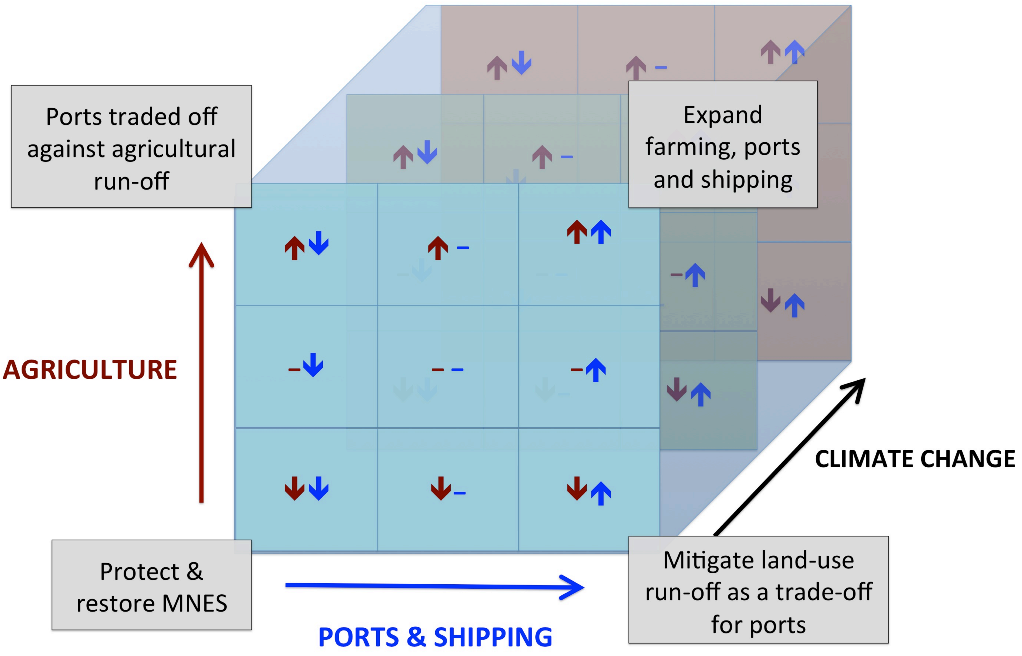


Figure 2.25. Possible combinations of two land-use activities: *Agriculture* and *Ports & Shipping*. The third axis represents different climate change scenarios: for example two or more carbon emission mitigation scenarios and a business-as-usual scenario.

In this framework, *alternatives* are constellations of scenarios distributed across the four GBR management areas (demonstration cases). Seven hypothetical alternatives are used here to provide examples of development alternatives for agriculture and port developments, management alternatives and combined development/management alternatives considering spatial trade-offs (Table 2.4). Developing alternatives is akin to developing strategic options and should ideally be done in consultation with stakeholders to ensure that a range of viable options are considered. The hypothetical alternatives listed in Table 2.4 provide the user with a range of options ranging from an exclusive focus on protecting and restoring ecosystem values (Alternative A) to an exclusive focus on development (Alternative D). Other alternatives, e.g. Alternative E, represent intermediate examples and spatial strategies for ports and agricultural development, mitigation, or geographic trade-offs.

Table 2.4. Hypothetical development alternatives across the four geographic demonstration cases (GBR management areas) used as an example in this report.

Cases	A: Restore and protect MNES	B: Status Quo	C: Expand agriculture (Ag)	D: Spread ports and expand Ag	E: Cluster ports & lessen Ag impacts	F: Cluster ports	G: Spread Ports
Cape York							
Ports	–	–	–	↑	–	–	↑
Agriculture	–	–	↑	↑	–	–	–
Wet Trop							
Ports	↓	–	–	↑	–	–	↑
Agriculture	↓	–	↑	↑	↓	–	–
Central							
Ports	↓	–	–	↑	↑	↑	↑
Agriculture	↓	–	↑	↑	↓	–	–
South							
Ports	↓	–	–	↑	↑	↑	↑
Agriculture	–	–	↑	↑	–	–	–

The status quo alternative in Table 2.4 assumes that keeping agriculture, port development and climate change trends *unchanged* will predict minor net changes in pressures on MNES. For simplicity, a common set of baseline probabilities is used for the four GBR sections (management areas). However, the user can build on expert opinion or data to construct different status quo scenarios for the different GBR regions to account for spatial heterogeneity in current trends and momentum in the ecosystems (Waycott et al. 2007, Grech et al. 2008a, Waycott et al. 2009, De'ath et al. 2012, McKenzie et al. 2012). The conservative assumption is made here that climate change is part of the status quo by adopting elevated baseline Bayes net probabilities of decline for corals and seagrass.

To make examples of framework navigation tractable for the user, only one universal *Zone of Influence* (ZOI) is used for agriculture run-off for all four geographic demonstration cases: a 30km band along the Queensland coast. This *ZOI* is indicated by a white boundary in Fig. 2.24 above. The 30km coastal zone contains the majority of remotely measured chlorophyll *a* concentrations (Schroeder et al. 2012) greater than 0.45 ug/L, considered a threshold value for observables impacts under GBRMPA's water quality guidelines (De'ath and Fabricius 2008, GBRMPA 2010).

Zones of influence for port developments are similarly simplified for the example, but in applying the framework should be represented by case-by-case risk areas of near-port dredging, anchoring on adjacent seagrass areas, and sediment resuspension near reef and seagrass areas. Determining zones of influence for ports need to account for spatial and temporal patterns of turbidity and sedimentation, separately and in combination. Ecological threshold values for sedimentation is still a work in progress on the GBR (GBRMPA 2010), as sedimentation is a dynamic process linked to turbidity, hydrodynamics, sediment characteristics (grain size), and duration of exposure, and has different effects on different species (Fabricius and Wolanski 2000, Philipp and Fabricius 2003, Schaffelke et al. 2005, Waycott et al. 2005, Sofonia and Anthony 2008). Threshold values for turbidity on coral reefs are unclear as they depend on a range of factors including particle characteristics (grain size, organic matter), hydrodynamics and water depth, the latter determining turbidity effects on light availability (Anthony et al. 2004). Empirical studies (e.g. Cooper et al. 2008) have suggested turbidity values of between 3 and 5 NTU (approximately 10-15 mg/L) as long-term threshold values for corals in shallow water. In deeper water, seagrasses are likely to be highly sensitive to prolonged increases in turbidity (Collier et al. 2008).

The examples in this report do not include risks from toxins, accidental spills or grounding accidents, or direct ship impacts on dugongs and turtles (Grech et al. 2008a), as these risk assessments require in-depth analyses of conditional probabilities from an array of related activities (Bateman 1996, Jones et al. 2005). Zones of Influence and potential impacts from ports and shipping activities are therefore likely to be underestimated in the examples.

To provide a template for the user to estimate risks associated with all seven alternatives in Table 2.4, a working example is provided below for the Cape York region. Subsequent calculations presented in this report for the remaining regions in the GBRWHA will build on this template. Calculations for the hypothetical case above (Tables 2.4) demonstrated that climate change is a strong driver of risk as it has a global Zone of Influence. In the following examples climate change is omitted, but the role of climate change is discussed with respect to how a warming climate would shift results and potentially affect decision-making.

2.3.6. Detailed example case: Cape York

The Cape York section of the GBR comprises approximately 9,300 km^2 of coral reefs, of which around 3,300 km^2 are within the simplified ZOI of 30 km from the coast that is used in this report (white boundary in Fig. 2.24). Within the 30 km *ZOI* are also around 5,500 km^2 of potential seagrass areas (Grech et al. 2011). Purple to orange areas in Fig. 2.24 represent dugong hotspots with predicted densities of 0.25 to 4 animals per km^2, respectively. The high concentration of dugong hotspots in the southern end of the Cape York section (Princess Charlotte Bay, Bathurst Bay and around to Cape Flattery) is consistent with a high concentration of seagrass areas (Fig. 2.26). Areas of corals, potential seagrass habitats and dugong hotspot areas are shown in Table 2.5.

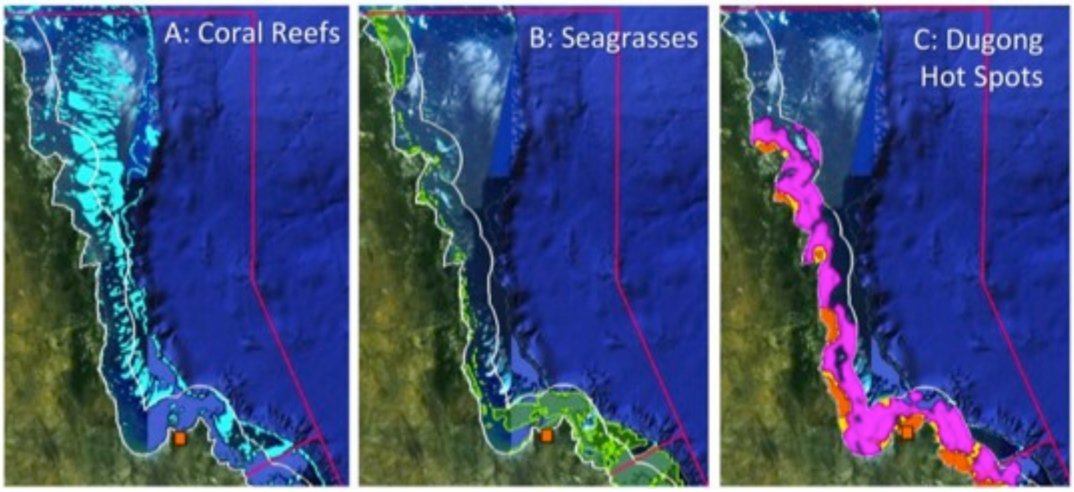


Figure 2.26. Distribution of coral reefs, potential seagrass habitats and dugong hot spots in the Cape York section of the GBR. **A:** Coral reefs are indicated by the light blue areas. **B:** Distributions of seagrass habitats based on combinations of data and models (DPI Fisheries, eAtlas). **C:** Dugong hot spots determined based on combinations of observations and density and distribution modelling (Grech and Marsh 2007). The white line is the 30 km zone used in this report as a simplified Zone of Influence for agriculture run-off. The orange square is the proposed location of a port development (Bathurst Bay).

Consistent with previous examples, the user should follow the six points below to calculate *Total Estimated Risk* as outlined earlier in this section. These points are repeated in summary form in User Box 2.3.

USER BOX 2.3 Calculating Total Estimated Risk

1. Estimate the *Zones of Influence* (*ZOIs*) for pressures for each scenario, for example based on water quality guidelines.
2. Estimate probabilities of change for each pressure node given activities based on expert knowledge or based on physical models.
3. Enter probabilities into the Bayes net(s), and record the probabilities of change for each ecosystem value (output values) within each *ZOI*.
4. Estimate the amount (e.g. area) of ecosystem value potentially impacted within each *ZOI*.
5. Multiply net probabilities of increase (**P**increase – **P**decrease) for ecosystem values by their extent (area, km^2) to calculate a value of *Estimated Risk (ER)*. NB: treat values as crude and tentative estimates that should be reviewed and, where necessary adjusted, by domain experts
6. Sum values of *Estimated Risk* over all ecosystem areas within *ZOIs* to estimate the *Total Estimated Risk* for the area of interest.

Point 1. Hypothetical *Zones of Influence* for agriculture and port developments in the Cape York section are listed in Table 2.5. Again, climate change is not included in examples except within the status quo scenarios, where the assumed climate change effect pertains to the entire area within each GBR region.

Table 2.5. Estimated areas of three ecosystem values within four *Zones of Influence* in the Cape York section (Fig. 2.26).

				Areas (km^2)	
Case	***Activity***	***Zone of influence***	***Coral Reefs***	***Seagrass***	***Dugong***
Cape York	**Agriculture High**	30 km band	3,304	5,500	13,100
	Port(s) and Ag High	30 km radius	200	900	600
	Agriculture Low	All minus Ag High	6,028	0	0
	Ports Low	All minus Ports High	9,132	4,600	12,500
		All (status quo)	*9,332*	5,500	13,100

Note that the *Zone of Influence* for agriculture is between 6 (seagrass) and 20 (Dugong) times greater than that of ports. This is partly a consequence of the assumption that port developments and operational activities have a relatively small foot print. Importantly, considering downstream effects such as dredge spoil dumping and the subsequent dynamics of fine material in spoil dumping grounds, shipping incidents and other consequences of increased traffic would reduce this ratio of agriculture to ports effects.

Point 2. Table 2.6A summarises alternatives for Cape York and associated scenarios, and Table 2.6B summarises Bayes net input probabilities associated with each scenario. Note that only four scenarios are deemed relevant for Cape York given the seven alternatives: increase in agriculture, increase in ports, increase in ports and agriculture, and status quo. As Cape York has some agricultural land-use, a decrease in agriculture is also a plausible scenario. Importantly, input probabilities in Table 2.6B are hypothetical only and represent exploratory values set by the team. Also note that probabilities of change for *Structural Damage and Erosion* (e.g. from anchoring, dredging or strong resuspension) are set conservatively low to compensate for the fact that a 30km radius is used for the port development. Where local knowledge is available, the user should set multiple ZOIs for ports to account for different risks. Again, the user should set these values via rigorous expert elicitation and based on information from simulation modelling of water and sediment transport.

Table 2.6. Summary of scenarios within (**A**) alternatives for Cape York and (**B**) associated probabilities of change for pressure nodes, *Nutrients*, *Turbidity and Sedimentation*, and *Structural Damage and Erosion*.

A: *Alternatives*

Cases	**A: Restore and protect MNES**	**B: Status Quo**	**C: Expand agriculture (Ag)**	**D: Spread ports and expand Ag**	**E: Cluster ports & lessen Ag impacts**	**F: Cluster ports**	**G: Spread Ports**
Cape York							
Ports	▬	▬	▬	⇧	▬	▬	⇧
Agriculture	▬	▬	⇧	⇧	▬	▬	▬

B: *Probabilities*

		Corals and Seagrasses						*Seagrasses*		
	Cape York	***Nutrients***			***Turbidity_Sed***			***Struct_Dam***		
Scenario	*Alternatives*	P_{inc}	P_{unc}	P_{dec}	P_{inc}	P_{unc}	P_{dec}	P_{inc}	P_{unc}	P_{dec}
Status quo	**A,B, E, F**	40	30	30	40	30	30	40	30	30
Agriculture increase, Ag↑	**C**	60	25	15	50	40	10	40	30	30
Port increase, Port ↑	**G**	50	30	20	70	20	10	60	30	10
Ag↑ and Port↑	**D**	70	20	10	90	10	0	60	30	10

Points 3 - 5. Calculations under these points are carried out together in Table 2.7. First, Bayes net probabilities for each zone of influence for each pressure node is entered into the table for each of coral reefs and seagrass ecosystems. Here, a sub table has been included for results pertaining to dugongs although dugongs are modelled as part of seagrass ecosystems. Net probability of increase is calculated as **P**increase – **P**decrease. This exclusively produces negative values (downside risk) in this example as only developments are considered.

Secondly, areas for each ecosystem value within each ZOI are entered and are then multiplied by the net probability of increase to obtain *Estimated Risk* within each ZOI. Note here that risks pertaining to all areas within the geographic demonstration case are calculated by also estimating risk for areas outside the influence of agriculture and/or ports based on the status quo.

Point 6. Lastly, to calculate *Total Estimated Risk*, *Estimated Risks* are summed within each scenario and over the whole geographic case area. The *Uncertainty Index* (stop lights in the right column) is a measure of the chance of other outcomes occurring (i.e. net increase or unchanged, see also Info Box 2.4).

Table 2.7. Results of *Total Estimated Risks* (*TER*) for four land-use scenarios in Cape York.

Coral Reefs	**Bayes Net output probabilities**					***Estimated Risks***		
Scenario	**P_{inc}**	**P_{unc}**	**P_{dec}**	**$\frac{P_{net\ inc}}{100}$**	**Area (km^2)**	***ER***	***TER***	**Uncertainty Index**
Status quo (little agriculture, no port)	39	12	49	-0.10	9,330	- 933	**- 933**	🟡
Agriculture (Ag)	25	11	64	-0.39	3,304	- 1,289	**-1,891**	🔴
Remaining ZOI for status quo	40	10	50	-0.10	6,026	- 603		🟡
Port	22	11	67	-0.45	200	- 90	**-1,003**	🔴
Remaining ZOI for status quo	39	12	49	-0.10	9,130	- 913		🟡
Ag and Port	11	9	80	-0.69	200	- 138	**-1,951**	🔴
Remaining ZOI for Ag	25	11	64	-0.39	3,104	- 1,211		🔴
Remaining ZOI at status quo	39	12	49	-0.10	6,026	- 603		🟡

Seagrasses	**Bayes Net output probabilities**					***Estimated Risks***		
Scenario	**P_{inc}**	**P_{unc}**	**P_{dec}**	**$\frac{P_{net\ inc}}{100}$**	**Area (km^2)**	***ER***	***TER***	**Uncertainty Index**
Status quo (little agriculture, no port)	38	13	49	-0.11	5,500	- 605	**- 605**	🟡
Agriculture (Ag)	25	11	64	-0.39	5,500	- 2,145	**-2,145**	🔴
Remaining ZOI for status quo	38	13	49	-0.11	-	-		🟡
Port	20	11	69	-0.49	900	- 441	**- 947**	🔴
Remaining ZOI for status quo	38	13	49	-0.11	4600	- 506		🟡
Ag and Port	13	9	78	-0.65	900	- 585	**-2,379**	🔴
Remaining ZOI for Ag	25	11	64	-0.39	4600	- 1,794		🔴
Remaining ZOI at status quo	38	13	49	-0.11	-	-		🟡

Dugong Hotspots	**Bayes Net output probabilities**					***Estimated Risks***		
Scenario	**P_{inc}**	**P_{unc}**	**P_{dec}**	**$\frac{P_{net\ inc}}{100}$**	**Area (km^2)**	***ER***	***TER***	**Uncertainty Index**
Status quo (little agriculture, no port)	38	13	49	-0.11	13,100	- 1,441	**-1,441**	🟡
Agriculture (Ag)	25	11	64	-0.39	13,100	- 5,109	**-5,109**	🔴
Remaining ZOI for status quo	38	13	49	-0.11	-	-		🟡
Port	20	11	69	-0.49	600	- 294	**-1,669**	🔴
Remaining ZOI for status quo	38	13	49	-0.11	12,500	- 1,375		🟡
Ag and Port	13	9	78	-0.65	300	- 195	**-5,187**	🔴
Remaining ZOI for Ag	25	11	64	-0.39	12,800	- 4,992		🔴
Remaining ZOI at status quo	38	13	49	-0.11	-	-		🟡

The results for *Total Estimated Risk* (*TER*) for Cape York indicated that increased agriculture in combination with ports represented the highest level of *TER* for corals, seagrasses and dugong conservation values. *TER* under increased agriculture doubled for corals and more than tripled for seagrass and dugong (Table 2.7). The increase in *TER* above status quo for all three ecosystem values under the port development scenario in absence of increased agriculture was relatively low, due to the small *Zone of Influence* set for ports in Table 2.5. Including impacts of dredge spoil dumping, anchoring, spills and grounding risk outside this minimal *ZOI* could see the risk from ports increase substantially beyond the highly conservative example used here. Also, risks from the port operations to seagrasses and dugongs are potentially underestimated here as the proposed port development in Bathurst Bay is in the immediate vicinity of a dugong hot spot and a potential high-density seagrass area (Princess Charlotte Bay, Fig. 2.26).

2.3.7. Interpretations of Estimated Risk (ER) and Total Estimated Risk (TER)

As highlighted in Info Box 2.5, *Estimated Risk* (*ER) and Total Estimated Ris (TER)* are used as indices to prevent the user adhering to the areal unit in risk interpretations. However, as activities and pressures can affect either probability of change, or the areal extent impacted, or both, the user may need to interpret whether probability or area are the strongest drivers of results. For example, pressures from ports and shipping may show a strong spatial pattern driven by the pattern of activities (dredging, spoil dumping, anchoring), with relatively high probabilities of impact in footprint areas. Therefore, the extent of *Zones of Influence* are likely to be a predominant variable. Conversely, agricultural land-use will mostly affect the quality of the water delivered through rivers. Therefore, probabilities of change will be the predominant variable as changing land-use activities have minimal effect on river flows and the extent of river plumes. Increased nutrients and sediment in land-use run-off, however, may increase their *Zones of Influence* somewhat as boundaries for observable change may expand. Lastly, because management interventions can address the extent of *Zones of influence* (and *Zones of Consequence*) as well as probabilities of change within *Zones of Influence*, interpretation of *ER* and *TER* should consider strategies for reducing probabilities of increase in pressures as well as their extent (as demonstrated in section 2.4).

2.3.9. Cumulative risks for all alternatives and GBR management areas

Based on the template above, the user is now able to estimate cumulative risks for all hypothetical alternatives and their nested scenarios for corals, seagrasses and dugongs. Consistent with the steps above ZOIs for agriculture and ports (and status quo as remaining area) for corals, seagrass and dugongs are listed in Table 2.8 for all management areas (demonstration cases).

Table 2.8. Estimated areas of coral reefs, seagrass meadows and dugong hotspots (conservation values) for the four GBR management areas. Areas for ecosystem values in the vicinity of existing or proposed port developments are tentative and results of those should be interpreted cautiously.

			Areas (km^2)		
Case	***Activity***	***Zone of influence***	***Coral Reefs***	***Seagrass***	***Dugong***
Cape York	**Agriculture High**	30 km band	3,304	5,500	13,100
	Port(s) & Ag High	30 km radius	200	900	600
	Agriculture Low	All minus Ag High	6,028	0	0
	Port(s) Low	All minus Ports High	9,132	4,600	12,600
		All (status quo)	*9,332*	5,500	13,100
Wet Tropics	**Agriculture High**	30 km band	1,410	6,600	4,350
	Port(s) & Ag High	30 km radius	50	100	200
	Agriculture Low	All minus Ag High	1,759	6,500	4,150
	Port(s) Low	All minus Ports High	3,119	0	150
		All (status quo)	*3,169*	6,600	4,350
Central Section	**Agriculture High**	30 km band	209	1,800	5,650
	Port(s) & Ag High	30 km radius	200	800	1,000
	Agriculture Low	All minus Ag High	5,141	0	0
	Port(s) Low	All minus Ports High	5,150	1,000	4,650
		All (status quo)	5,350	1,800	5,650
Southern Section	**Agriculture High**	30 km band	300	1,400	3,800
	Port(s) & Ag High	30 km radius	100	150	300
	Agriculture Low	All minus Ag High	5,924	0	0
	Port(s) Low	All minus Ports High	6,124	1,250	3,500
		All (status quo)	6,224	1,400	3,800

Further, Bayes net probabilities for all combinations of scenarios within alternatives are presented in Table 2.9. Note here that scenarios, e.g. combinations of changes (or no change) in agriculture and/or ports developments are nested within development/management alternatives A-G.

Table 2.9. Bayes net input probabilities used as examples across all demonstration cases for coral reefs and seagrass ecosystems for the seven alternatives. Letters A-G refer to the alternatives and indicate how scenarios are allocated to alternatives for each geographic demonstration area. For coral reefs, probabilities of *increase*, *unchanged* and *decrease* for *Storms* were set to 33%/33%/33% and for *Ocean Warming* was to 40%/30%/30%, respectively, for all alternatives. For seagrasses, probabilities of *increase*, *unchanged* and *decrease* for Ocean Warming Mild and Ocean Warming Severe were both set to 40%/30%/30% for all alternatives, assuming equal present-day baseline for both scenarios.

					Corals and Seagrasses						*Seagrasses*		
	Cape York	***Wet Tropics***	***Central***	***South***	***Nutrients***			***Turbidity_Sed***			***Struct_Dam***		
Scenario	*Alternatives*				P_{inc}	P_{unc}	P_{dec}	P_{inc}	P_{unc}	P_{dec}	P_{inc}	P_{unc}	P_{dec}
Status quo	**A,B, E, F**	**B,F**	**B**	**B**	40	30	30	40	30	30	40	30	30
Agriculture increase, Ag↑	**C**	**C**	**C**	**C**	60	25	15	50	40	10	40	30	30
Agriculture decrease, Ag↓		**E**			10	30	60	10	40	50	40	30	30
Port increase, Port ↑	**G**	**G**	**F, G**	**E, F, G**	50	30	20	70	20	10	60	30	10
Port decrease, Port ↓				**A**	30	30	40	10	30	60	10	30	60
Ag↑ and Port↑	**D**	**D**	**D**	**D**	70	20	10	90	10	0	60	30	10
Ag↓ and Port↑			**E**		30	30	40	60	30	10	60	30	10
Ag↓ and Port↓		**A**	**A**		20	35	45	10	30	60	10	30	60

Lastly, following points 3-6, *Estimated Risk* and *Total Estimated Risk* are calculated for each scenario and distributed across the table across demonstration areas within alternatives (Table 2.10). Across all alternatives, *Total Estimated Risk* was highest for Cape York for all ecosystem values, explained principally by its larger areas of coral reefs, seagrass habitats and dugong hotspots close to the coast. In contrast, TER was generally lowest in the southern region as coral reefs are far from the coast and seagrass and dugongs are less dense than in the northern regions. Sections 2.4 and 2.5 explore how the results for these alternatives can be used in a structured decision making-process.

Table 2.10. Summary table for *Total Estimated Risk* (*TER*) to ecosystem values for the seven management/development alternatives in Table 3.3. Note that *TER* here indicate downside risk as negative values (amber and red) and upside risks as positive values (green) to guide management interventions. Colour scale is indicative and is used only to guide the user to identify the scenarios, locations and ecosystem values with the lowest or highest estimated risks (indices scaling with probability and area affected).

	MNES	A: Restore and protect MNES	B: Status Quo	C: Expand agriculture (Ag)	D: Spread ports and expand Ag	E: Cluster ports & lessen Ag impacts	F: Cluster ports	G: Spread Ports
Cape York	Corals reefs	- 933	- 933	-1,891	-1,951	- 933	- 933	- 1,003
	Seagrass habitats	- 605	- 605	-2,145	-2,379	- 605	- 605	- 947
	Dugong Hotspots	-1,441	-1,441	-5,109	-5,187	-1,441	-1,441	- 1,669
Wet Tropics	Corals reefs	- 513	- 317	- 726	- 741	374	- 317	- 334
	Seagrass habitats	2,754	- 660	-2,574	-2,604	2,772	- 660	- 695
	Dugong Hotspots	1,837	- 435	-1,349	-1,508	1,827	- 435	- 505
Central	Corals reefs	408	- 535	- 596	-2,164	- 555	- 605	- 605
	Seagrass habitats	796	- 180	- 558	- 882	- 34	- 460	- 460
	Dugong Hotspots	2,423	- 565	-1,752	-2,225	740	- 915	- 915
South	Corals reefs	- 601	- 622	- 709	- 719	-1,280	-1,280	- 640
	Seagrass habitats	- 62	- 140	- 434	- 516	- 385	- 385	- 193
	Dugong Hotspots	- 224	- 380	-1,178	-1,362	- 970	- 970	- 485

2.4 Identify management levers and revisit fundamental objectives

Analyses of cumulative risk and consequences for MNES proxies have so far been without consideration of the levers available to a manager to reduce risks and adverse impacts. For some scenarios that clearly entail unacceptable impacts, the judicious identification and implementation of management interventions may lead to acceptable outcomes.

The nature of available levers or interventions will be shaped and constrained by the specific policy setting of the decision. Among others, management levers to address land-use runoff may include:

- Adoption program for best practice among landholders
- Compliance regulation
- Program to buy-back and rehabilitate high impact properties
- Bioremediation buffers
- Gully restoration

Management levers to address port impacts may include:

- Land-based disposal of dredge spoil
- Adoption of international best practice
- Improved management of ship traffic within the GBRWHA

For any individual development proposal the challenge that now arises concerns (a) what management levers are most effective, and (b) what scale of operation (if applicable) is required to satisfy a test of acceptable risk. There are potentially thousands of alternatives for the spatial and temporal configuration of management interventions across the GBRWHA. The diagnostic capabilities of Bayes nets (see section 2.2) provide a sound basis for discerning effective and ineffective interventions.

INFO BOX 2.6: Expert judgement

All methods of defensible decision-making require at least coarse judgments of risks and consequences associated with future, uncertain events, demanding use of expert judgement. It is beyond the capabilities of current causal understanding to obtain reasonable estimates of risk and consequence for all possible configurations of management intervention. Instead, identification of a small number of discrete alternatives is more pragmatic, largely because the burden in elicitation of expert judgement is less onerous. The downside of a non-exhaustive search of all alternatives is that optimal or near optimal alternatives may not be included in the sub-set of discrete alternatives considered. To avoid poor outcomes, alternatives need to be creative and sample a range of operating levels and candidate activities (Gregory et al. 2012).

For any discrete alternative, expert judgement is required to inform the magnitude of any change in the probabilistic description of pressure nodes in the Bayes nets and the characterisation of zones of influence. A modest elicitation burden is important because considerable effort is required to insulate against common frailties in expert judgement, including fatigue, overconfidence and motivational bias (Burgman 2005). Sound protocols for elicitation of expert judgment include the opinions of multiple experts and emphasise anonymity and feedback to guard against anchoring and deference to authority (Ayyub 2001). Thoughtful framing of questions can assist considerably in buffering against overconfidence (Spiers-Bridge et al. 2010).

2.4.1 Identify management levers

A useful tool to help identify alternatives for management intervention is a *strategy table* (Gregory et al. 2012). In the hypothetical example used here, the strategy table comprises the various candidate management interventions within each section of the GBR to address the primary objectives: protection of MNES. For the broader SDM analyses, the task also involves specification of costs, and potentially who bears the cost (government, ports and port users or the agriculture industry). The hypothetical alternatives in Table 2.11 show combinations of management and/or development scenarios across the four geographic case areas, of which some represent management actions without further development (Alternative A), some represent combinations of management and development and geographic tradeoff (Alternative E), and some are development alternatives only (Alternatives C and G). One purpose of this alternative constellation is to illustrate, starting with a strategy table, how risks and impacts of development may be reduced through deployment of management intervention and how such interventions change the performance of alternatives from the perspective of decision-making.

Importantly, the task does not require a forecasting capacity to specify how much management intervention is required to compensate for additional risks posed by development. The technical task of revising estimates of cumulative risk in the presence of management intervention is the domain of predictive modelling using the same methods deployed in the characterisation of cumulative risk in the absence of management intervention (Section 2.3). Rough and ready judgements may be used in the exercise, but it is important to compile a range of alternatives that vary in the nature of interventions chosen, their cost, and who pays, so that key trade-offs can be illuminated. There are also a range of other considerations that may need to be taken into account in this decision-making process that are not explored in these examples (for example, regulation may be low-cost for government to implement, but could be high-cost to industry in terms of compliance). Here, the key trade offs are the ones in which management interventions lead to improved performance from an efficacy, feasibility and cost perspective to gain net benefits for MNES.

In consultation with workshop participants (see participant list in Appendix 3), a single management intervention strategy was compiled for three of the development proposals (‘expand agriculture’, ‘spread ports and expand agriculture’ and ‘spread ports’). For the ‘cluster ports’ development scenario, two alternative management strategies were included. Also included is an approximation of current management interventions under the status quo. Finally, an expansive intervention strategy (‘reduced impact – restore and protect MNES’) was added to improve the Status Quo scenario consistent with GBRMPA’s objective to reverse the decline of ecosystem values. For the purpose of these illustrative examples, only one level and a narrow set of mitigation options for each alternative were used. In reality, the user should analyse several intervention levels, strategies and targeted mitigation investments to enable a comprehensive assessment of environmental risks and benefits against intervention options.

A hypothetical strategy table is presented in Table 2.11. For each of the four sections of the GBR the table details hypothetical examples of management interventions that could be undertaken and who bears the cost, together with the scale of development proposed for ports and agriculture. The alternatives vary markedly in their details. Alternatives C and D propose a doubling of agricultural productivity (relative to the status quo). Alternatives D, E, F and G involve a 230% increase in port capacity. Two alternatives (C and D) seek to mitigate the risks posed by land run-off across all four sections of the GBR. Alternative E concentrates this investment in the Wet Tropics and Central sections. Alternatives F and G focus mitigation effort on the risks posed by ports, with lesser emphasis on land run-off.

The total (hypothetical) cost of management interventions for all development proposals range from \$220M per annum to \$963M per annum - far more than the level of investment under the status quo (~ \$40M pa).

Table 2.11. Hypothetical strategy table outlining alternative scenarios for development and management intervention.

	A: Reduced impact (restore and protect MNES)	B: Status Quo	C: Expand agriculture	D: Spread Ports and Expand Agriculture	E: Cluster ports & lessen Ag impacts	F: Cluster ports	G: Spread Ports
Ports and shipping - cape york (Mt/yr)	0	0	0	70	0	0	70
alternative disposal of dredge spoil ($M/yr)							1 (gov) 99 (ports)
adoption of international best practice ($M/yr)							1 (gov) 99 (ports)
bioremediation buffers ($M/yr)							
Agriculture - cape york ($B/yr)	0.03	0.03	0.06	0.06	0.03	0.03	0.03
adoption program for best practice ($M/yr)	5 (gov)	5 (gov)	5 (gov) 15 (ag)	5 (gov) 15 (ag)		5 (gov) 1 (ag)	
compliance regulation ($M/yr)							
buy back and rehabilitation ($M/yr)							
gully restoration ($M/yr)							
Ports and shipping - wet tropics (Mt/yr)	40	40	40	80	40	40	80
alternative disposal of dredge spoil ($M/yr)	20 (gov)						1 (gov) 99 (ports)
adoption of international best practice ($M/yr)	30 (gov)						1 (gov) 99 (ports)
bioremediation buffers ($M/yr)							
Agriculture - wet tropics ($B/yr)	1.15	1.15	2.30	2.30	1.15	1.15	1.15
adoption program for best practice ($M/yr)	15 (gov)	15 (gov)	15 (gov) 45 (ag)	15 (gov) 45 (ag)	40 (gov) 40 (ag)	15 (gov) 3 (ag)	
compliance regulation ($M/yr)					20 (gov) 20 (ag)		
buy back and rehabilitation ($M/yr)	80 (gov)		15 (gov) 15 (ag)	15 (gov) 15 (ports)			
gully restoration ($M/yr)	20 (gov)						
Ports and shipping - central (Mt/yr)	100	100	100	200	200	200	200
alternative disposal of dredge spoil ($M/yr)	20 (gov)					100 (ports)	1 (gov) 99 (ports)
adoption of international best practice ($M/yr)	30 (gov)					100 (ports)	1 (gov) 99 (ports)
bioremediation buffers ($M/yr)						100 (ports)	
Agriculture - central ($B/yr)	1.26	1.26	2.52	2.52	1.26	1.26	1.26
adoption program for best practice ($M/yr)	15 (gov)	15 (gov)	15 (gov) 45 (ag)	15 (gov) 45 (ag)	40 (gov) 40 (ag)	15 (gov) 3 (ag)	
compliance regulation ($M/yr)					20 (gov) 20 (ag)		
buy back and rehabilitation ($M/yr)	80 (gov)		15 (gov) 15 (ag)	15 (gov) 15 (ports)		5 (ports)	
gully restoration ($M/yr)	20 (gov)						
Ports and shipping - south (Mt/yr)	100	100	100	200	310	310	200
alternative disposal of dredge spoil ($M/yr)	20 (gov)				10 (ports)	200 (ports)	1 (gov) 99 (ports)
adoption of international best practice ($M/yr)	30 (gov)				10 (ports)	200 (ports)	1 (gov) 99 (ports)
bioremediation buffers ($M/yr)						200 (ports)	
Agriculture - south ($B/yr)	1.20	1.20	2.40	2.40	1.20	1.20	1.20
adoption program for best practice ($M/yr)	15 (gov)	5 (gov)	5 (gov) 5 (ag)	5 (gov) 5 (ag)	10 (ports)	5 (gov) 1 (ag)	
compliance regulation ($M/yr)							
buy back and rehabilitation ($M/yr)	40 (gov)		5 (gov) 5 (ag)	5 (gov) 5 (ports)		10 (ports)	
gully restoration ($M/yr)	20 (gov)						
Ports and shipping TOTAL (Mt/yr)	240	240	240	550	550	550	550
Agriculture - TOTAL ($B/yr)	3.64	3.64	7.28	7.28	3.64	3.64	3.64
mgnt intervention - government - TOTAL ($M/yr)	460	40	75	75	120	40	8
mgnt intervention - ports - TOTAL ($M/yr)	0	0	0	35	30	915	792
mgnt intervention - agriculture - TOTAL ($M/yr)	0	0	145	110	120	8	0

To help the user implement the strategy table into a revised cumulative risk assessment, Table 2.11 provides suggested changes in Bayes net input probabilities and percent changes in *Zones of Influence*. Again, note that changes in probabilities and *ZOIs* are hypothetical only and are scaled simply with the size of interventions, ignoring any variation in the efficiency of management interventions.

Table 2.12. Hypothetical changes in Bayes net probabilities and *Zones of Influence* (*ZOIs*) associated with management interventions ("MI", $M per year) under. Highlighted numbers are the total hypothetical investments for ports and agriculture listed in Table 2.11

Cases	**A: Restore and protect MNES**				**B: Status Quo**				**C: Expand agriculture (Ag)**				**D: Spread ports and expand agriculture (Ag)**				**E: Cluster ports & lessen Ag impacts**				**F: Cluster ports**				**G: Spread Ports**			
Cape York	DEV	MI	$\Delta P_{n\,in}$ (%)	ΔZOI (%)	DEV	MI	$\Delta P_{n\,in}$ (%)	ΔZOI (%)	DEV	MI	$\Delta P_{n\,in}$ (%)	ΔZOI (%)	DEV	MI	$\Delta P_{n\,in}$ (%)	ΔZOI (%)	DEV	MI	$\Delta P_{n\,in}$ (%)	ΔZOI (%)	DEV	MI	$\Delta P_{n\,in}$ (%)	ΔZOI (%)	DEV	MI	$\Delta P_{n\,in}$ (%)	ΔZOI (%)
Ports	–	0			–	0			–	0			↑	0			–	0			–	0			↑	200		
Nutrients			0	0			0	0			0	0			0	0			0	0			0	0			0	0
Turb&Sed			0	0			0	0			0	0			0	0			0	0			0	0			15	-30
Str_Dam_Er			0	0			0	0			0	0			0	0			0	0			0	0			15	-30
Agriculture	–	5			–	5			↑	20			↑	20			–	0			–	6			–	0		
Nutrients			2	0			2	0			5	0			5	0			0	0			2	0			0	0
Turb&Sed			2	0			2	0			5	0			5	0			0	0			2	0			0	0
Str_Dam_Er			0	0			0	0			0	0			0	0			0	0			0	0			0	0
Wet Trop																												
Ports	↓	50			–	0			–	0			↑	0			–	0			–	0			↑	200		
Nutrients			0	0			0	0			0	0			0	0			0	0			0	0			0	0
Turb&Sed			5	-10			0	0			0	0			0	0			0	0			0	0			15	-30
Str_Dam_Er			5	-10			0	0			0	0			0	0			0	0			0	0			15	-30
Agriculture	↓	115			–	15			↑	90			↑	90			↓	120			–	18			–	0		
Nutrients			10	0			4	0			8	0			8	0			10	0			4	0			0	0
Turb&Sed			10	0			4	0			8	0			8	0			10	0			4	0			0	0
Str_Dam_Er			0	0			0	0			0	0			0	0			0	0			0	0			0	0
Central																												
Ports	↓	60			–	0			–	0			↑	0			↑	0			↑	300			↑	200		
Nutrients			0	0			0	0			0	0			0	0			0	0			0	0			0	0
Turb&Sed			5	-10			0	0			0	0			0	0			0	0			20	-40			15	-30
Str_Dam_Er			5	-10			0	0			0	0			0	0			0	0			20	-40			15	-30
Agriculture	↓	115			–	15			↑	90			↑	90			↓	120			–	23			–	0		
Nutrients			10	0			4	0			8				8	0			10	0			5	0			0	0
Turb&Sed			10	0			4	0			8				8	0			10	0			5	0			0	0
Str_Dam_Er			0	0			0	0			0				0	0			0	0			0	0			0	0
South																												
Ports	↓	50			–	0			–	0			↑	0			↑	20			↑	600			↑	200		
Nutrients			0	0			0	0			0	0			0	0			0	0			5	0			0	0
Turb&Sed			5	-10			0	0			0	0			0	0			4	-8			25	-50			15	-30
Str_Dam_Er			5	-10			0	0			0	0			0	0			4	-8			25	-50			15	-30
Agriculture	–	75			–	5			↑	20			↑	20			–	10			–	16			–	0		
Nutrients			10	0			4	0			4	0			4	0			3	0			4	0			0	0
Turb&Sed			10	0			4	0			4	0			4	0			3	0			4	0			0	0
Str_Dam_Er			0	0			0	0			0	0			0	0			0	0			0	0			0	0

2.4.2. Review of objectives and attributes

The alternatives for development and their co-packaged management intervention strategies invoke consideration of a broader set of fundamental objectives beyond consideration of whether or not qualitative predictions of cumulative impacts pose acceptable or unacceptable risk to MNES (or their proxies).

Objectives were defined and discussed in section 1. Here, the four different types of objectives are summarised briefly (see also Info Box 1.1):

- *Strategic objectives*: objectives influenced by all of the decisions made over time by the organization or individual facing the decision at hand. While useful as guiding principles in organisational settings, strategic objectives are commonly too ambiguous for inclusion in a decision analysis (e.g. an objective for a 'sustainable' environment).
- *Fundamental objectives*: the ends objectives used to describe the consequences that essentially define the basic reasons for being interested in the decision.
- *Means objectives*: objectives that are important only for their influence on achievement of the fundamental objectives.
- *Process objectives*: objectives concerning how the decision is made rather than what decision is made.

Objectives in structured decision-making should appeal only to fundamental values. A common mistake is to confuse ‘means objectives’ with ‘fundamental (ends) objectives’. Means objectives are intermediate goals that serve as stepping-stones towards the things that are of fundamental concern (Keeney and Gregory 2005).

Attributes assist in making objectives comprehensible and consequences estimable (Gregory et al. 2005). Attributes may be qualitative or quantitative, or a mix of both. There are three kinds of attributes - natural units, proxies and constructed scales (Keeney and Gregory 2005). In general, natural units are better than proxies. Where natural units are unavailable, a choice between a proxy and a constructed scale is required. For social and cultural elements of a decision problem there are usually no natural units and proxies may fail to capture relevant concerns. Constructed scales involve qualitative ordinal scenarios built on a Likert scale. When assuming linear marginal value functions, care is required to ensure scenarios faithfully map to a linear scale (see Gregory et al. 2012 pp. 106 – 114).

Assuming a subset of alternatives offer reasonable prospects for passing the acceptable risk test, consideration is required on whether the benefits of development outweigh the costs of management intervention, and whether or not it’s reasonable (or feasible) to impose that cost on the public and/or private sector. Table 4.3 describes the fundamental objectives for this more substantial decision problem.

Table 2.13. Fundamental objectives for the assessment of development proposals packaged with alternative management intervention strategies.

	Objective		Attribute	Preferred direction
Primary objectives	Corals	• Cape York • Wet Tropics • Central • South	Total Estimated Risk (TER)	More upside risk is better Less downside risk is better
	Seagrass	• Cape York • Wet Tropics • Central • South	Total Estimated Risk (TER)	More upside risk is better Less downside risk is better
	Dugongs	• Cape York • Wet Tropics • Central • South	Total Estimated Risk (TER)	More upside risk is better Less downside risk is better
Secondary objectives	Total port capacity		Million tonnes pa (Mta)	More is better
	Agricultural production		Farm gate value ($B)	More is better
	Cost of management interventions	• to government • to ports and port users • to agriculture	$M	Less is better

In the next section, consequences of each of the seven alternatives are analysed against fundamental objectives to guide decision-making. At this point the user should review whether consequences and mitigation options are consistent with fundamental objectives and current policies. This serves three purposes; i) ensuring that any recommendations have a clear legislative basis, ii) identifying any gaps between current policy provisions and recommended mitigation options, and iii) ensuring that recommendations can be clearly communicated to stakeholders.

2.5 Consequences and Trade-Offs (Decision Analysis)

The consequences of each alternative against each objective now require estimation as the next step in decision-making. The most substantial task here is the preparation of revised estimates for cumulative risk estimates against each endpoint (MNES or their proxies) in each region of the GBR in the presence of specified management interventions. The task involves changing the probabilistic status of pressure variables in each Bayes net together with revised characterisation of zones of influence. For the purpose of illustrating the decision-support capabilities of the *CISDM* framework, detailed analysis was not undertaken. The estimates reported below reflect no more than the intuitions of the authors of this report, informed in part by the judgements of workshop participants. These estimates are unlikely to be representative of outcomes of the detailed analysis, which is plainly warranted in this high stakes setting. These estimates are used simply to illustrate the concepts and process of effective decision-making.

Formal decision protocols have advantages over unaided decision-making to the extent that they capture sound logic. Apart from buffering against cognitive limitations and negative group dynamics, a documented and traceable protocol will encourage decision-makers to be clear about judgements and assumptions (Bedford and Cooke 2001). Two interacting flaws are commonly encountered in risk-based decision support: (a) incoherent treatment of the essential connections between social or organisational values and the scientific knowledge necessary to predict the likely impacts of management actions, and (b) relying on expert judgment about risk framed in qualitative and value-laden terms, inadvertently mixing the expert's judgment about what is likely to happen with personal or political preferences (Maguire 2004). Structured decision-making seeks to avoid these flaws through explicit separation of the task of causal judgment from the task of articulating value judgments or trade-offs (Failing et al. 2007, Ananda and Herath 2009).

The choice of any method for dealing with a multi-objective problem itself involves a trade-off between the desirability of adherence to normative axioms of rational decision-making and the practicalities of time constraints, demands on technical proficiency, and the willingness and capacity of stakeholders to engage. The approach to trade-offs described here compromises normative ideals for the sake of accessibility and ease of use, while buffering against common traps in decision-making (Hammond et al. 2006). It seeks to provide good solutions rather than optimal solutions.

In the context of the case studies these trade-offs include:

- the extent to which poor outcomes for ecosystem values in one section of the reef can be compensated for by desirable outcomes in other sections, and
- the extent to which the anticipated benefits of development compensate for the costs of management intervention.

These trade-offs can only be made for those alternatives that (at least approximately) satisfy a test of acceptable risk on primary objectives dealing with ecosystem values. Again, it is important to note that estimated consequences here are based on qualitative assessments of cumulative impacts and do not address the magnitude of impacts.

There are three core elements to any multi-objective decision problem: (1) alternatives, (2) expected consequences, and (3) trade-offs. In decision analysis, these core elements are organised in a *consequence table*, which is a structured presentation of the consequences of cumulative impacts to primary objectives (ecosystem values via *Total Estimated Risk*, *TER*) including consideration of candidate management interventions (Table 2.14). To assess the overall merit of one alternative against another, consequences need to be considered across fundamental objectives and resolve trade-offs through articulation of societal or organizational preferences, in this case primary (MNES) versus secondary objectives. There are two ways to undertake this task:

1. Informal articulation of trade-offs through consideration of the consequence table (Table 2.14) and identification of *dominated alternatives* and *redundant objectives*.
2. Formal weighting and aggregation using multi-attribute value theory (see Appendix 4).

The reasoning involved in informal treatment of trade-offs is demonstrated using the consequence table below (Table 2.14).

Table 2.14. Consequence table for the assessment of development proposals packaged with alternative management intervention strategies against a benchmark requirement to *improve* the status of MNES (or their proxies). Red cells indicate estimates that are ≥ 10% worse than the corresponding estimates under the grey-shaded benchmark. Green cells indicate estimates that are ≥ 10% better than the benchmark. Note that estimates of *Total Estimated Risk* (*TER*) for MNES proxies are indicative only. Values for *TER* are risk indices scalable with predicted probabilities of change and areas of MNES components affected.

			Attribute	A: Reduced impact (restore and protect MNES)	B: Status Quo	C: Expand agriculture	D: Spread Ports and Expand Agriculture	E: Cluster ports & lessen Ag impacts	F: Cluster ports	G: Spread Ports
Primary objectives	Cape York	Corals	TER	-891	-891	-1869	-1902	-891	-891	-957
		Seagrass	TER	-559	-559	-1604	-1874	-559	-458	-920
		Dugongs	TER	-1316	-1316	-3805	-3985	-1316	-1060	-1651
	Wet Trop	Corals	TER	638	-118	-422	-425	611	-118	-131
		Seagrass	TER	1670	-462	-1910	-1677	2203	-529	-558
		Dugongs	TER	1041	-284	-1167	-1067	1294	-327	-385
	Central	Corals	TER	-441	-520	-580	-653	-464	-606	-606
		Seagrass	TER	608	-130	-492	-668	51	-386	-386
		Dugongs	TER	1555	-400	-1601	-1685	948	-755	-755
	South	Corals	TER	-580	-622	-695	-699	-622	-619	-635
		Seagrass	TER	-58	-99	-400	-391	-284	-280	-180
		Dugongs	TER	-216	-267	-1091	-1032	-748	-748	-398
Secondary objectives	Port capacity		Mta	240	240	240	240	550	550	550
	Agricultural production		$B/yr	3.64	3.64	3.64	7.28	7.28	3.64	3.64
	Cost of mgmt interv - govt		$M/yr	460	460	40	75	75	120	40
	Cost of mgmt interv - ports		$M/yr	0	0	0	0	35	30	915
	Cost of mgmt interv - agriculture		$M/yr	0	0	0	145	110	120	8

Table 2.15. Relative declines (percentages) in *Total Estimated Risk* between unmitigated and mitigated alternatives, that is following management interventions outlined in the strategy table (Table 2.11, see also Table 2.12). Values are calculated as ($TER_{mitigated}$ – $TER_{unmitigated}$)/$TER_{unmitigated}$. Values are positive because management interventions lead to increased upside risk (see Info Box 2.5).

		A: Restore and protect MNES	B: Status Quo	C: Expand agriculture (Ag)	D: Spread ports and expand Ag	E: Cluster ports & lessen Ag impacts	F: Cluster ports	G: Spread Ports
Cape York	Corals	4	4	1	3	4	4	5
	Seagrass	8	8	25	21	8	24	3
	Dugongs	9	9	26	23	9	26	1
Wet Trop	Corals	72	62	42	43	63	62	61
	Seagrass	39	30	26	36	21	20	20
	Dugongs	43	35	13	29	29	25	24
Central	Corals	1	3	3	9	18	0	0
	Seagrass	24	28	12	24	250	16	16
	Dugongs	36	29	9	24	28	18	18
South	Corals	0	0	2	4	5	6	3
	Seagrass	7	30	8	24	26	27	7
	Dugongs	4	30	7	24	23	23	18

As noted above, the notion of acceptable impact for ecosystem values can be assessed against one of several benchmarks. In this illustrative analysis, outcomes for two possibilities are shown

1. Benchmarking against a fundamental objective of reversing decline in MNES ('reduced impact – protect and restore MNES').
2. Benchmarking against the status quo.

Table 2.14 compares the performance of alternatives against a scenario broadly consistent with the first of these (A. Reduced impact – restore and protect MNES). Note that this scenario is not uniformly successful in reversing or arresting declines, with cumulative risks reported for MNES proxies in the Cape York and Southern sections exposed to some net downside risks due to the effects of climate change (ocean warming) and baseline changes in water quality built into the analyses (**P**increase/**P**unchanged/**P**decrease set to 40%/30%/30%). Nevertheless, on the basis of this comparison (A as benchmark) none of the alternatives B-G passes the test of acceptable risk. Alternative E provides improved upside risk for seagrass in the Wet Tropics that may adequately compensate for greater downside risks in the Central and Southern sections, but the performance of this alternative for corals and seagrass is clearly deficient against the Alternative A benchmark. Similarly, Alternative G fails to provide sufficient mitigation against risks posed to seagrass and dugongs. The outcome is that none of the alternatives can be considered desirable in the context of a benchmark requiring environmental improvement in the extent of corals, seagrass and dugongs. Planners may wish to revisit alternatives for management intervention (or the scale and intensity of development), or abandon all alternatives should they consider the costs of management intervention to be prohibitive.

Benchmarking against the status quo (i.e. maintain environmental values at current levels) provides contrasting outcomes, at least for the hypothetical consequences reported here (Table 2.16). Although alternatives C and D clearly fail a test of acceptable risk, alternatives E and F appear worthy of further consideration.

Table 2.16. Consequence table for the assessment of development proposals packaged with alternative management intervention strategies against a benchmark requirement for MNES to be no worse off than anticipated under the status quo. Red cells indicate estimates that are ≥ 10% worse than the corresponding estimates under the grey-shaded benchmark. Green cells indicate estimates that are ≥ 10% better. Note that estimates of total estimated risk (*TER*) for MNES are indicative only.

			Attribute	A: Reduced impact (restore and protect MNES)	B: Status Quo	C: Expand agri-culture	D: Spread Ports and Expand Agri-culture	E: Cluster ports & lessen Ag impacts	F: Cluster ports	G: Spread Ports
Primary objectives	Cape York	Corals	TER	-891	-891	-1869	-1902	-891	-891	-957
		Seagrass	TER	-559	-559	-1604	-1874	-559	-458	-920
		Dugongs	TER	-1316	-1316	-3805	-3985	-1316	-1060	-1651
	Wet Trop	Corals	TER	638	-118	-422	-425	611	-118	-131
		Seagrass	TER	1670	-462	-1910	-1677	2203	-529	-558
		Dugongs	TER	1041	-284	-1167	-1067	1294	-327	-385
	Central	Corals	TER	-441	-520	-580	-653	-464	-606	-606
		Seagrass	TER	608	-130	-492	-668	51	-386	-386
		Dugongs	TER	1555	-400	-1601	-1685	948	-755	-755
	South	Corals	TER	-580	-622	-695	-699	-622	-619	-635
		Seagrass	TER	-58	-99	-400	-391	-284	-280	-180
		Dugongs	TER	-216	-267	-1091	-1032	-748	-748	-398
Secondary objectives	Port capacity		Mta	240	240	240	550	550	550	550
	Agricultural production		$B/yr	3.64	3.64	7.28	7.28	3.64	3.64	3.64
	Cost of management intervention - govt		$M/yr	460	40	75	75	120	40	8
	Cost of management intervention - ports		$M/yr	0	0	0	35	30	915	792
	Cost of management intervention, agricult.		$M/yr	0	0	145	110	120	8	0

The preparation of a consequence table itself offers substantial insulation against the pitfalls of unaided decision-making. However, unless the decision problem can be meaningfully simplified to a handful of objectives and alternatives, the cognitive demands on decision-makers and stakeholders can lead to poor outcomes. In many instances, a consequence table can be simplified through identification of

- practically dominated alternatives, and
- redundant objectives.

In the context of the fundamental objective to ensure net benefits to MNES all of the scenarios, other than A, fail a test of acceptable risk. This includes Status Quo inferring that current arrangements would need additional interventions to achieve the desired outcomes. For illustration purposes further analysis against the Status Quo scenario shows alternatives C and D to be dominated alternatives that can be omitted from the analysis. Thereafter, there are two objectives, which are more or less equal in their performance across alternatives – dugongs at Cape York and agricultural production. These too can be omitted. This is not to say that dugongs at Cape York or agricultural production are unimportant. Redundant objectives are simply those that do not help to distinguish the merit (or dismerit) of alternatives. The consequence table is now reduced to three development proposals (E, F and G) and fifteen objectives, shown below (Table 2.17). While still difficult, it is possible that decision-makers and stakeholders can negotiate a preferred alternative on this basis without recourse to formal techniques for dealing with trade-offs.

Table 2.17. Reduced consequence table for the assessment of development proposals packaged with alternative management intervention strategies against a benchmark requirement for MNES to be no worse off than anticipated under the status quo. TER: *Total Estimated Risk*.

			Attribute	A: Reduced impact (restore and protect MNES)	B: Status Quo	E: Cluster ports & lessen Ag impacts	F: Cluster ports	G: Spread Ports
Primary objectives	Cape York	Corals	TER	-891	-891	-891	-891	-957
		Seagrass	TER	-559	-559	-559	-458	-920
	Wet Trop	Corals	TER	638	-118	611	-118	-131
		Seagrass	TER	1670	-462	2203	-529	-558
		Dugongs	TER	1041	-284	1294	-327	-385
	Central	Corals	TER	-441	-520	-464	-606	-606
		Seagrass	TER	608	-130	51	-386	-386
		Dugongs	TER	1555	-400	948	-755	-755
	South	Corals	TER	-580	-622	-622	-619	-635
		Seagrass	TER	-58	-99	-284	-280	-180
		Dugongs	TER	-216	-267	-748	-748	-398
Secondary objectives	Port capacity		Mta	240	240	550	550	550
	Cost of management intervention - govt		$M/yr	460	40	120	40	8
	Cost of management intervention - ports		$M/yr	0	0	30	915	792
	Cost of management intervention - agriculture		$M/yr	0	0	120	8	0

The test of acceptable risk now needs to be considered more closely. In particular, regulators need to assess the extent to which poor outcomes for MNES proxies in one section of the reef can be compensated for by desirable outcomes in other sections. If no such compensation is allowed then none of the remaining three proposals satisfy the requirements for approval. These requirements could only be met if all primary objectives for an alternative were unshaded or green in Table 2.17.

If compensatory trade-offs between reef sections are permitted, the decision problem can be simplified further by summing *Total Estimated Risks* for each of corals, seagrass and dugongs, as shown in Table 2.18. To make the problem even more cognitively accessible, Table 2.18 reports only the total cost of management interventions without a breakdown of who pays. Here it can be seen clearly see that, from the perspective of the regulator charged with protecting MNES, the best alternative is 'E. Cluster ports & lessen Ag impacts'. It outperforms alternatives F and G (and the status quo) on seagrass and dugong objectives and is approximately equally meritorious for corals. For stakeholders representing development interests, the choice among the three alternatives is equally clear and consistent with that of the regulator. The improvement in port capacity is the same across E, F and G, but the costs of management intervention are strikingly more affordable for Alternative E than F or G.

Managers still have a choice to make between Alternative E and the status quo. Returning to Table 2.27, the hypothetical $270M annual cost of management intervention under Alternative E is nominally broken down as a $120M cost to government, a $30M cost to ports and a $120M cost to agriculture. If these parties see sufficient benefits in the development scenario to justify these costs, then formal approval of Alternative E (or some variant involving minor changes) would be sought. Of course, it may be difficult to obtain such a commitment from all three parties. Note that in the hypothetical scenarios, Alternative E includes a 230% increase in port capacity but no change in agricultural productivity. It may not be feasible for agriculture to pay $120M in these circumstances. Where the cost of risk mitigation falls largely to Government the decision on whether or not to instigate development rests on whether the public benefits of the development outweigh the costs of management intervention.

Table 2.18. Collapsed consequence table comparing the performance of alternatives against *E. Cluster ports & lessen Ag impacts*.

		Attribute	B: Status Quo	E: Cluster ports & lessen Ag impacts	F: Cluster ports	G: Spread Ports
Primary objectives	Corals	TER	-2151	-1365	-2234	-2329
	Seagrass	TER	-1250	1411	-1653	-2044
	Dugong	TER	-2268	178	-2889	-3188
Secondary objectives	Port capacity	Mta	240	550	550	550
	Cost of management intervention	$M/yr	40	270	963	800

Importantly, by collapsing section–specific *Total Estimated Risks* into overall summary values, this analysis assumes a unit area at risk in any one section is equivalent in ecological utility to a unit area in any other section. This assumption is plainly naive. Where the ecological value of coral (or seagrass or dugong) in Cape York is considered (on an equal areal basis) to be distinctly greater than coral in the southern section, then the summary consequences reported in Table 2.18 are a poor basis for decision-making. Likewise, if decision-makers are uneasy about compensating poor performance in one part of the reef with better outcomes in other parts then Table 5.4 is inappropriate. It is important to note that Alternative E was associated with strikingly good outcomes in the Wet Tropics, and plainly poor outcomes in the south. The spatial distribution of risk under Alternatives F and G were more even (Table 2.17). To insulate against naive value judgements made using collapsed summary consequences, formal elicitation of trade-offs is required (see Appendix 4).

2.6 Policy and management solutions

The final step in the *CISDM* framework (i.e., step 6, Figs. ES1 and 1.1) represents the decision to implement a management solution or policy revision. Along with step 1 these decisions are the responsibility of decision makers based upon the advice of managers and the cumulative risk assessments developed by scientists. The link between steps 6 and 1 ensures that implementation of the CISDM framework completes the adaptive management cycle (Info Box 6.1), but also that it can accommodate uncertainties posed by a changing environment.

While contemporary policies and management solutions in the Great Barrier Reef World Heritage Area already embrace the principles of adaptive management, a challenge to its effective implementation has been the ability to address multiple pressures in complex ecological systems (GBRMPA 2009). The CISDM framework provides a practical mechanism for model-based assessments of cumulative impacts to inform adaptive management plans. This approach, however, potentially requires a paradigm shift in marine resource management; namely the acceptance of qualitative models based upon expert knowledge and judgements, and probability forecasts based upon future environmental scenarios as the foundations for strategic management decisions. Currently, most decisions are based upon extrapolation from long-term trends in resource condition. The prospect of a changing climate interacting with regional and local-scale land-use activities means that past trends may be poor prognostic indicators of the future conditions of MNES. Application of the CISDM framework provides a transparent and defensible method for making management decisions for complex ecosystems that can be rapidly modified as conditions change and more information becomes available.

Implementation

Effective implementation of the CISDM framework will be dependent upon the availability of information inputs required for each step. For example, clear objectives that define the decision frame and desired outcomes are needed in step 1 to govern the rest of the process. Monitoring and evaluation of the success of individual management solutions is critical to implement the adaptive management cycle. Monitoring information is also required to test and refine the qualitative models, cumulative impact forecasts and inputs to the Bayes nets developed in steps 2 and 3 of the framework.

The CISDM framework relies on qualitative models to provide a causal understanding of the complexities of the ecological processes that sustain MNES, and to predict responses to cumulative pressures and management interventions. They provide a means to integrate knowledge for scientists, managers and other stakeholders, and also inform the design and focus of monitoring programs for MNES and for the effectiveness of management actions. They complement monitoring programs by suggesting or predicting likely patterns of correlation in the monitoring data, and in return, their predictions are amenable to testing by this data. In particular, analysis of the qualitative models can be used to identify the most information rich indicator variables to monitor, both as a means to distinguish the most likely cause of an observed response among multiple pressures, but also as a means to distinguish the most likely model among an array of alternatives. It is expected that most of the qualitative models will be found wanting, and to some degree or another, inconsistent with observations. Here the Bayes nets can be used to ascribe a relative degree of consistency and utility. As knowledge and understanding increase through the monitoring program, and companion research, falsified models will require revision and updating. The models will also require updating as a function of changes in the environment, and also from new technologies or priorities of managers or policy makers.

Current efforts to integrate environmental monitoring programs in the Great Barrier Reef World Heritage Area have already benefited from the draft CISDM framework tools. The qualitative models have been used to assess individual monitoring programs such as seagrass watch and dugong surveys, and consider the efficacy of potential management interventions. In the future, key indicators of resilience and the most sensitive indicators for MNES could be identified and integrated into monitoring programs based upon the qualitative models and Bayes nets. Integration of the CISDM framework components and monitoring programs with spatial data systems would enable the production of dynamic zones of influence and consequence maps. This approach would deliver real-time ecosystem exposure and sensitivity estimates that enable both tactical and strategic management responses. Such a system would provide significant benefits for managers, decision makers and proponents as a readily accessible tool that spatially summarises key ecosystems risks and their causes.

Full implementation of the CISDM framework will require extensive work that is beyond the scope of the current project. The benefits of implementation would be a tool that researchers can use to synthesis the key findings of their work, managers can use to define the spatial and temporal boundaries for assessments, and decision makers can use to transparently make decisions and policy revisions based upon the best available science.

2.7 Framework limitations and caveats

The key strength of the CISDM framework is that it assists users such as marine park managers and other stakeholders make sense of the many pathways of multiple stressors impacting cumulatively on complex ecosystems such as coral reefs. As the framework is qualitative in nature and designed to provide guidance rather than predict precise outcomes, however, a list of limitations needs to be considered when the framework is used in a decision-making context:

- Qualitative basis. Because ecosystem models used in the CISDM framework are qualitative, users can have confidence in the *direction*, but not *precision* of results.
- As a consequence, the framework does not allow prediction of magnitudes of change in pressures or ecosystem values.
- Conditional probabilities for the Bayes nets that are derived from qualitative models depend on a number of assumptions and protocols associated with simulation results from Hosack et al. (2008). These simulations are based on a limited and generic set of model structures that are not specific to those presented in this report. Moreover, the simulations were based on variations in the strength of interactions that are also not necessarily specific to the models presented here. Accordingly, model results presented here are meant only to inform general and relative predictions of system dynamics, without emphasis on precision of the results or the strength of specific relationships between variables.
- Model structures in this version of the CISDM framework are parsimonious and deliberately simplified for the purpose of tractability. Future versions could include the ability to expand nodes or groups of nodes to include key food web components (e.g. predatory fish and links to fishing, or processes not within the scenarios or contexts considered here.
- Zones of Influence (ZOIs) are a highly tractable and practical concept for mapping cumulative stressors, but require a significant elicitation burden on experts, and should ideally be accompanied by model simulations.
- Likewise, estimated effects of management interventions on Bayes net probabilities require expert elicitation and ideally model simulation.
- The Zones of Influence and Zones of Consequence provide spatial representations for model input and output. However, connectivity with respect to source and sink reefs for larval recruitment is not otherwise incorporated in the model. Future iterations of Bayes net models will enable this.
- *Estimated Risk* assumes scaling with probability of change as well as with ecosystem area potentially impacted. Review is required on a case-by-case basis.
- *Total Estimated Risk* assumes that risks in different *ZOIs* are independent and therefore additive. Future versions of the CISDM framework will allow users to account for spatial inter-dependency.

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Appendix 1 - Qualitative Models

Modelling Approach

The use of models for the strategic assessment is guided by a strategy of model building that ultimately seeks a unification of different modelling approaches to better understand, predict and intervene in complex ecological and socio-economic systems (Levins 1966, 1998). The underlying premise is that there are three desired properties of models: generality, realism and precision. A model that attempts to maximize all three properties, however, quickly becomes impractical to apply and difficult to understand. This impasse necessitates a trade-off, where one can choose to emphasize two properties over a third, leading to three alternative modelling approaches.

Quantitative process models.—Models that emphasise precision and realism over generality gain precise predictions for highly specified details of a system's biological and ecological components, processes and relationships. Such models produce precise and testable predictions, and are favoured by mangers who ask "How much do I have to spend on X to get this amount of Y." Such models, however, typically require significant amounts of data to input to a process of parameterization. These models are tuned to the specific context from which their data were drawn (i.e., they lack generality), and thus are not easily transferred to new applications without additional data gathering, adapting the parameters and calibration.

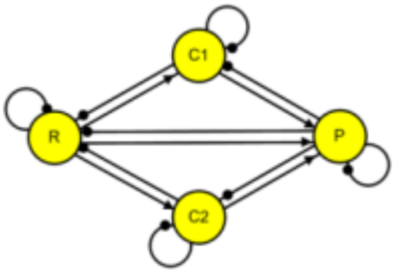
Statistical models.—Models that emphasise precision and generality over realism gain precise testable predictions based on correlations among system variables. Such models are useful for describing general patterns with measured confidence, and are more easily exported to novel situations, but they come with a similar burden of data acquisition as above, and one is left with less understanding of the underlying processes, as correlation is not synonymous with causation.

Qualitative process models.—Models that emphasise realism and generality over precision are free from the constraint of extensive and expensive data collection, and while predictions are not precise, they are nonetheless rigorous in their derivation and testable. Models are based on the qualitative interpretation of processes, and do not require exact specification of functions or parameter values. Here the process of model building requires general questions of: "Does a variable have a positive or negative effect on another variable?; "Is a function increasing or decreasing, above or below a threshold?" Predictions are expressed in terms of directional change in a variable, i.e., increase, decrease, no change, or as inequalities that highlight key relationships or parameters in the system.

Each approach has its own inherent strengths, and each can provide useful results. Models based on each approach will necessarily be derived from different simplifying assumptions, and each purposefully leaves something out about how the world works. The dilemma is not about which approach is better, as each to its own end is incomplete but serves the common goals of understanding, prediction and intervention. Rather, the aim is to confront the problem of complexity with an array of alternative models drawn from each approach. Then, if the different models arrive at similar results, even though they are based on different assumptions, the user has a robust conception about how the world works that is relatively independent of model details (Levins 1966).

Bayes nets are used in this framework to give a probabilistic representation of qualitative models. This representation is based on the relative degree of sign determinacy for qualitative predictions of response (Box 1 below), which is derived from an analysis of the number of possible pathways of influences through the qualitative model (Hosack et al. 2008).

Compared to the system in Info Box 2.1, the signed digraph below is a more complex system, composed of a basal resource (R), two mid trophic-level consumers (C1 and C2), and a top level predator that consumes R, C1 and C2. This added complexity creates multiple pathways with opposite signs between P and R.



Here the predicted response of R due to an input to P is ambiguous, because there are now three paths leading from P to R, two positive (P —● C1—● R, P —● C2 —● R) and one negative (P —● R). The abundance of the resource can thus be predicted to either increase or decrease. This ambiguity can be approached in two ways. One is to apply knowledge of the relative strength of the links connecting P to R. If P was only a minor consumer of R then the R would be predicted to increase. Alternatively, if R was the main prey of P, and C1 and C2 amounted to only a minor portion of its diet, then R would be predicted to decrease in abundance.

It is often the case, however, that the decision maker lacks sufficient knowledge of the strength of the links involved in a response prediction. In these instances a statistical approach developed by Dambacher et al. (2003a) and Hosack et al. (2008) can be used that provides a probability of sign determinacy for response predictions. Through computer simulations, path strengths can be randomly allocated to qualitative models, and the signed determinacy of responses predictions compared to the relative balance of positive and negative paths. Where there are an equal number of positive and negative paths between variables, then an increase or decrease in a variable is equally likely. In the above example with two positively signed paths and one negatively signed path, there is a net of one positive path (i.e. it is considered that a negatively signed path cancels a positively signed path) out of a total of three paths. In computer simulations, a predicted increase in R would occur 77% of the time.

The ratio of the net to the total number of paths in a response prediction has been determined to be a robust means of assigning probability of sign determinacy to response predictions. These probabilities of sign determinacy can then be used as conditional probabilities for Bayes Nets.

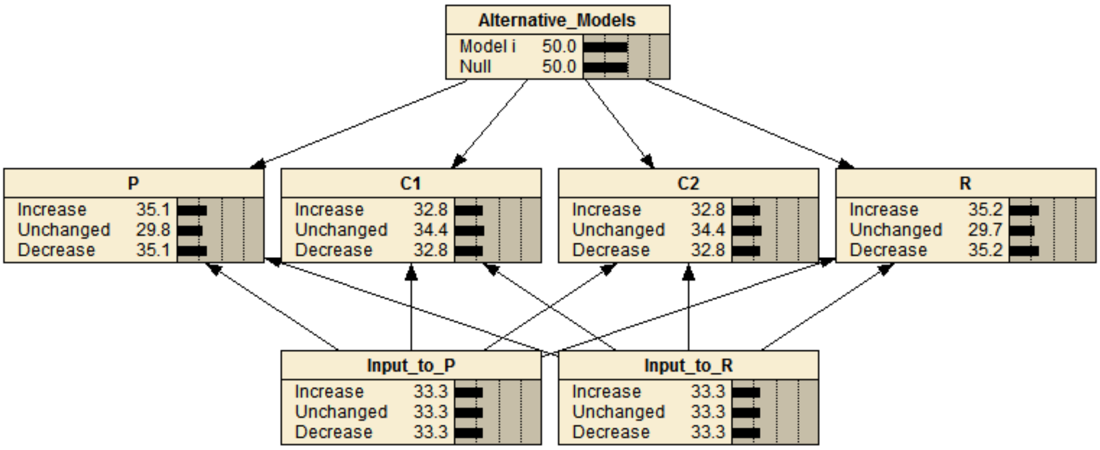
Using a simple but relevant analogy of a pilot flying through clouds, a Bayes net informs to what extent the aircraft is climbing, descending or in level flight. This opens up a set of four opportunities for the manager. Firstly, Bayes nets allow *prediction* of the probability for change in a value node caused by a probability for change in a pressure node. This predictive function is key to the analysis of risks associated with scenario building and structured decision-making.

Secondly, the manager can use Bayes nets to run system *diagnostics* against set objectives. In other words, by setting the objective for a given MNES to, for example, 100% probability of increase, the manager can diagnose what changes in pressure nodes (e.g., nutrients and/or ocean warming are required to meet that objective. This framework mainly uses analyses based on prediction and diagnostics. *Validation* and *sensitivity analyses* are additional analytical functions that are mainly useful to inform the selection of indicators for monitoring programs and evaluation of the effectiveness of management actions.

Bayes nets are derived from artificial intelligence research and are probabilistic tools used to address a wide range of problems, including medical diagnoses (Kahn Jr et al. 1997) and environmental modelling and management (Wooldridge and Done 2004, Wooldridge et al. 2005, Uusitalo 2007). Technically, Bayes nets represent conditional probabilities between variables as a network of nodes with causal links between them analogous to qualitative models, with the exception that Bayes nets are unable to handle feedbacks). Contrary to nodes in the qualitative models, which simply depict ecosystem variables, each Bayes net node contains one or several probability distributions depending on the number of linkages to or from the node. In the framework used here, each probability distribution consists of three likelihood categories: (1) *Increase*, (2) *Unchanged*, and (3) *Decrease*. If a node has no incoming links (i.e., it is a parent node representing an activity or a driver) it has only one probability distribution, which can be manipulated by the user according to scenarios. However, if it is a child node (i.e., a value) with, for example, three parents (i.e., exposures) linking to it, the child node has three probability distributions, one for each combination of possible values of the parent nodes. The probability distributions of the child nodes can be set by experimental data, expert opinion, or in the case of this framework, by converting information from qualitative models using statistical analyses (heuristics) of sign determinacy based on model structure (Dambacher et al. 2003, Hosack et al. 2008).

A significant limitation to Bayes nets is that it is not practical to incorporate feedback cycles into the network's graph structure (i.e., they are almost always acyclic networks), as doing so requires an enormous amount of data and complicated simulations. Thus, in practice, feedback processes common to ecological systems cannot be explicitly included in a Bayes net. The way around this limitation typically involves eliciting predictions from experts of how an ecosystem will respond to a given pressure. However, the models used by an expert to make predictions are typically conceptual constructs and are not explicitly recorded, which makes them difficult to examine, falsify or communicate to the public, each of which are serious limitations to any adaptive research, monitoring or management program.

Hosack et al. (2008) addressed this limitation by providing the means to incorporate the consequences of feedback processes within an acyclic Bayes net, which is accomplished by embedding probabilities from qualitative model predictions within the Bayes net's conditional probability tables. Below is the resultant Bayes net for the above model system.

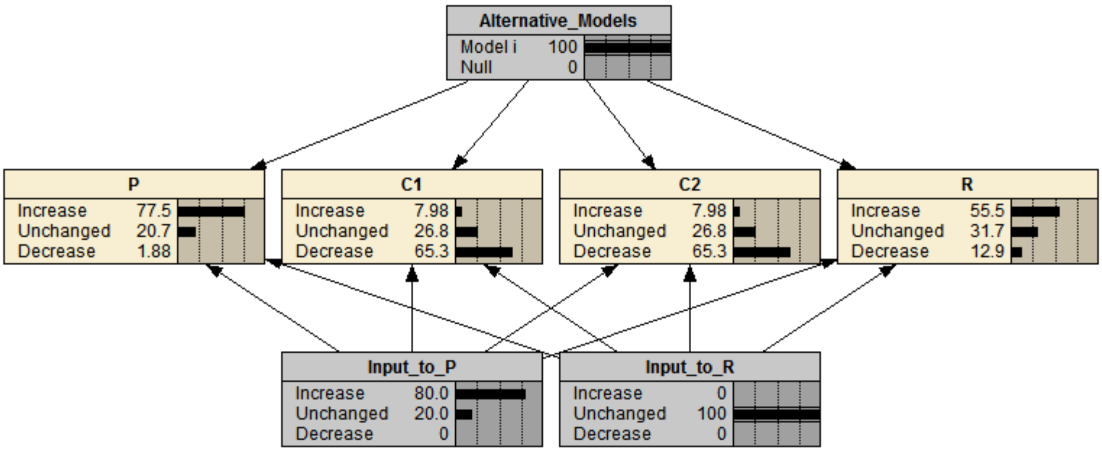


The general structure for a Bayes net derived from signed digraphs starts with a single parent node on the top that represents the probability for alternative models. There is at least one or more alternative model that is compared to a null model, which is a qualitative model that predicts all responses (+, -, 0) for variables with equal probability. In the middle row are child nodes that give the probabilities for qualitative predictions of responses to inputs to the system. These inputs are driven by one or more parent nodes on the lower row of the network. The above Bayes net is shown in a state with no probabilities attributed to parent or child nodes.

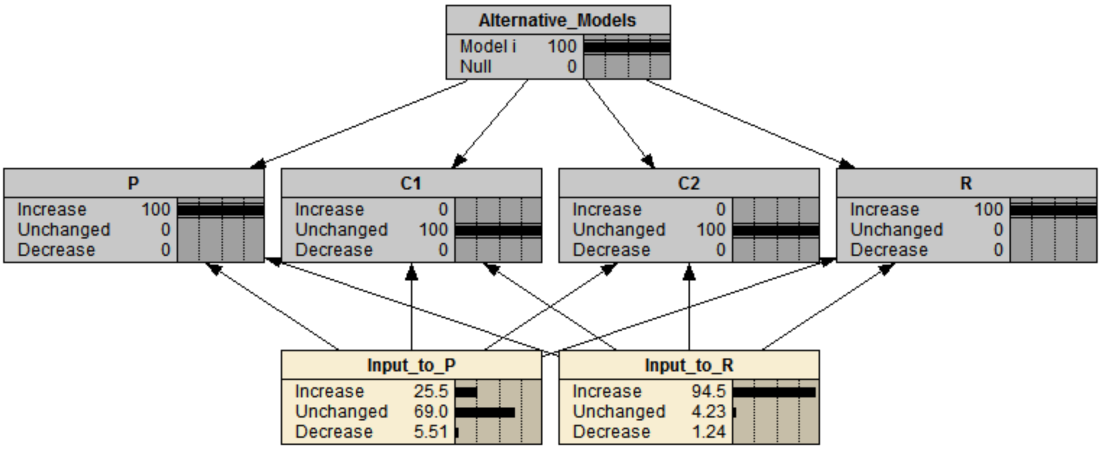
This Bayes net structure allows for four basic analyses: *prediction, diagnosis, validation and sensitivity*. Of these, this report makes its greatest use of prediction and diagnosis, while the latter two analyses are central features of an integrated monitoring and management program.

Prediction.—What is the probability that the equilibrium level of a variable will change given an input to the system? These probabilities are conditional upon the likelihood of an input to one or more of the system's variables and prior belief in the alternative models. In the below scenario, the user may have confidence in the choice of Model (i), but have chosen a likelihood of 80% that there has been an input to variable P. The resulting probabilities for qualitative response predictions are observable along the middle row of nodes. In this work predictions are used to compare the likely consequence of a management action. In the below example, a management action that effects a positive input to P would be judged to most likely be a benefit to P and R, and a detriment to C1 and C2.

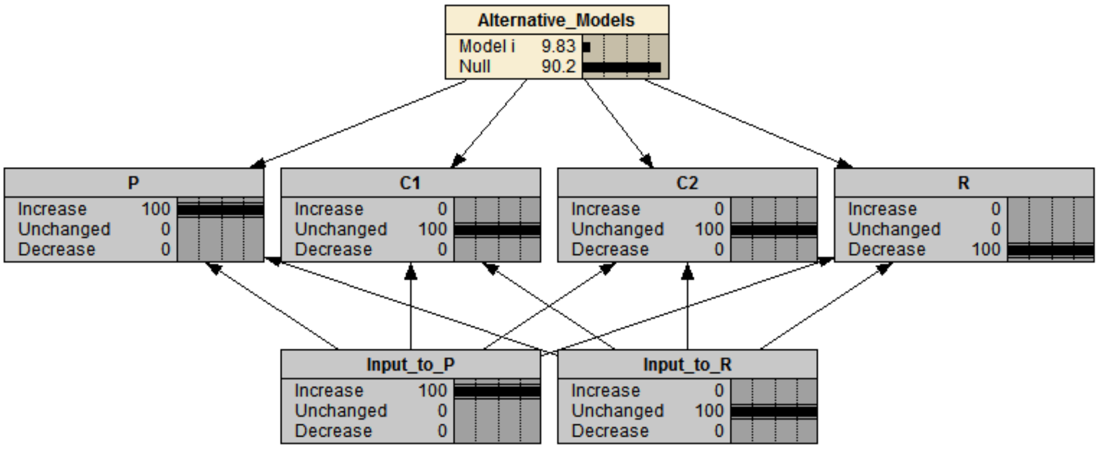
Here an important caveat is repeated from the main text, and stress that when considering the probabilities for the qualitative predictions, it is essential to remember that they are based on a relatively crude measure of sign determinacy derived from analysis of the qualitative models. As such, the reported probabilities are contingent on the context and assumptions that are implicit within the signed digraph models, and also on the particular details of the numerical simulation studies used to generate the probability values (Hosack et al. 2008). Here the use of Bayes Nets for analysis of these probabilities is intended only to highlight large relative differences between model predictions, and the exact value of any given prediction, or small differences between multiple predictions, should not receive undue emphasis.



Diagnosis.—What is the most likely cause of input to the system? Given a prior belief in the correct model structure, and observations of change in the system variables, levels of likelihood are attributed to each of the possible input variables. In the below example an input to R receives a relatively high likelihood (i.e., 94.5%), while only a relatively small likelihood for change (<31.1%) is attributed to P. This framework employs the logic of diagnosis to identify potential management interventions. For instance, if one wished to affect an increase in both P and R, but not in C1 and C2, then the below analysis suggests an effective intervention would be through a positive input to R.

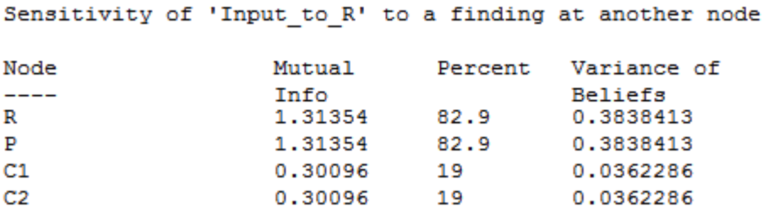


Validation.—How consistent with empirical evidence are the predictions of alternative models? Given user confidence that a perturbation to a system has occurred, and also the level of certainty in qualitative responses of the variables, the user can judge the relative consistency of model predictions with observations, thus allowing model testing and falsification. In the below example, there is complete certainty in the source of input and the direction of change of each variable. Here Model (i) is less consistent with observations than a null model, indicating that it performed worse than pure chance. This function is most useful for judging system understanding and the conceptual model(s) that underpin an integrated monitoring and management program.



Sensitivity.—Which variables are most sensitive to perturbations of other variables? Sensitivity analyses deduce the influence of one variable on another through a measure of mutual information. This analysis is especially useful in deciding which variables to measure or observe in order to test the consistency of competing alternative models, or to efficiently diagnose the most likely source of an input; thus it is especially important for identifying potential ecological indicators for monitoring programs.

For the example system, if the user accepts Model (i) as the most likely model and the user is interested in diagnosing if there has been an input to R, then the below sensitivity analysis suggests that variables R and P would be the most informative (i.e., greatest mutual information) and thus logical priorities for monitoring, while variable C1 and C2 would not.



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Sensitivity of 'Input_to_R' to a finding at another node

Node                Mutual      Percent    Variance of
----                Info                   Beliefs
R                   1.31354     82.9       0.3838413
P                   1.31354     82.9       0.3838413
C1                  0.30096     19         0.0362286
C2                  0.30096     19         0.0362286
```

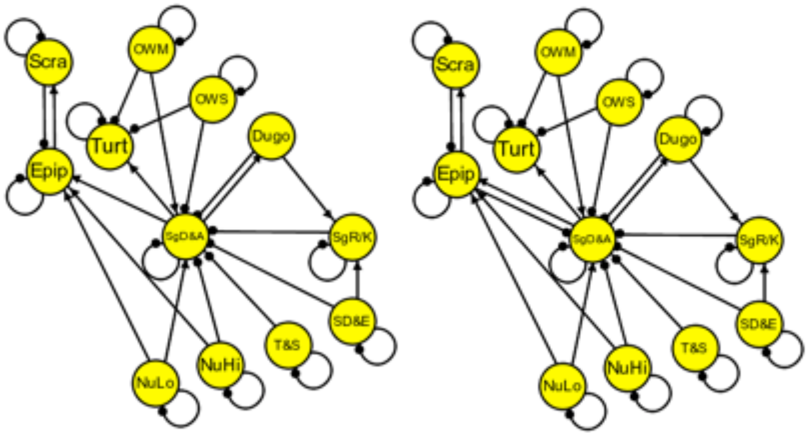
Development of Qualitative Models - Participants in Expert Workshops

Seagrass ecosystems

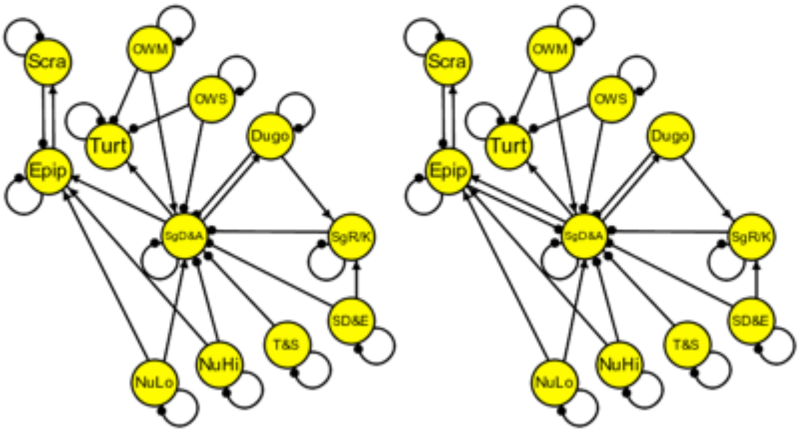
A qualitative model of cause-and-effect relationships between stressors and key selected GBRWHA attributes was completed for GBRWHA seagrass ecosystems in an expert workshop on 10th October 2012. The workshop brought together Australia's leading researchers in seagrasses and associated faunas, GBRMPA managers, water quality experts, and ecosystem modellers:

Dr Rob Coles, Seagrass Watch, Qld Gov/James Cook University (JCU)
Dr Len McKenzie, Seagrass Watch, Qld Gov/ JCU
Dr Michael Rasheed, DAFF
Dr Alana Grech, ARC CoE, JCU
Prof Michelle Waycott, DEWNR, SA
Jon Brodie, Tropical Biology, JCU
Stephen Ban, ARC Coe, JCU
Roger Beeden, RSP Project Manager, GBRMPA
Dr Rachel Pears, RSP Project Manager, GBRMPA
Dr Mark Read, GBRMPA Manager, Species Conservation
Hugh Yorkston, GBRMPA
Dr Katherine Martin, GBRMPA
Donna Audas, GBRMPA
Bronwyn Houlden, GBRMPA
Cherie Malone, GBRMPA Spatial Data Centre
Carol Honchin, GBRMPA
Dr Jeffrey Dambacher, CSIRO
Dr Scott Wooldridge, AIMS
Dr Ken Anthony, AIMS

This first expert workshop established the important module of activities and exposures generic for all ecosystems in the GBRWHA (Fig. 4). Four ecosystem models were elicited covering the range of hypotheses about processes acting in the system (Fig A2.1 below). For examples, some experts question whether epiphytes growing on seagrass leaves were impacting seagrass growth or survival, and to what extent dugongs are exclusively dependent on seagrass for survival.



Seagrass (i) **Seagrass (ii)**



Seagrass (iii) **Seagrass (iv)**

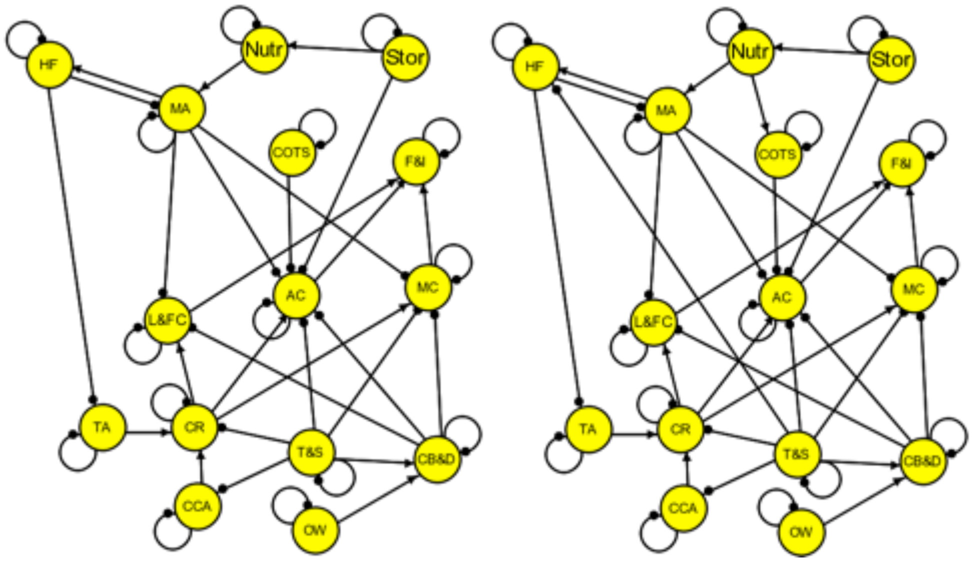
Figure A2.1. Alternative signed digraph models of seagrass ecosystems; Dugo: dugong, Epip: epiphytes, NuHi: nutrients high, NuLo: nutrients low, OWM: ocean warming mild, OWS:ocean warming severe, Scra: scrapers (prawns and fish), SD&E: structural damage and erosion, SgD&A: seagrass distribution and abundance, SgR/K: seagrass *r* versus *K* life-history strategy, T&S: turbidity and sedimentation, Turt: turtle.

Model 1: Epiphytes do not affect seagrasses, dugongs are not density dependent
Model 2: Epiphytes do affect seagrasses, dugongs are density dependent
Model 2: Epiphytes do not affect seagrasses, dugongs are density dependent
Model 2: Epiphytes do affect seagrasses, dugongs are not density dependent

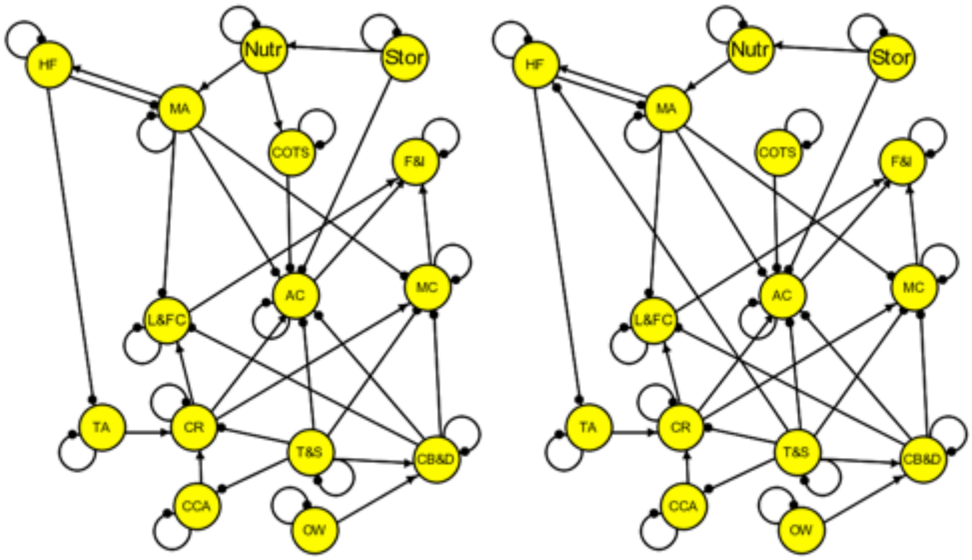
Coral reef ecosystems

This workshop brought together 12 high-ranking scientists considered with expertise in the fields of coral reef biology, ecology and ecosystem modelling. Here, the team built on the pressure and activities module developed in the seagrass workshop and developed four alternative models for coral reef ecosystems (Fig. A2.2 below). The expert team included:

Prof Morgan Pratchett, ARC CoE, JCU
Prof Bette Willi, ARC CoE, JCU
Dr Ashley Frisch, ARC CoE, JCU
Dr Katharina Fabricius, AIMS
Dr Nick Graham, ARC CoE, JCU
Dr Aaron MacNeil, AIMS
Dr Stuart Kininmonth, GBRMPA
Dr Angus Thompson, AIMS
Roger Beeden GBRMPA
Dr Laurence McCook, GBRMPA
Dr Jeffrey Dambacher, CSIRO
Dr Scott Wooldridge, AIMS
Dr Ken Anthony, AIMS



Coral reef (i) **Coral reef (ii)**



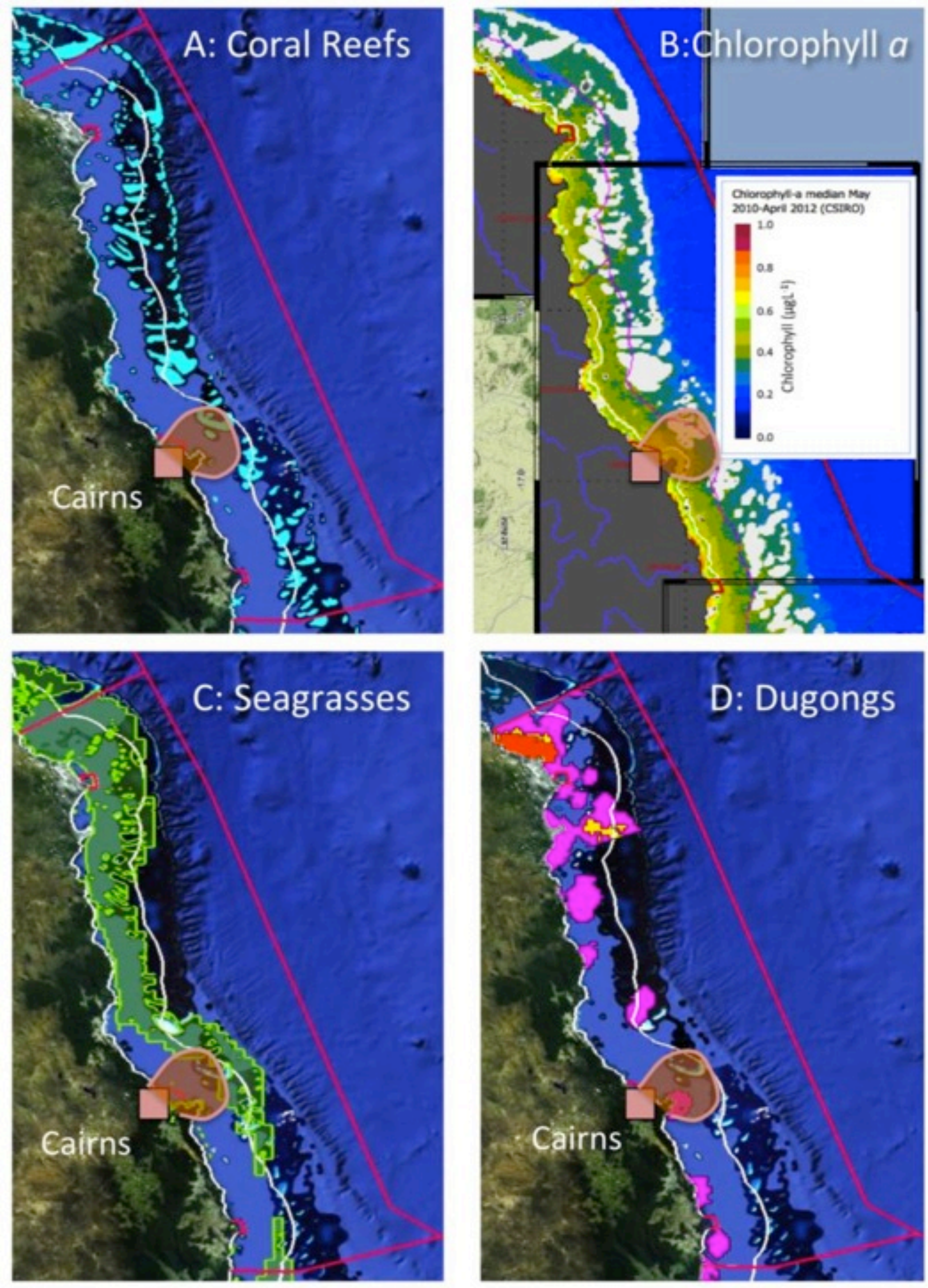
Coral reef (iii) **Coral reef (iv)**

Figure A2.2. Alternative signed digraph models of coral reef ecosystems; AC: *Acropora* corals, CB&D: coral bleaching and disease, CCA: crustose coralline algae, COTS: crown of thorns starfish, CR: coral recruitment, F&I: fishes & invertebrates, HF: herbivorous fishes, L&FC: laminar and foliose corals, MA: macro algae, MC: massive corals, Nutr: nutrients, OW: ocean warming, Stor: storms, TA: turf algae, T&S: turbidity and sedimentation.

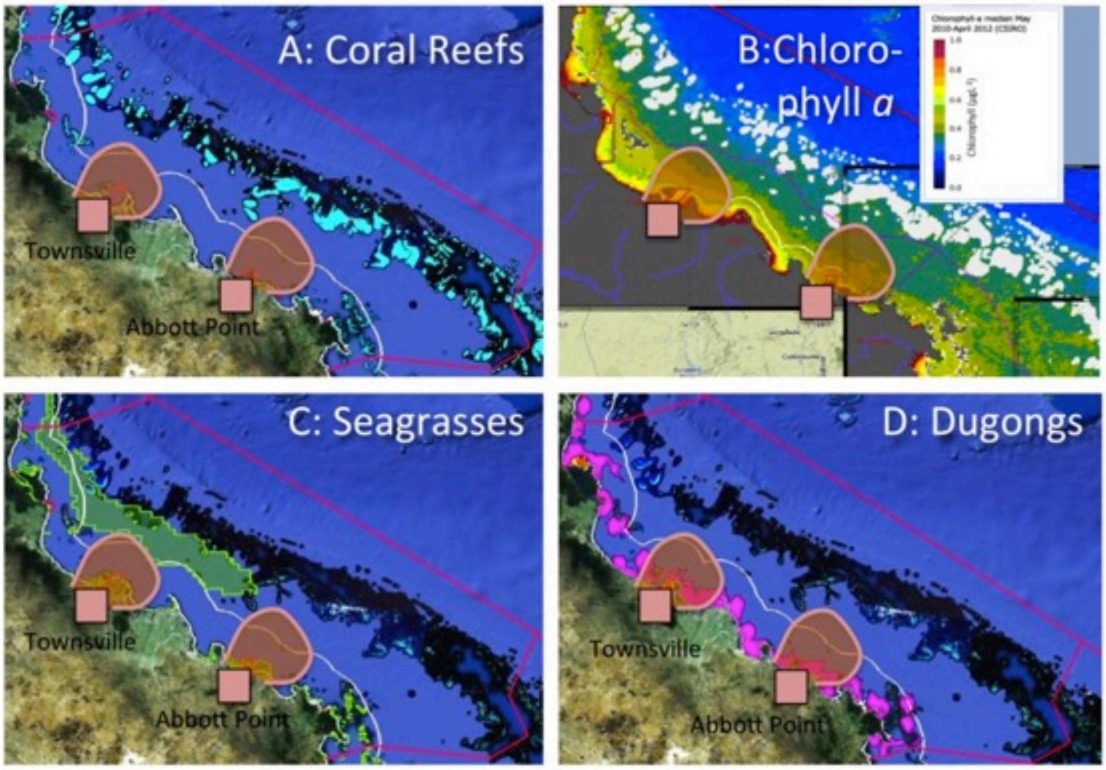
Model 1: Nutrients do not affect COTS, turbidity and sedimentation does not affect herbivores
Model 2: Nutrients do affect COTS, turbidity and sedimentation does affect herbivores
Model 2: Nutrients do affect COTS, turbidity and sedimentation does not affect herbivores
Model 2: Nutrients do not affect COTS, turbidity and sedimentation does affect herbivores

Appendix 2 – Assessment of Cumulative risk

Wet Tropics



Central Section



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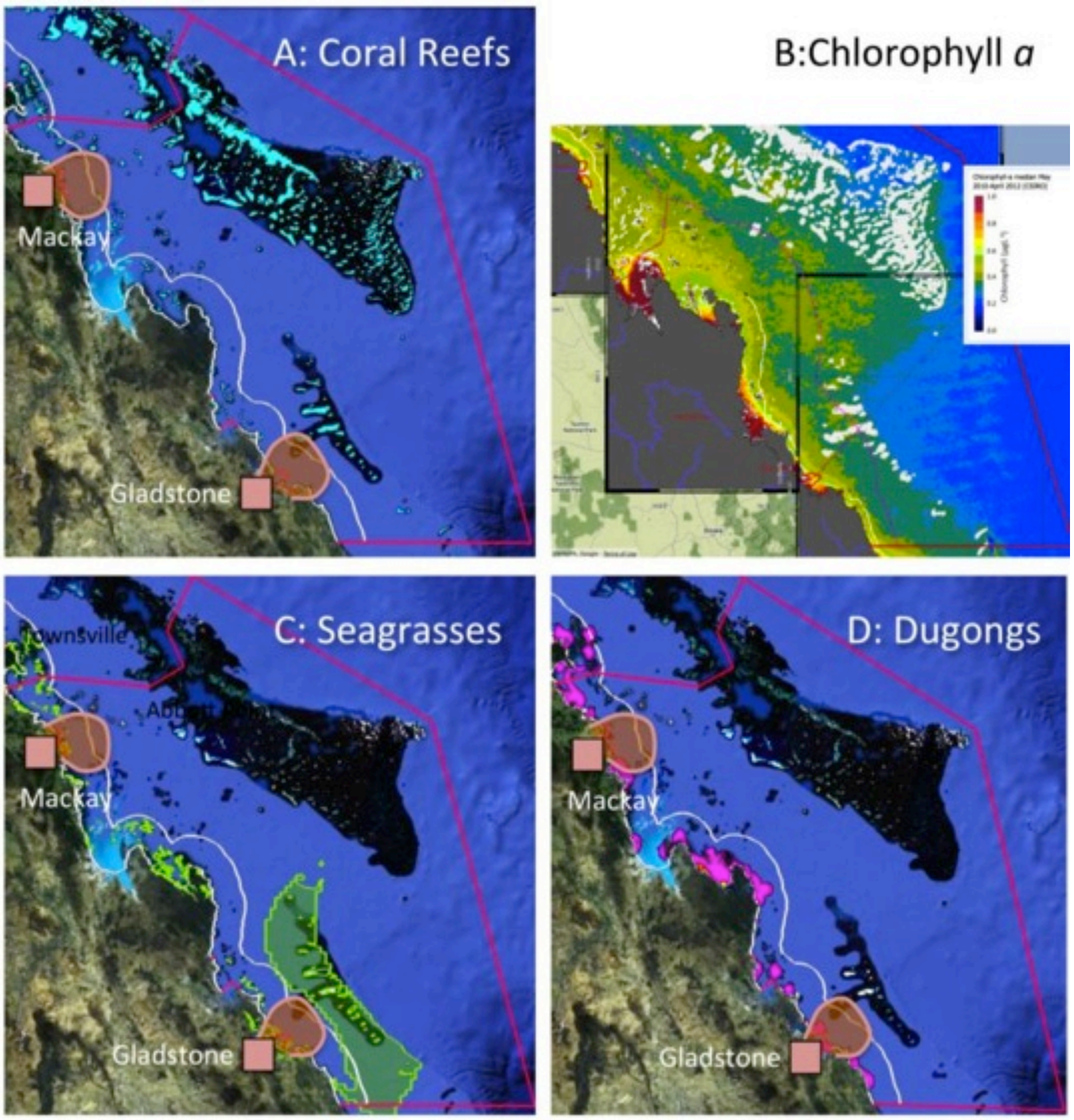

Appendix 3 – Identify risk mitigation alternatives and revisit fundamental objectives

Participants of Stakeholder workshop "Towards informing Environmental Decisions in the Great Barrier Reef World Heritage Area"

Prue Addison (recorder)	Uni of Melbourne
Claire Andersen	Dept of Premier and Cabinet
Ken Anthony (chair)	AIMS
Roger Beeden (facilitator)	GBRMPA
Anthea Bennett	Gladstone Ports Corporation
John Bennett	Dept of Env & Heritage Protection
Ryan Black	Department of the Environment
Scott Condie	CSIRO
Stephanie Cooper	Department of the Environment
Jeffrey Dambacher	CSIRO
Simon Divecha	Adelaide Uni
Simona Duke	North Qld Bulk Ports
Josh Gibson	GBRMPA
Bronwyn Gillanders	Adelaide Uni
Margaret Gooch	GBRMPA
Katrina Goudkamp	GBRMPA
Claire Hanratty	GBRF
Emma Heywood	Department of the Environment
Tom Kaveney	BHP Billiton
Annie Keys	Department of the Environment
Russell Kelley	Russell Kelley
Phillip.Kohn	Coordinator-General
John Lane	Dept of Env & Heritage Protection
Lyndon Llewellyn	AIMS
Peter McGinnity	GBRMPA
John Olds	National Parks
Rachel Pears	GBRMPA
Julia Playford	DSITIA
Mark Read	GBRMPA
Richard Quincey	GBRMPA
Mike Ronan	Dept of Env & Heritage Protection
Britta Schaffelke	AIMS
Chloe Schauble	GBRMPA
Vern Veitch	Deputy Mayor, Tsv City Council
Peter Vidler	Dept of Transport and Main Roads
Terry Walshe	Uni of Melb (facilitator)
Andrew Walls	DEEDI

Appendix 4 – Alternatives, Consequences and Tradeoffs

Multi-attribute value theory (MAVT)

The description of MAVT that follows is adapted from Bedford and Cooke (2001) and (Keeney 2007). The task of MAVT is to find a simple expression for the decision-maker's value function *v* over two or more relevant attributes. The additive value model is commonly used, in the form

$$v(x_1,\ldots,x_n) = \sum_{i=1}^{n} w_i v_i \left(x_i\right)$$

where the w_i are the weights and the v_i are marginal value functions.

A marginal value function is a value function for any single attribute in isolation (Figure 1). A formal way of eliciting a marginal value function is as follows. Suppose that the user wants to determine a value function for x_1. Write the vector of attributes exclusive of x_1 as $\underline{y} = (x_2,\ldots,x_n)$. The user can pick two values for the attribute x_1, say $l < h$, and arbitrarily assign $v_1(l) = 0$ and $v_1(h) = 1$ (assuming that lower values of the attribute are worse than higher values). The user would now want to interpolate and find a number $m_{0.5}$ between *l* and *h* so that $v_1(m_{0.5}) = 0.5$ (see Figure 2 below). To do this the user can pick a value for the other attributes, $\underline{y}$, and seek a 'worse' value for the other attributes $\underline{y}'$ so that for some $m_{0.5}$ between *l* and *h*,

$$(l, \underline{y}) \sim (m_{0.5}, \underline{y}'), \text{ and}$$

$$(m_{0.5}, \underline{y}) \sim (h, \underline{y}').$$

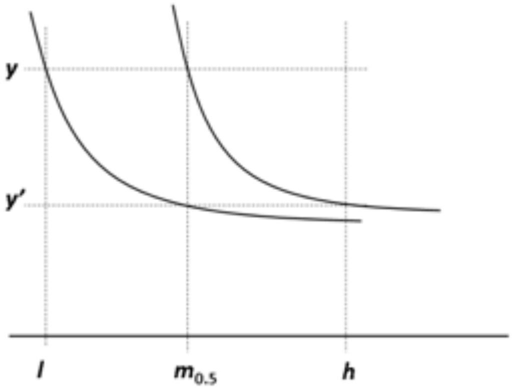

Figure 2. Formal elicitation of a single attribute value function.

Writing $v_{\underline{y}}$ for the weighted sum of the value functions in $\underline{y}$ produces

$$v_1(l) + v_{\underline{y}}(\underline{y}) = v_1(m_{0.5}) + v_{\underline{y}}(\underline{y}'),$$

$$v_1(m_{0.5}) + v_{\underline{y}}(\underline{y}) = v_1(h) + v_{\underline{y}}(\underline{y}'),$$

which together gives $v_1(m_{0.5}) = 0.5$. In this (laborious and cognitively demanding) way the decision analyst can interpolate the value function for as many points as desired. The same procedure is required for each attribute.

A common simplification is to assume linearity between $v_1(l) = 0$ and $v_1(h) = 1$. It avoids the tedious demands of formal elicitation and is reasonable over the local range of consequences associated with most problems (Durbach and Stewart 2009)((Keeney and von Winterfeldt 2007).

Having obtained marginal value functions the user needs to weight them. This can be done formally by the method of indifferences, akin to the underpinnings of stated preference techniques used in evaluation of non-market impacts in benefit-cost analysis (Bennett and Blamey 2001). Suppose that x_1 and x_2 are the first two attributes, and that $\underline{b}$ is the vector of remaining attributes. Let x_1^* and x_2^* and $\underline{b}$ * be the attribute values for which the marginal value functions are zero. Then find values $x_1 \neq x_1^*$ and $x_2 \neq x_2^*$ such that

$$(x_1,\ x_2^*,\ \underline{b}\,^*) \sim (\,x_1^*, x_2,\ \underline{b}\,^*)$$

then $w_1v_1(x_1) = w_2v_2(x_2)$. Proceeding this way the user can get $n - 1$ linear equations relating weights (without loss of generality it can assumed that weights sum to 1), and solve for the w_i. Again, the method is laborious and cognitively demanding.

There are many shortcut methods for eliciting weights (Hajkowicz et al. 2000). Of these, the swing weight method has been shown to be one of the more effective, both in terms of its efficiency and its insulation against abuse (Fischer 1995). Whatever method is used in their elicitation, the interpretation of the weights is critical. Methods that do not explicitly deal with indifferences are prey to abuse. Users are inclined to specify weights that reflect the relative importance of the attributes, irrespective of the units or the range of consequences relevant to the decision context. But the weights have units because the underlying attribute scales have units. A change of $-w_i^{-1}$ units on scale i is always compensated by a change of $+w_j^{-1}$ units on scale j. Changing the units or range of an attribute *must* lead to a change in the weights.

For the *additive* value model to be valid the attributes need to be *mutually preferentially independent*. That is, the value ascribed to any given amount of attribute i cannot be conditioned by the level available of attribute j.

In practice, the assumption of preferential independence is reasonable if the set of objectives is consistent with the following properties (Keeney 2007):

- Complete – all of the important consequences of alternatives in a decision context can be adequately described in terms of the set of fundamental objectives.
- Non-redundant – the fundamental objectives should not include overlapping concerns.
- Concise – the number of objectives should be minimal.
- Specific – each objective should be specific enough so that consequences of concern are clear and attributes can readily be selected or defined.
- Understandable – any interested individual knows what is meant by the objectives.

Where objectives satisfy these properties there is a strong case for use of simple weighted summation. While the analyst needs to be careful to ensure preferential independence, the mechanics of MAVT are straightforward. Arithmetic operations are simple and easy to implement in a spreadsheet.

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Marine Park Authority