Marine Biodiversity Hub

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Technical Report describing Guidelines for analysis of cumulative impacts and risks to the Great Barrier Reef (Part 1)

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Important Disclaimer

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EXECUTIVE SUMMARY

The purpose of this document is to provide guidance on the assessment of cumulative risks and impacts in the Great Barrier Reef (GBR). The guidance is intended to be applied at a regional or plan of management level, and at a development application level. The guidance details the necessary concepts and outlines a series of steps to work through and link multiple pressures with their impacts on identified values. It is not meant to replace existing frameworks and guidance for standard environmental risk assessments, rather it is intended as a supplement to these approaches that facilitates the understanding and assessment of cumulative impacts in complex ecosystems of the GBR.

For each step, this guidance provides criteria to select the appropriate tools or methods to use in cumulative impact analysis. The tools and methods identified will provide robust assessments and will reduce the uncertainty at each step. While a full and rigorous environmental risk assessment can take various forms and have many steps, this guidance is specifically designed to address analysis of cumulative impacts within a standard risk assessment framework. Beyond the guidance provided in this work, we anticipate the need for a “tool-box”, largely internet based, to provide access to existing and developing resources and approaches for completing the more technically challenging steps of the risk assessment. This report (Part 1) describes the steps in the guidelines and their application. Part 2 will describe a detailed case study from the GBRMPA region and a plain language summary that can be used by proponents and regulators as an entry point to the technical guidelines contain summaries, specific to Great Barrier Reef Marine Park Authority (GBRMPA), Queensland (QLD) State Government and Department of Agriculture, Water and the Environment (DAWE).

KEY STEPS IN CUMULATIVE IMPACT ANALYSIS

Step 1 Understanding Pressures

For the area under consideration for the plan of management, the intensity and distribution of pressures should be mapped. This should include consideration of both the spatial intensity and the temporal pattern.

Step 2 Understanding Values

The environmental values of the GBR have been described as having outstanding universal value and are listed as a Matter of National Environmental Significance (MNES) under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act). There are a great number of values identified in GBR, and the values of any location within the Reef can be ecological, social, economic or cultural. All these values have a spatial component; thus, a practical approach to systematically assess cumulative impacts is to use habitats as a proxy for the values they contain. Environmental, social, cultural and economic values can be identified within these habitats as being derived from components (i.e., species, habitats, processes) of GBR ecosystems, and should be identifiable with conceptual system models.

Step 3: Conceptual Models of Key Habitats

Conceptual models need to portray the ecological system at a level of resolution that is useful to the purposes of the risk assessment, striking a balance between simplicity and complexity. The level of resolution should be checked against the pressure and values identified to ensure that values that occur in the habitats can be included in the conceptual models and that the pressures acting on those values, can also be included.

Step 4: Zone of Influence

The zones of influence that define the spatial extent over which a pressure influences a value need to be mapped spatially but can also be presented in tabular format. Iterative steps between identifying the zone of influence and defining the conceptual models may be required to ensure that derived assessment and measurement end-points are meaningful and measurable.

Step 5: Risk Assessment and Uncertainty

The existing impacts and potential risks of new activities or development projects that can potentially affect values need to be calculated. Cause-effect models can be used to identify measurement end-points for each of the assessment end-points associated with the values. The cumulative impact of existing and potential pressures should be calculated for each measurement endpoint. Risks of each new activity can be compared against the desired environmental condition.

1. INTRODUCTION

The analysis of cumulative impacts represents a major challenge for managers, proponents and scientists. Pressures from one or more sources may interact and result in non-linear consequences, and can be the product of different exposures, time lags, or threshold responses (Johnson 2016). Cumulative impacts can result from a single activity repeatedly producing a single pressure, a single activity producing multiple pressures, multiple activities producing a single pressure, or multiple activities producing multiple pressures (Foley et al. 2017). Uthicke et al. (2016) provide examples of cumulative impacts caused by both single and multiple pressures. Despite their familiarity, cumulative impacts are challenging to identify and monitor and the lack of an approach to identify and manage cumulative impacts in the marine environment was highlighted in the State of the Environment Report 2016 (Evans et al. 2018).

Cumulative impacts can be of four general types: additive, synergistic, antagonistic (compensatory) and masking (Crain et al. 2008; Folt et al. 1999; Hegmann et al. 1999; Noble 2010; O et al. 2015; Seitz et al. 2011; Sonntag et al. 1987). Additive impacts are incremental additions to, or deletions from, a fixed storage where each increment or deletion has the same individual impact (Hegmann et al. 1999; Sonntag et al. 1987). Synergistic impacts (also referred to as amplifying or exponential impacts) magnify the consequence of individual pressures to produce a joint consequence that is greater than their additive impacts or risks. Antagonistic or compensatory impacts produce a joint consequence that is less than additive, and masking impacts produce essentially the same consequence for the ecosystem or social component as would occur with exposure to one of the pressures alone.

An additive approach is considered a reasonable first approximation of cumulative risk where there is little information available (O et al. 2015). Studies have found that while evidence shows synergistic and antagonistic interactions are common, when examining cumulative impacts from multiple pressures, the interactions are generally additive (Crain et al. 2008; Darling and Cote 2008). An additive approach is considered precautionary based on the assumption that it will overestimate cumulative impacts that are antagonistic or masking (O et al. 2015); however, the impacts may be underestimated using this approach if the interactions between pressures is synergistic. Determining how different pressures interact is therefore important to the rigor of a cumulative impact assessment.

Studies have examined cumulative impacts on habitat types in marine ecosystems at global (Halpern et al. 2008; Vorosmarty et al. 2010), and regional scales (Ban et al. 2010; Clarke Murray et al. 2015b; Foden et al. 2011; Grech et al. 2011; Halpern et al. 2009; Korpinen et al. 2012; Micheli et al. 2013; Selkoe et al. 2009). Less frequently, assessments are applied at the level of species (Maxwell et al. 2013) and ecosystem (Allan et al. 2013). The spatial and temporal scale of the disturbance or proposed project is a key factor in cumulative impact assessments. Many projects or disturbances concentrated in a small area over a short time can result in cumulative impacts related to a crowding effect (Johnson 2016). An area may be resilient against some level of disturbance, but if that level is exceeded faster than the natural recovery rate, then the disturbance could exceed an ecological or societal threshold for a valued component (Johnson 2016).

Cumulative impact assessments are considered an initial step towards accounting for cumulative impacts on ecological components in ongoing environmental assessments (Clarke Murray et al. 2014) and have long been considered an essential part of the environmental impact assessment (EIA) toolbox (Stelzenmüller et al. 2018). Cumulative assessments encompass a broad set of approaches and are focused primarily on the most valued components of the system.

Cumulative impacts can also affect social and economic aspects of a system. They can be experienced by people who are exposed to a recurring number of environmental events in which a special natural resource is continuously degraded, or in which a series of institutional changes are consecutively implemented to better protect a natural resource. In both instances, people are apt to feel social impacts associated with the loss of, or access to, the resource. Depending on the nature of the relationship, the accumulation of social and economic impacts can result in severe social consequences and can erode the ability of people to cope and adapt (Marshall and Marshall 2007, Marshall et al. 2007).

Perhaps the most recent is the effect of two consecutive massive bleaching events on the Great Barrier Reef. The social effect has been termed, ‘reef grief’, in which about half of all residents, tourists, and tourism operators and about a quarter of all commercial fishers have reported high levels of grief associated with the decline of the coral reef (Marshall et al*. in review*). Similarly, policy changes can be introduced too rapidly, or too frequently, and can accelerate the rate at which thresholds of coping are reached. In many instances, the costs and benefits of resource protection are redistributed and can alter the social dynamics within a community (Marshall 2007). Once thresholds are reached, the resilience of resource-dependent people is eroded, and this can be detrimental to effective resource governance.

1.1 Context for cumulative impact assessment

The Reef 2050 CIM Policy highlights the need for evidence-based approaches and greater integration of risk assessments with whole-of-reef monitoring and adaptive management programs. Fig. 1 is a fully detailed depiction of standard ecological risk assessments, where risk assessments can generally be divided into three successive stages. The first stage is devoted to determining the scope of the assessment. Key outputs of this first stage include determination of the spatial scale of the assessment, a set of assessment and measurement endpoints, an agreement on risk acceptance criteria for measurement endpoints, and selection of methods and models to be used in the calculation of risk. In the second stage a calculation of risk is made with an associated level of uncertainty. The resulting calculations are then compared with risk acceptance criteria within the context of a risk management process. The third and final stage involves the monitoring and validation of the assessment. It should be noted that while Fig. 1 attempts to depict all possible steps and processes, not all may be necessary in any one assessment, but are shown here for comparison, a means to identify gaps and a framework for integrated monitoring and management. This guidance document is meant as a supplement to standard ecological risk assessment practices to better meet the needs of the GBR cumulative impact management (CIM) policy.

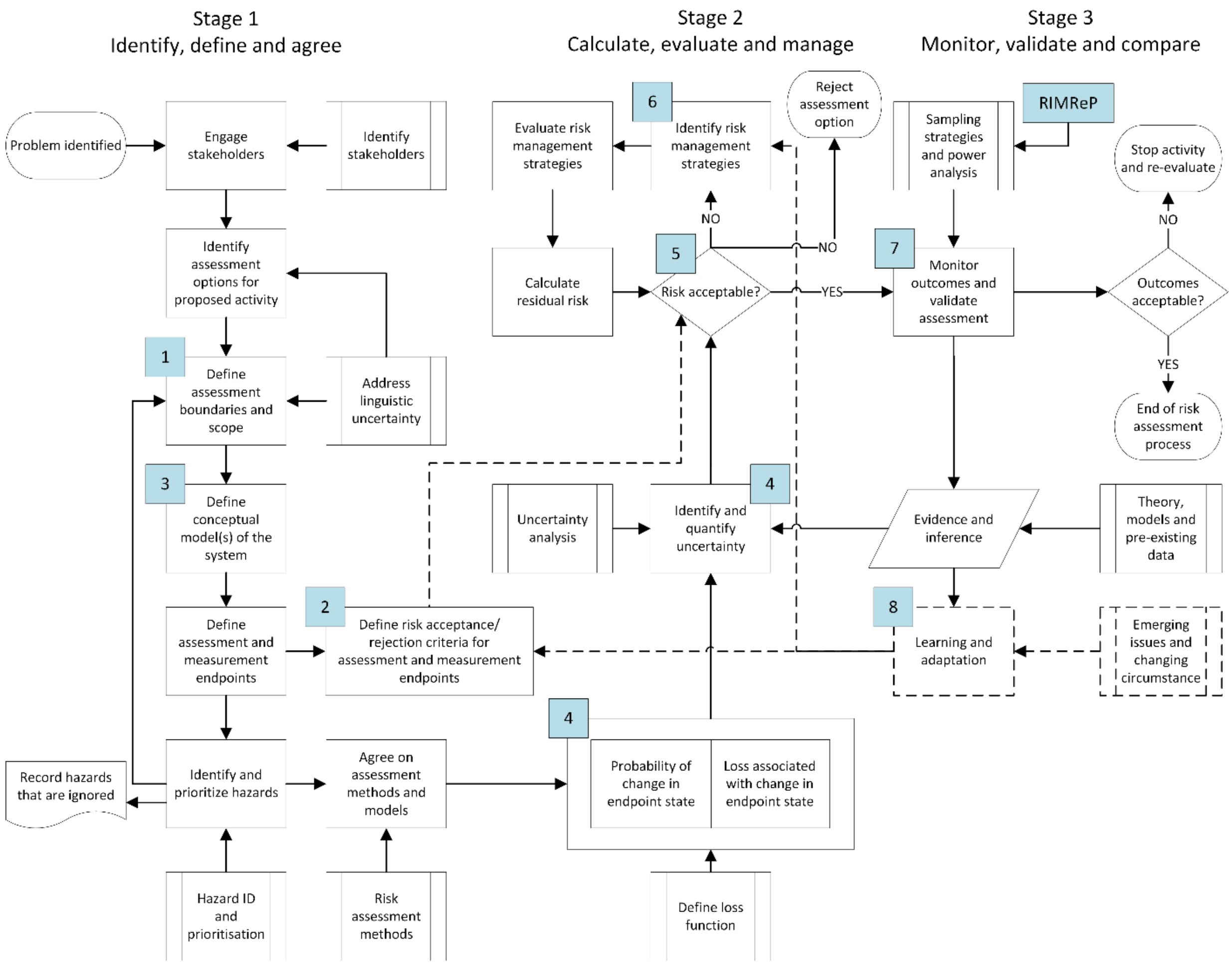


Figure 1. Detailed depiction of evidence-based environmental risk assessment and management processes, with three general stages devoted to scoping, risk calculation and management, and monitoring and validation (adapted from Hayes et al. 2007 and Stirling et al. 2018). Numbered boxes correspond to steps emphasized in the GBR Cumulative Impact Management Policy (Table 1), dashed lines represent pathways and processes added to the framework to enable decision making and adaptive management encouraged by the Policy, with sampling designs being informed by guidance from the Reef Integrated and Monitoring and Reporting Program (RIMReP).

The CIM Policy emphasizes eight steps of the assessment process (Table 1) and includes the main features of a standard assessment (i.e., see numbered blue coloured boxes in Fig. 1), with steps 1–7 covering off on key processes within each of the three assessment stages. In standard ecological risk assessments, there is typically a discrete timeline for the risk assessment and management process. Applications for individual development projects eventually come to a juncture where the application is either denied, or the project is successfully realized, and the assessment is validated, at which point there can be a conclusion to the risk assessment process. The assessment of cumulative impacts in the GBR, however, will more typically occur at scales much larger than an individual project (e.g., GBR Strategic Assessment and Outlook Report), which requires consideration of expanded spatial and temporal scales.

Table 1. Steps for cumulative impact assessments emphasized in GBR Cumulative Impact Management Policy (GBRMPA 2018).

1. Determine the program, plan or project area boundaries based on an understanding of likely direct, indirect and consequential impacts of the decision.
    a. Identify the relevant drivers, pressures and impacts; the space and time scale at which they occur; and any planning or project-specific contributions.
    b. Identify affected values, the space and time scale at which they occur, and consider connectivity between values.
2. Determine the current condition of affected values, and their desired state.
3. Examine the cause and effect of planning, program or project-specific impact contributions.
4. Undertake a risk assessment.
5. Compare the outcome of the assessment with the desired outcome for the state of the value or process and relevant standards and guidelines.
6. Design and apply management measures based on the mitigation hierarchy.
7. Monitor evaluate and report.
8. Drive continuous improvement by adapting plans, programs and actions in response to new information, emerging issues and changing circumstances.

Taking a long-term approach, the CIM Policy also calls for the introduction of adaptive management into the assessment process (step 8, Table 1). This necessitates the modification of the standard risk assessment framework (*i.e.*, dashed-line processes and links in Fig. 1). Making this adaptive process fully functional within the framework will require a greater emphasis by managers to define desired outcomes and desired future conditions, and a tighter coupling of these with predefined risk acceptance-rejection criteria and management strategies. The Reef Integrated Monitoring and Reporting Program (RIMReP) also provides a key role in administering guidance and development of monitoring designs and protocols.

The overall approach of this document is aimed at supplementing and facilitating assessment of cumulative impacts through five general steps: 1) Understanding Pressures, 2) Understanding Values, 3) Conceptual Models of Key Habitats, 4) Zone of Influence and 5) Risk Assessment and Uncertainty. The first four of these establish the scope of the assessment through the combination of values, pressures and conceptual models to define a zone of influence for a given pressure and value. Outputs from these steps provide the key ingredients for the identification of risk assessment endpoints, the selection of assessment methods, and the calculations of risk and uncertainty. Guidance is provided within the risk calculation step by providing the means to assess the sufficiency of methods and models against the relative complexity of the underlying ecological system, with the intent of providing clarity where risk is judged and managed.

2. GUIDANCE FOR ASSESSMENT OF CUMULATIVE IMPACTS AND RISK

The CIM Policy identifies the assessment of the existing cumulative impacts as an important step in the development of new regional management plans, such as the GBR Plans of Management, and in the approvals process for new activities and developments. Meeting this requirement will require a mapping of the current state of the marine environment, the values that have been identified, the pressures occurring in the region, and the risk of potential impacts to those values. A key ingredient will be the description of the desired environmental condition for each of the values that have been identified with predefined risk acceptance and rejection criteria. An understanding of how impacts from multiple pressures interact is a desirable feature of the assessment.

Necessary preconditions to enable cumulative impact analysis

This information needs to be comprehensive to the level required by GBRMPA and readily accessible to proponents.

1. Desired environmental status or conditions for identified values and habitats should be described at the scale of plan of management or regional scale. These desired conditions should inform assessments of projects and developments proposed within a given region.
2. Indicators should be described that are relevant to the current state of environmental conditions.
3. Key GBR habitats should be described and identified spatially to the best resolution possible.

2.1 Step 1: Understanding Pressures

For the area under consideration, the intensity and distributions of pressures should be mapped. This should include consideration of both their spatial intensity and temporal pattern.

2.1.1 What types of pressure are there?

The spatial footprint of pressures can be classed as:

- restricted (located under the footprint of pressure - direct)
- dispersed (spreading beyond the footprint – indirect)
- regional

The temporal footprint can be:

- repeated
- simultaneous
- chronic

Considering all potential pressures, including climate change, within and adjacent to the planning region is required to identify emerging risks.

Example 1. Footprints and pressures

Restricted pressures may include fishing or physical disturbance due to construction of infrastructure and moorings. **Dispersed** footprints may include sediment discharge from a source, eutrophication and other water-borne pollutants. **Regional** footprints may include biological pressures such as crown of thorns starfish, increasing marine heatwaves, acidification or cyclones.

Repeated footprints are pressures were the same pressure is repeated in multiple, but separate activities. Commercial fishing is an example of a **repeated restricted** pressure. **Simultaneous** pressures occur at the same time but have different footprints. Construction of infrastructure may have generated multiple **simultaneous** pressures such physical disturbance, sedimentation and noise, all of which will have different spatial footprints. Finally, **chronic** pressures are present within an area all the time. For example, increases in ocean acidification will apply a chronic pressure to the entire GBR.

Available spatial data tend to be related to activities, not on the scale of the pressure itself (Ban et al. 2010), with few exceptions (e.g., spatial data obtained from noise propagation models). Activity categories should be split as far as the data will support and is appropriate for the analysis, and it should also capture the temporal scale of the activity (repeated, simultaneous, or chronic) and the spatial footprint (restricted, dispersed, and regional). Activities categories should be mapped to individual pressures (e.g., the noise from activities, their direct physical footprint, and dispersed footprint should all be separated), allowing the GIS representation of the data to be grouped if required.

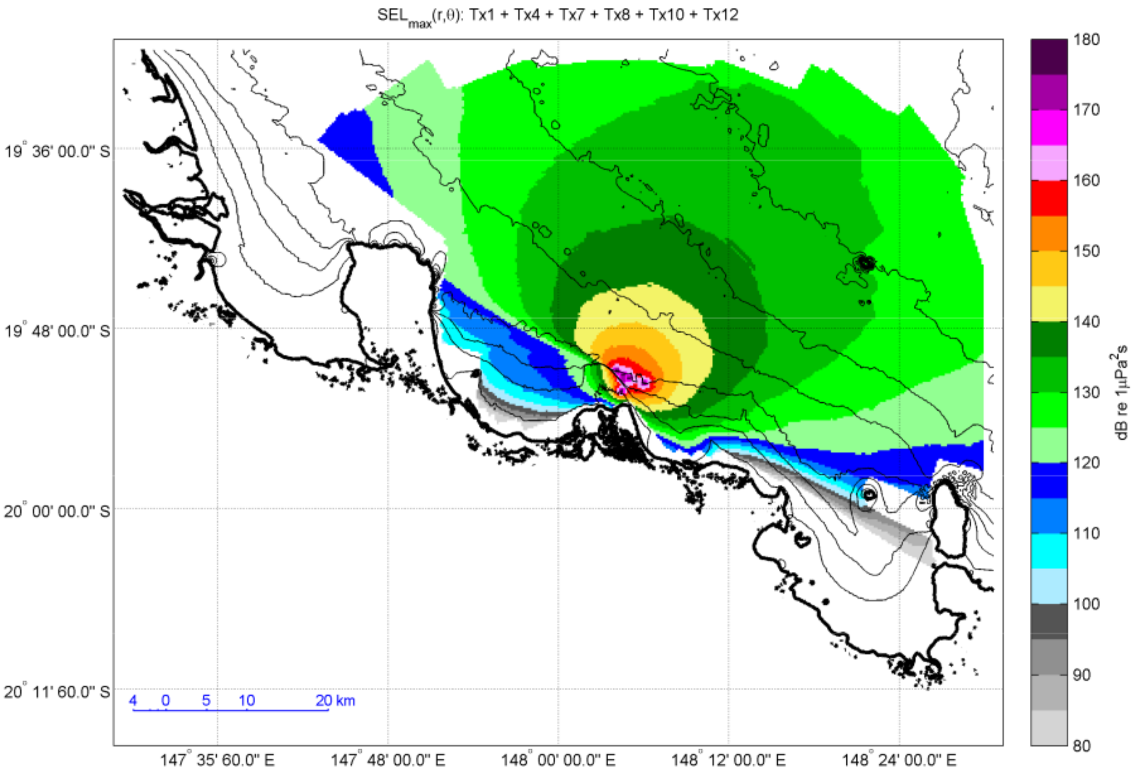
2.1.2 Checklist for the assessment of pressures

There are many approaches that can be used to map pressures (*e.g.*, GIS, spatial interpolation, and dynamic models) and it can be difficult to specify a single model that is appropriate in all circumstances. However, the characteristics of good approaches can be summarised from the scientific literature and existing applications (*e.g.*, Abbot Point CIA, GBR Strategic Assessment). Below is a checklist of considerations to conduct pressure mapping and identify sufficient models. Distinct applications should be tested against these characteristics to ensure that the mapping is adequate. Where a particular mapping of pressure does not adequately address one or more of these characteristics then it should attract a concomitant level of uncertainty that is propagated through the calculation of risk.

Specific Questions	**Caveats**
Data Availability	
Is there sufficient data available on pressures for the area of interest?	If no, consider not undertaking assessment until sufficient data is collected, modelled or sought through expert opinion OR apply the precautionary principle and assign high potential impact for those areas of interest with unknown pressures
Are available data on different pressures at comparable spatial and temporal scales?	if no, caution needs to be taken to ensure that the spatial and temporal scale are appropriate to enable estimation of impact
Is there data on the historical distribution and intensity of the pressures?	if no, historical impacts will not be able to be estimated
Do the available pressure data have comparable resolutions for all pressures considered?	if no, differing resolutions may mean some pressures are given a higher weighting than would otherwise be expected.
Are empirical data available or are the data inferred, modelled, or based on expert option?	if empirical data is not available then additional questions should be addressed as below
If the presence of the pressure is inferred from models or expert opinion the following additional characteristics should be considered.	
Does the model/expert opinion incorporate uncertainty into the pressure estimate?	if no, additional caution should be applied to the estimate of pressure
What is the confidence in the spatial prediction (if appropriate)?	if low, additional caution should be applied to the estimate of pressure
What is the confidence in the temporal prediction (if appropriate)?	if low, additional caution should be applied to the estimate of pressure
Does the model generate measurable outputs or scores that can be compared with observed pressure status?	if no, the model cannot be verified and should be treated with significant caution.
Does the model/expert opinion consider the maximum potential value of pressures?	if no, the maximum value of the pressure needs to be estimated so that the maximum potential impact can be calculated
Does the model/expert opinion provide sufficient information to use to estimate potential impacts	if no, the impacts of pressures need to be calculated for cumulative impact assessment

Example 2. Abbot Point expansion

The proposal to expand at Abbot Point required a significant amount of pressure mapping assessments to understand the potential impacts of port development activities. One of the pressure maps created was the distribution and intensity of sound in the water from pile driving as the infrastructure was developed. Numerical models were used to map the expected propagation of noise from pile driving at the terminal locations (Abbot Point CIA 2013)



2.1.3 Key Resources

Standard sets of pressure data at multiple scales are available from multiple sources. Leveraging these key resources (listed below) will assist proponents and regional managers. These are not comprehensive, and additional fine scale analysis may be necessary for specific developments.

eReefs

The eReefs project has developed a near-real-time information system to deliver data to scientists and reef managers involved in environmental decision-making (www.eReefs.info). The data available includes hydrodynamic, sediment, and biogeochemical models and ocean colour and SST remote-sensing products. A data visualisation portal (http://portal.ereefs.info/) allows users to search for datasets by variable (i.e. chlorophyll), thus accessing both model and observations products within the same visualisation tool. Commonly accessed processed data products (such as monthly averages, degree heating weeks etc.) have been further processed and are available on the AIMS eReefs portal https://aims.ereefs.org.au/aims-ereefs.

eReefs data has been used to estimate the state of the GBR (Robiliot et al. 2018), and for setting river nutrient and sediment reduction targets (Brodie et al. 2017). The data available within eReefs can be an important resource for cumulative risk assessments, both at Regional and project levels, and can also provide information on the historical environmental condition.

NESP Marine Biodiversity Hub

The NESP Marine Biodiversity Hub has compiled a set of pressure data time series for offshore activities. The data can be found on SeaMap Australia (https://seamapaustralia.org/) in the NESP Marine Biodiversity Hub Layers (in third part layers).

GBRMPA Cumulative Impact Management Policy

A list of potential Pressures to be considered are listed in Table A1.1 of the Cumulative Impact Management Policy. This list has been drawn from the Great Barrier Reef Strategic Assessment Report. Additional details for the pressures can be obtained in this report.

GBRMPA Outlook Report

The GBRMPA Outlook report provides a summary of the status and trends of the different pressures that are impacting the reef and the drivers that are influencing those pressures. The outlook report is updated every 5 years, with the latest report published in 2019.

http://www.gbrmpa.gov.au/our-work/outlook-report-2019

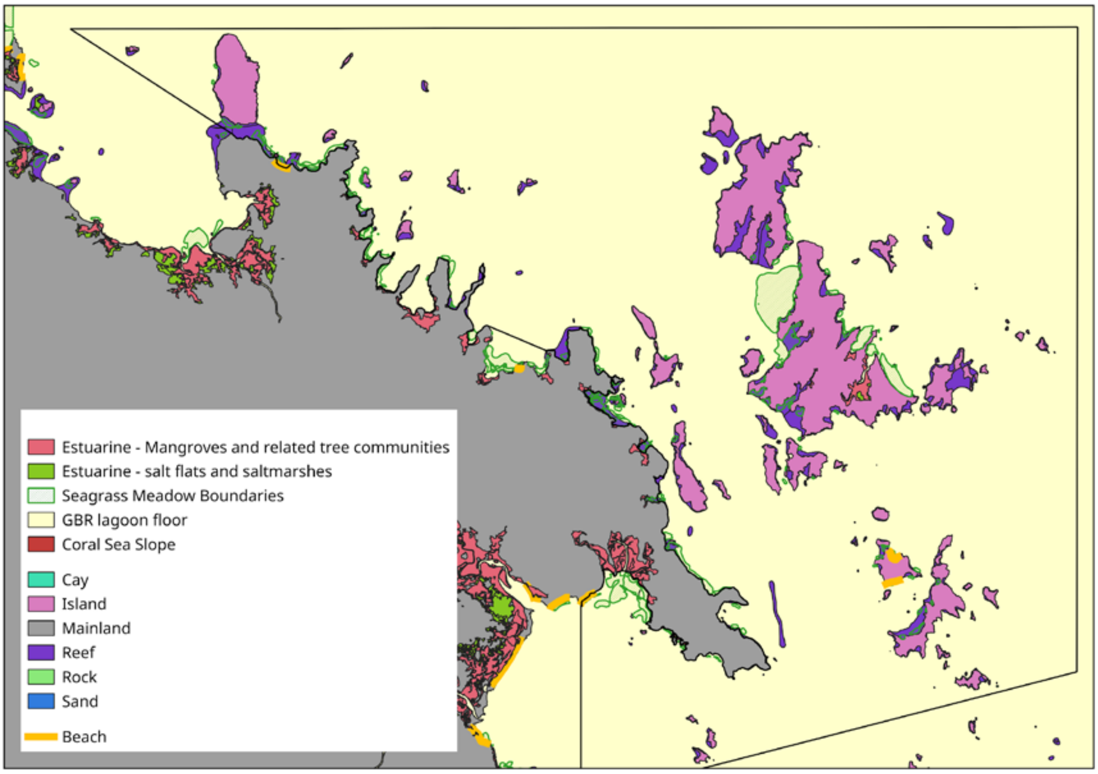
2.2 Step 2: Understanding Values

The values needing to be addressed in an assessment can be ecological, social, economic or cultural in nature; specific environmental values of the GBR have been described in Table A4.1 of the GBRMPA CIM Policy. They are comprised of properties that have Outstanding Universal Value or are Matters of National Environmental Significance (MNES), which are species and habitats listed under the Environmental Protection and Biodiversity Conservation Act.

The number of species that might require consideration can be overwhelming. A practical approach is to use ecosystems associated with key habitats and processes as a proxy where key species or species groups are known to depend on them for their survival growth or reproduction. Environmental, social, cultural and economic values can also be linked to these habitats or associated species through conceptual models (described in Step 4). Key habitats identified for the GBR are listed in Table A4.1 of GBRMPA's Cumulative Impact Management Policy.

Example 3. Mapped habitats of Whitsundays

The distribution of mapped habitats from state and commonwealth data sources within the Whitsundays Plan of Management Area. Many of the key habitats have been mapped through a variety of projects and can be combined to show to distribution of many of the habitats. These can then be used as a proxy for the values that occur in those areas. For instance, seagrass beds (or seagrass meadows in below image) provide a critical food resource for Dugongs (MNES) and Turtles (MNES) and nursery habitat for a broad range of fish species (GBRMPA value). The seagrass bed provides the services to support these species and thus a spatial context for how different pressures will impact them.



Each of the habitats should be mapped for the area under consideration in a plan of management or project proposal.

2.2.1 What types of values are there?

The likelihood of occurrence of values can fall into five categories:

1. **Known**: the species or ecological community was or has been observed on the site.
2. **Likely**: a medium to high probability that a species or ecological community occurs on the site.

3. **Potential**: suitable habitat for a species or ecological community occurs on the site, but there is insufficient information to categorise the species or ecological community as being likely or unlikely to occur.

4. **Unlikely** to occur: a very low to low probability that a species or ecological community occurs on the site.

5. **Not occurring**: habitat on the site and in the vicinity is unsuitable for the species or ecological community.

There are two classes of information to support this categorisation: 1) Direct observations from field surveys or other sources of direct observations that provide the known locations of (*e.g.*, scientific surveys, citizen science, museum collections); 2) Inferred occurrence (Likely, Potential, Unlikely) based on either expert knowledge or modelling of the distributions from known occurrences.

Direct Observations

Sampling design advice can be found in the NESP Marine Biodiversity Hub field manual in Foster et al. (2018) and documents in development by the Reef Integrated Monitoring and Reporting Program. The field manual discusses the relevant necessary and sufficient conditions in designing sampling programs for monitoring and sampling, emphasising several key design criteria:

- Efficiency of design
- Uncertainty reduction
- Sampling space and time
- Specifics for different gears types.

The manual recommends that spatially balanced designs are adopted to ensure that each new sample is providing the maximum amount of new information, and that samples from different surveys can be integrated. This will aid in reducing the amount of uncertainty in the statistical analysis of the monitoring and survey data and increase its utility. To ensure that the temporal variation in occurrence can be captured, sampling through time (as well as space) should be attempted. Finally, the gear-specific characteristics will determine the form of the observations and how likely the value of interest will be observed.

Inferred Occurrence

The occurrence of values can be derived from two distinct sources: expert opinion and statistical or machine learning modelling. Expert opinion has been used extensively to map the distribution of species where information is very limited. However, caution should be taken in using these maps as biases are well known and they will significantly overestimate the areas used by species and miss critical habitat. Statistical and machine learning models may be used where there are enough observational data on spatially extensive covariates to predict the distribution of the desired values (*e.g.,* species or habitats). There is extensive literature on the application of both machine learning and statistical modelling to predicting single and multispecies distributions (Warton et al. 2002).

Social and Cultural Values

The term 'values' is commonly used to refer to many related but different concepts. We provide a simple framework, drawing on Brown (1984), to help distinguish and relate three core value concepts:

Held values: the nature of that relationship is shaped by the values they hold within themselves: for example, their moral compass.

Relational values: primarily, the importance or value of a thing derives from how people experience the thing; the relationship between people and the thing.

Assigned values: things are often described in very specific ways for particular purposes: example to reflect their importance in a value relationship or connect them to a decision-making process.

2.2.2 Checklist for the assessment of values

Below are considerations for the mapping of values and identifying sufficient models. Additionally, guidance on issues of appropriate scale, uncertainty, and data and knowledge gaps can be found in Appendix A. Where a mapping of values does not adequately address one or more of these characteristics then it should attract a concomitant level of uncertainty that is propagated through the calculation of risk.

Specific Questions	**Caveats**
Data Availability	
Is there sufficient data available on values for the area of interest?	If no, consider not undertaking assessment until sufficient data is collected, modelled or sought through expert opinion OR apply the precautionary principle and assign high potential impact for those areas of interest with unknown values.
Are data on values available on comparable spatial and temporal scales to the pressures?	if no, caution needs to be taken to ensure that the spatial and temporal scale are appropriate to enable estimation of impact
Are baseline data available?	if no, historical impacts will not be able to be estimated, and it will be difficult to determine if an impact has occurred
Do available data on values have comparable resolutions for all values?	if no, differing resolutions may mean some values are given a higher weighting than would otherwise be expected.
Are empirical data available or are the data inferred, modelled, or expert option?	if no, empirical data is not available then additional questions should be addressed
If the presence of the values is inferred from models or expert opinion the following additional characteristics should be considered.	
Is there a clear link between the outputs of the model and the values	if no, the model may not accurately predict where values occur
Does the model incorporate uncertainty?	If no, additional caution is necessary as the reliability of predictions cannot be determined.
What is the confidence in the spatial prediction (if appropriate)?	If no, additional caution is necessary as the reliability of spatial predictions cannot be determined.
What is the confidence in the temporal prediction (if appropriate)?	If no, additional caution is necessary as the reliability of temporal predictions cannot be determined.
Does the model generate measurable outputs or scores that can be compared with observed environmental status?	if no, the model cannot be verified and should be treated with significant caution.
Are multispecies predictions used? if yes, the additional considerations below should be considered:	
Is it possible to robustly estimate how many multispecies groups there are (e.g. the number of assemblages, communities)?	If no, the exact number of assemblages/communities cannot be determined, and some areas may be over/under predicted.
Can the spatial distribution of multispecies groups be estimated?	If no, caution must be taken in generalising across a landscape/seascape.
Can the uncertainty in group membership and the spatial distribution of each group be estimated?	If no, additional caution is necessary as the membership of groups cannot be determined.
Can the species composition within each group be estimated?	If no, caution must be taken in extrapolating to species distributions
Can the environmental characteristics of each group (i.e. the functional form of the relationship between the group and the environmental covariates) be estimated?	If no, caution must be taken extrapolating into environments that are unsampled.

2.2.3 Key Resources

GBRMPA Outlook Report: The GBRMPA Outlook report provides a summary of the status and trends of the different values in the GBR Marine Park. The outlook report is updated every 5 years, with the latest report published in 2019.

http://www.gbrmpa.gov.au/our-work/outlook-report-2019

Significant species and habitat data can be found at:

Integrated Marine Observing System: http://imos.org.au/

eAtlas: https://eatlas.org.au/

Species Profile and Threats Database: http://www.environment.gov.au/cgi-bin/sprat/public/sprat.pl

Atlas of Living Australia: https://www.ala.org.au/

Seamap Australia: https://seamapaustralia.org/

Social and Economic Long-Term Monitoring Program (*SELTMP)*: The SELTMP for the Great Barrier Reef is gathering long-term data specific to Reef users, communities and industries, and providing new insights into relationships between people and this iconic natural resource. The SELTMP synthesises existing socio-economic data from a wide range of sources, then fills key knowledge gaps by conducting large-scale surveys of Reef user groups. https://research.csiro.au/seltmp/.

Methods for robust sampling:

Field Manuals for Marine Sampling to Monitor Australian Waters (Przeslawski et al. 2018):

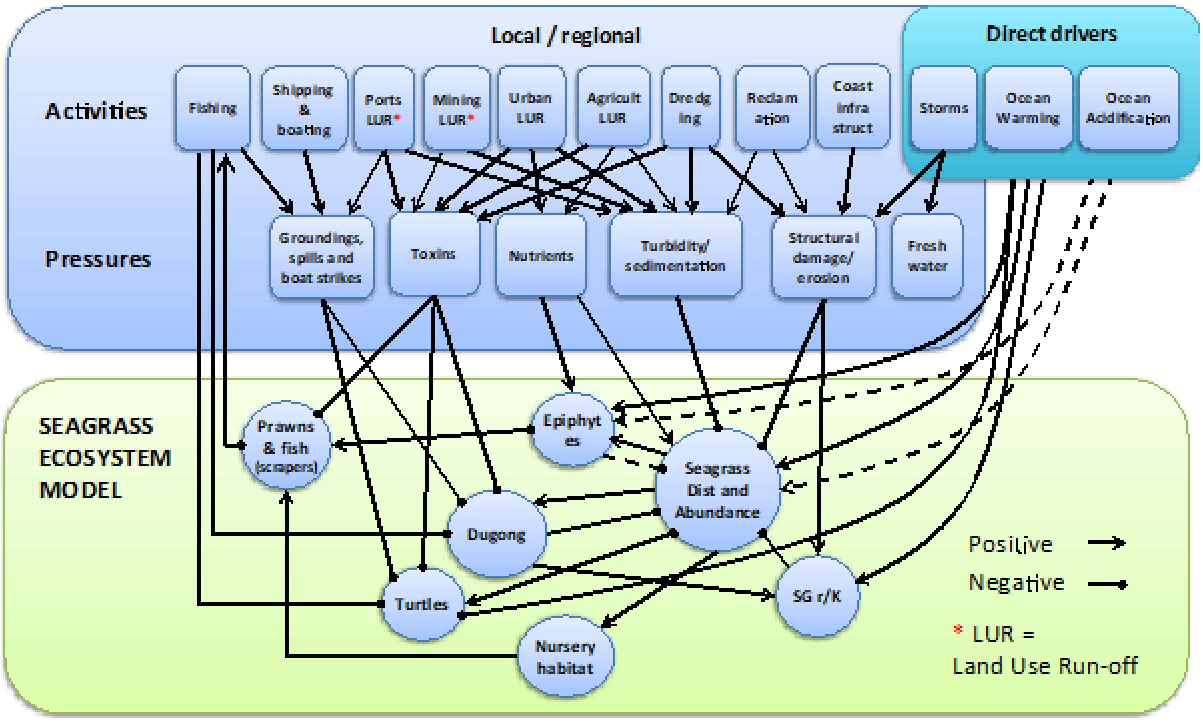
https://www.nespmarine.edu.au/tags/field-manuals-marine-sampling-monitor-australian-waters

2.3 Step 3: Conceptual Models of Key Habitats

Conceptual models play a foundational role in the risk assessment process. Their most basic function is to represent a collective understanding about how an ecosystem works. Conceptual models should represent valued components and processes in an ecosystem; document current understanding about how these components and processes are related; identify how natural and anthropogenic pressures can affect the system; and lastly identify knowledge gaps and key uncertainties. It is important that the formulation of a conceptual model occurs early in the risk assessment process as it determines how the assessment will be approached and has a major influence on the identification and selection of assessment and measurement endpoints. The formulation of a conceptual model would ideally occur after the first stage of assessing pressures and values was completed. The conceptual model might then lead to a second iteration to assess further pressures or values that were recognised as important in, or to, the system.

Example 4. Seagrass ecosystem model

A conceptual model of how seagrass is affected by multiple pressures. The model uses the tool of sign directed graphs to show positive and negative direct effects between variables. The main goal of the model is to demonstrate how seagrass distribution and abundance is affected by natural processes, its importance to valued components of the GBR (*e.g.*, dugong, turtles, nursery habitat for fishes) and how it is impacted by pressures emanating from various natural and anthropogenic drivers and activities. Uncertainty in ecological processes is depicted by dashed-line links. SG r/K is a model variable that represents different species of seagrass (SG), where fast growing *r* species are favoured by frequent disturbance and grazing, and slow growing *K* species of seagrass are favoured by low levels and disturbance and grazing.



2.3.1 What is a conceptual model?

There is no prescriptive rule about the exact form a conceptual model should take, or by what tool or method it is constructed. These considerations are determined by the underlying complexity of the ecological system with respect to how its valued components can conceivably be affected by pressures, and management interventions. Conceptual models need to portray the ecological system at a level of resolution that is useful to the purposes of the risk assessment, including all relevant details while striking a balance between simplicity and complexity. The level of complexity of the conceptual model will in many respects dictate the level of analytical complexity in the calculation of risk; see *Step 5. Assessment of Risk and Uncertainty* for discussion of sufficiency of analytical tools with respect to level of system complexity, and *Detailed Case Study 1: Quantifying cumulative impacts on coral reef* *ecological communities on the Great Barrier Reef* for an example of how complexity of conceptual model framed an analysis of risk for fish biomass and corals.

In assessments, the role of conceptual models is to:

1. Represent the important components and processes in the system that represent values.
2. Document assumptions about how these components and processes are related.
3. Show how these components and processes are causally linked to anthropogenic pressures.
4. Identify knowledge gaps or other sources of uncertainty.
5. Provide a causal narrative of how the system works and is affected by pressures to support management decision making and reporting.

2.3.2 Checklist for a conceptual model

Below are considerations for using conceptual models in ecological risk assessments. Additional guidance on approaches to address complexity and can be found in Appendix A. Where a conceptual model does not adequately address one or more of these characteristics then it should attract a concomitant level of uncertainty that is propagated through the calculation of risk.

Specific Questions	Caveats
Is the context of the conceptual model clearly defined?	
Does the conceptual model of the system capture the same temporal and spatial scales as desired for the assessment/of interest?	if no, caution needs to be taken to ensure that the spatial and temporal scale are appropriate to enable estimation of impact
Are the spatial and temporal limits of the system clearly identified?	if no, additional consideration should be given to defining the limits to ensure that the model captures the relevant parts of the system for management
Does the conceptual model include ecosystem components that adequately represent key species, habitats and processes (i.e., resource flows, ecological relationships, and disturbance regimes)?	If no, potential ecosystem impacts from pressures may not be well described
Can you actually measure the outputs of the system, identify indicators and monitor the outcomes	
Does the conceptual model describe how the pressures, values and ecosystem components relate to each other and interact?	If no, potential ecosystem impacts from pressures may not be well described
Are the assessment endpoints (the ecosystem components that will be monitored) represented in the conceptual model?	if no, the direct impacts of pressures on ecosystem components they impact are not well described
Are there alternative ways that pressures could impact values or alternatives for how the ecosystem might be structured?	if yes, then each different conceptual model should be considered in the assessment

2.3.3 Key Resources

Prototype conceptual models for some of the 12 key habitats identified in Table A4.1 of the GBRMPA CIM Policy have been created (*Appendix A Conceptual Models of Key Habitats*). These may be applied, or used as starting points, within an assessment, but should be first be checked to ensure the models adequately represent the values and pressures within the zone of influence ascribed to the project or plan of management.

Examples of existing conceptual models for GBR habitats can be found in Anthony et al. (2013), Dambacher et al. (2012), Dambacher et al. (2013) and Kuhnert et al. (2014); additional models will become available through ongoing RIMReP publications.

http://elibrary.gbrmpa.gov.au/jspui/bitstream/11017/3385/8/RIMReP-Strategy-Update-2018.pdf

2.4 Step 4: Zone of Influence

The zone of influence for each combination of value and pressure needs to be spatially mapped. This can be described as a table indicating where any pressure has the potential to cause an observable change in a component of the system that can impact a value either directly or indirectly. This table may start as the full combination of Tables A1.1 and Table A4.1 of the GBRMPA Cumulative Impact Management Policy but will be rapidly simplified as combinations of values and pressures that cannot exist in the area under consideration are removed. Iterative steps between the zone of influence and the conceptual models may be required to identify assessment and measurement end-points.

2.4.1 What is a Zone of Influence?

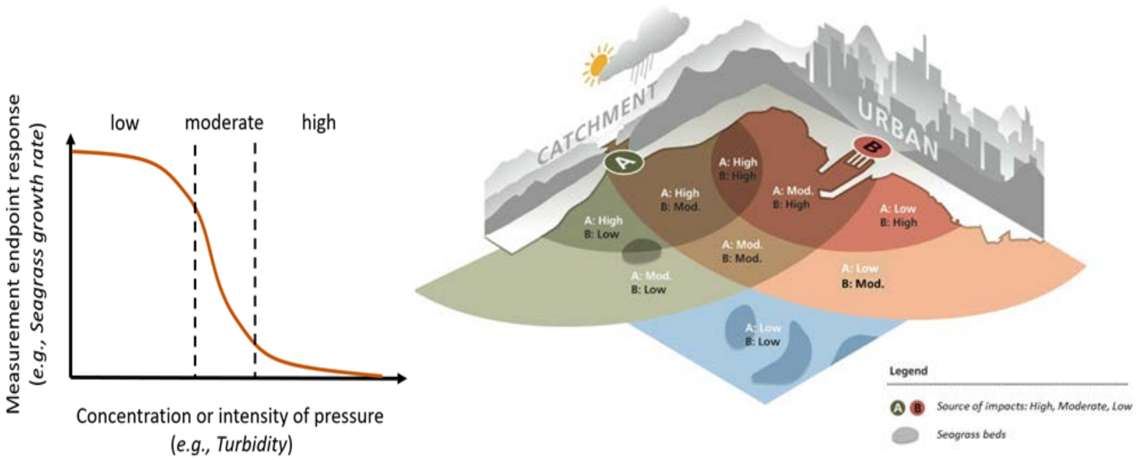
The concept of a zone of influence (Anthony et al. 2013) supports a spatially explicit assessment of cumulative impacts and is based on a mapping of the relative intensity or concentration of a given pressure in two- or three-dimensional space with respect to its potential to impact ecosystem values. Its definition or construction will likely require several iterations that consider the influence of a pressure on the system against the magnitude of thresholds for system components or values with respect to specific assessment and measurement endpoints.

At its core, a zone of influence relies upon a well-defined dose-response type relationship between a pressure and its immediate influence or impact on a key component of the ecosystem, which may or may not itself represent a recognized value. For instance, there is little concern about an immediate causal influence of turbidity on dugong populations, rather its impact is conceived as occurring through its adverse influence on the growth rate or abundance of seagrass, a principle food resource of dugongs. Thus, a zone of influence for dugongs with respect to the pressure of turbidity will depend on a dose-response relationship between turbidity and seagrass. Pressures may be distinguished as having a discrete entry point into the ecological system, as in the former example, or they may a have a broad impact on multiple entry points into the ecosystem, as in the damaging effects of cyclones on numerous species and habitats across the GBR.

Dose response relationships are used to define threshold values for acceptable and unacceptable levels of impact to the system for a given pressure. These threshold values are used to demarcate when or where pressures are likely (or unlikely) to have a significant and observable impact on key components of the ecosystem. A zone of influence is defined by area that encompasses a valued component of the ecosystem where there is an exceedance of an intensity or concentration of a pressure beyond an accepted threshold for an assessment endpoint associated with that value. A fundamental aspect of assessing cumulative impacts is to distinguish specific sources of a pressure of concern from existing or background levels, whether they are from anthropogenic or natural sources.

Example 5. Zone of influence for turbidity and seagrass

Dose-response relationship for turbidity and growth rate of seagrass with defined threshold levels of impact that are used to delineate zones of influence for a restricted (urban port) and dispersed (catchment) source; adapted from Anthony et al. (2013).



2.4.2 Checklist for Zone of Influence

Below are considerations for zones of influence; additional guidance for development and applications of zones of influence and identification of measurement and assessment endpoints can be found in Appendix A. Where a zone of influence does not adequately address one or more of these characteristics then it should attract a concomitant level of uncertainty that is propagated through the calculation of risk.

Specific Questions	**Caveats**
Are Pressures linked to ecosystem components	
Is the response variable of the dose-response relationship clearly represented in the ecosystem's conceptual model?	if no, the conceptual model should be reconsidered to ensure that identified responses variables are represented
Is the zone of influence based on a well-defined dose-response type relationship (demonstrated and measured clear impact) relevant to the valued components of the ecosystem?	if no, care must be taken to ensure that the effect of pressures can be linked to values
Are threshold values sufficiently detailed to address the biology of the response variable (e.g., do they address breakpoints in effects on key variables such as seagrass growth increasing or decreasing at relatively low or high levels of nutrients)?	if no, uncertainty about the threshold for a response should be considered
Do threshold values address a range of effects that are relevant to management concerns and desired future conditions of associated values?	If no, additional caution is necessary as the reliability of predictions cannot be determined.
Is uncertainty in the dose-response relationship adequately assessed and documented?	
If based on empirical data, does the dose-response relationship included error bounds?	if no, uncertainty about the threshold for a response should be considered
If based on modelling studies is there documentation of variation in modelling results?	if no, additional evidence of the dose-response relationship should be sought
If based on expert opinion is there documentation of the elicitation process and attendant level of uncertainty?	if no, additional evidence of the dose-response relationship should be sought
Does the zone of influence adequately address or document different sources of pressures relevant to the assessment?	
Is the granularity of the pressure data sufficient to address the pattern of distribution in the response variable of the dose-response relationship and the distribution pattern of valued components of the system?	if no, caution needs to be taken to ensure that the spatial and temporal scale are appropriate to enable estimation of impact
Are concentrations or intensities of existing pressures adequately differentiated from pressures associated with proposed projects and plans of management?	if no, care needs to be taken to distinguish the effects pressures from other potential sources of impact
Are anthropogenic sources of pressures adequately differentiated from natural or otherwise background levels of pressures (i.e., turbidity from a catchment includes natural sources from sediment transport but also from runoff associated with land use practices)?	if no, care needs to be taken to distinguish the effects pressures from other potential sources of impact

2.4.3 Key Resources

The construction of zone of influence is based on the mapping of pressures and values with respect to predetermined thresholds for concentration or intensity of pressures. See sections of this report for mapping pressures and values.

Information on threshold values for some pressures relevant to the GBR can be found in GBRMPA (2010).

2.5 Step 5: Risk Assessment and Uncertainty

2.5.1 How to conduct a cumulative risk assessment

Existing impacts and potential risks of new activities to the values as identified in steps 1-4 need to be calculated. The cause-effect models can be used to identify measurement end-points for each of the assessment end-points (values) that have been identified. A single measurement endpoint may be relevant for multiple assessment end-points. For each measurement endpoint, the cumulative impact of existing pressures should be calculated. Risks of new pressures from new activities beyond the existing pressures can be compared against the desired environmental condition.

There are multiple methods available for calculating cumulative risk and impact. To assist the selection of methods for risk assessment criteria have been developed that can assist in deciding which method is appropriate for assessing impact and risk to the values identified in habitats. The criteria are based on the complexity of the habitat in question and the suitability of the method and data to that level of complexity.

Example 6 . Cumulative stress on coral reefs

The cumulative stress on coral reefs was estimated for a variety of scenarios of port development, agriculture and climate change using Bayes nets (Anthony et al. 2014); ER: estimated risk, TER: total estimated risk. Outputs show that combinations of climate change, agriculture and port development would have a significant risk if all three occurred at the same time. However, similar risks occurred if there was a COTS outbreak combined with agriculture. This emphasises the need to adaptively manage the impacts as the risk profile of an area changes.

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

Assessing uncertainty

Due to the complexity of the systems that are typically considered under cumulative impact scenarios the quantification of uncertainty in both the likelihood and consequence of potential impacts should be considered. Recommendations to address uncertainty when assessing cumulative impacts include:

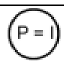
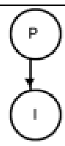
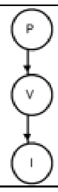
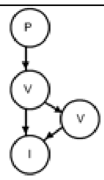
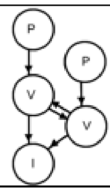
- Conduct additional field experiments to identify cumulative impacts of multiple disturbances and distinguish between single and cumulative impacts (Crain et al. 2008).
- Conduct additional controlled laboratory experiments explicitly testing a small number of significant pressures and their interactions to gain knowledge of the underlying mechanisms (Clarke Murray et al. 2014).

- Conduct research on how multiple pressures interact (accounting for non-additive interactions) to evaluate the relative impact of different pressures and the cumulative impacts of their interactions (Crain et al. 2008).
- Develop and refine methodologies that allow for the explicit incorporation of uncertainty into models and management decision-making frameworks (Batista et al. 2014; DFO 2012; O et al. 2015; Samhouri and Levin 2012).

Tools for Assessing Cumulative Impact

Models and tools are commonly used for visualisation, assessment, and management of cumulative impacts and their specific research and management goals. They fill the gaps in primary research by addressing issues and complexity that are difficult to mimic or test in a lab or field setting (Uthicke et al. 2016). For example, GBRMPA managers largely rely on qualitative tools to assess risks from cumulative impacts associated with development proposals (Uthicke et al. 2016). The selection of tools is determined by the ecosystem component and available input data (expert knowledge, qualitative, or quantitative) being assessed (Stelzenmüller et al. 2018). A range of tools, from simple lists to quantitative models (Table 2), are used to undertake assessment of the relationships between impacts and values that underpin matters of national environmental significance.

Table 2. Tools sufficient to address estimation of risk for different levels of system complexity.

Tools	Complexity of cause-effect relationship: None[1]	Simple[2]	Directed[3]	Diffuse[4]	Feedback[5]
					
1. Unstructured list	✔	✔			
2. Objective-indicator matrix	✔	✔			
3. Structured list		✔	✔		
4. Value-impact matrix		✔	✔		
5. Conceptual diagram or cartoon		✔	✔		
6. Influence diagram		✔	✔	✔	
7. Fuzzy cognitive map		✔	✔	✔	
8. Statistical model		✔	✔	✔	
9. Bayesian network			✔	✔	✔[6]
10. Qualitative process model				✔	✔
11. Quantitative process model				✔	✔

[1]No cause-effect relationship, the pressure is the indicator; methods beyond objective-indicator matrices not needed.
[2]Pressure directly impacts indicator variable; methods beyond statistical models not needed.
[3]Pressure directly impacts a variable that has knock-on effects to indicator variable; methods beyond Bayesian networks not needed.
[4]Pressure indirectly impacts an indicator variable via multiple interaction pathways.
[5]Multiple pressures simultaneously impact complex system with feedbacks between variables.
[6]With difficulty; standard Bayesian networks limited to acyclic graph structures. Dynamic Bayesian networks can account for feedbacks, but are difficult to parameterize and analyze, typically making them impractical for complex systems (but see Box 4 for application with qualitative process models).

P	pressure or impact
V	system variable – an element of the ecological or human system or benefit derived from that system that forms part of the cause-effect relationship but is not measured
I	indicator variable – a measurable indicator (it could be a specific ecosystem element (e.g. seagrass abundance) or benefit derived from the ecosystem (e.g. income) – or a surrogate measure for the health of MNES)

Previously the Authority has undertaken impact assessments using structured lists value-impact matrices (GBRMPA 2009), conceptual diagrams, influence diagrams (GBRMPA 2009) and quantitative models. Simple tools like unstructured lists can be used as a first step in impact assessment. It defines the scope of the impacts to be considered but is insufficient on its own, as it does not convey any understanding of interactions between values and impacts. A structured list only connects the identified impacts to direct drivers and activities.

Value-impact matrices can be used to comprehensively assess the past and current effect of each impact on each biodiversity, Indigenous heritage and historic heritage value. While these matrices present a comprehensive understanding of the effects of each impact and provide an indication of the severity of the total set of impacts acting on an individual value, they do not allow consideration of complex interactions and cumulative impacts. There are often derived from overlapping pressures and values in a GIS application.

Conceptual diagrams, influence diagrams, and fuzzy cognitive maps have been used to map relationships between different impacts, values and processes. These types of diagrams can be employed during the process of building qualitative process models, the 10th tool in the hierarchy.

Qualitative process models can be used to assess the impact of multiple drivers and activities that act simultaneously on ecological systems. Such models can be used to document how key pressures affect coral reefs and seagrass meadows (including dugong). The models are readily developed in workshops with experts in these fields. A key advantage of qualitative models is that they provide a relatively rapid and flexible means to understand system dynamics, predict the direction of change in cumulative impacts and consider potential management interventions. Because they can be constructed and analysed relatively quickly, they can be used to compare alternative models about how a system works. Predictions from these models, however, are only qualitative, and address only the direction of change, not magnitude.

Statistical models are empirical models that relate the assessment endpoint to a suite of pressures that may or may not directly impact the endpoint. They require data that spatially and temporally matches the pressures to the endpoints and some understanding of how the pressures are related to the endpoint. They are very effective at identifying thresholds and usually provide an estimate of the uncertainty of that prediction. They cannot, however, identify causality directly, but when combined with qualitative process models can identify the quantitative tipping points of the causative relationships between pressure and endpoints. The combination of a statistical model (a structural equation model) with a conceptual model is explored in Detailed Case Study.

The last tool in the hierarchy, quantitative process models, is useful where management questions require definition of critical thresholds for limits to acceptable change in an MNES. As such models need large amounts of data, they have only had a limited use in the GBRWHA, but the modelling approaches continue to be developed.

In these guidelines we advocate a staged and complementary approach, where model complexity gradually increases to support increasing knowledge and experience of the assessment team. Qualitative process models are used for initial assessments of cumulative impacts, and quantitative process models are employed where there are critical management questions and sufficient data. Knowledge gained from analysis and testing of qualitative models can be used to better focus the application, and inform the construction, of quantitative process models.

For large complex systems that are subject to cumulative impacts, it is useful to employ the additional tool of Bayesian networks — which are a type of statistical model that represents system variables and their conditional dependencies. Bayesian networks based on qualitative models can carry out four basic analyses to aid integrated adaptive management: prediction, diagnosis, validation and sensitivity. Qualitative model predictions, embedded within a

Bayesian network, provide an ideal means to consider different development scenarios and to make concurrent assessments of the relative effectiveness of management interventions and monitoring programs.

2.5.2 Checklist for cumulative risk assessment

Canonical cases of differing levels of system complexity (Fig. 2) have been summarised from table 2 (described in Hayes et al. (2015) and (Table 2.1 in the GBR Strategic Assessment). These canonical cases can be used to describe generic forms of complexity that can expected in cumulative impact assessment scenarios. The suitability of different methods can be tested against each case as a demonstration of the applicability of different methods.

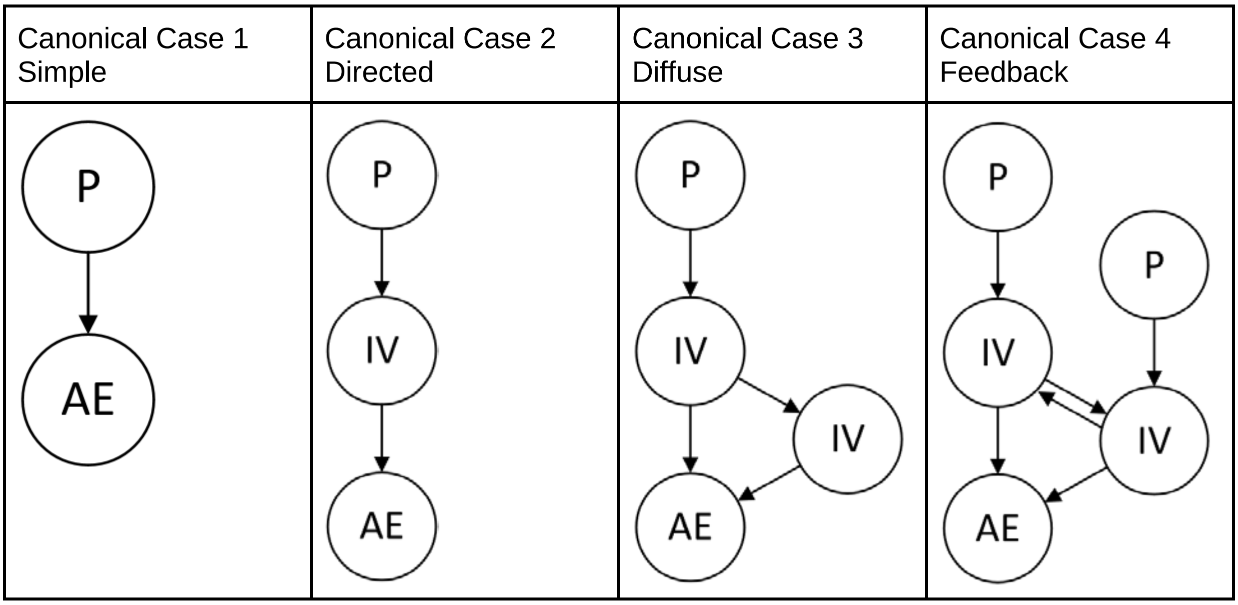


Figure 2. Canonical cases of complexity in cause-effect relationships for pressures (P) having direct or indirect effects on assessment endpoints (AE) and intervening variables (IV); simple: pressure directly impacts assessment endpoint, directed: pressure indirectly impacts assessment endpoint through an intervening variable, diffuse: assessment endpoint impacted indirectly via multiple interaction pathways, feedback: multiple pressures simultaneously impact complex system with feedbacks between variables; adapted from Hayes *et al*. (2015).

Sufficient conditions for methods for a given level of complexity in a risk assessment can be assessed using three key criteria:

1. Is the method sufficient to address the complexity of the system being assessed?
2. Does the method generate measurable outputs that can be tested?
3. Is there sufficient data available to generate a prediction of risk for the given method?

If a method does not meet the criteria, then additional levels of precaution should be applied to any new activities that generate that pressure and additional monitoring should be focused on the measurement endpoint until the more appropriate methods can be used.

To assist the selection of methods for risk assessment, the following criteria can assist in understanding the appropriateness of different methods to assessing impact and risk for the values identified in habitats. This list has been adapted from Smit and Spaling (1995), Hayes et al. (2012) and Table 2.1 from the GBR Strategic Assessment.

Question	Response
Can the method predict the spatial distribution of cumulative impacts?	If no, if the expected spatial distribution of impacts is large then additional analysis may be necessary to predict all impacts.
Can the method identify alterations to ecosystem components and processes such as nutrient cycling, predation, habitat modification, sedimentation, light penetration?	If no, absence of understanding of key processes may mean that ecosystem responses are not well characterised.
Does the method imply the link between multiple pressures and values or is this explicitly described in the approach?	If implied, additional information will be necessary to ensure that the pressures cause a change in the values
Can the proposed methods assess the indirect effects caused by the pressures on values?	If no, caution must be taken to ensure indirect effects (mediated through the ecosystem) that may change the magnitude and direction of change in values are accounted for.
Can the method assess facilitative effects of multiple pressures on values be detected?	If no, caution will need to be taken to ensure that pressures that facilitate impacts from other pressures are accounted for.
Can the method distinguish between masking, antagonistic, additive and synergistic links between multiple pressures and values?	If not, the full impact of pressures may not be properly estimated.
Are non-linear links between pressures and ecosystem components possible?	If no, inflection points and transitions in impact may not be well estimated
Can the method distinguish between the impacts of a single pressure acting sequentially?	If no, assessment may not capture the full impact of pressures acting through time.
Can the method distinguish between the impacts of multiple pressures acting simultaneously or sequentially?	If no, assessment may not capture the full impact of pressures acting through space and time.
Can the method include future impacts in the predictions?	If no, it will not be possible to predict the future risks of pressures
Can the method produce an estimate of uncertainty in the predictions in likelihood and consequence?	If no, additional caution is necessary as the estimate of impact and risk may be not be accurate.
Can the method incorporate temporal variation and time lags?	If no, assessment may not capture the full impact of pressures acting through time.

Each of the methods identified in Hayes et al. (2015) and the Strategic Assessment has been scored against the above criteria as Sufficient (2), Partially Sufficient (1) or Insufficient (0). The aggregate score for each method given each canonical case was used to rank the relative appropriateness of the method for the given level of complexity identified in the system's cause-effect model. As a rough guide, for a given level of complexity, methods with aggregate scores of less than 7 should not be used, scores of less than 10 should be used with caution and scores of greater than 10 will be sufficient to assess the risks with a properly formulated model.

Canonical Case 1: Simple														
Method	Spatial	Alterations	Explicit Link	Indirect Effects	Facultative	Masking etc	Non-Linear	Sequential Pressures	Multiple Pressures	Future effects	Uncertainty	Temporal Pressures	Data Requirements	Total
Unstructured list	2	1	1	1	1	1	0	0	2	2	0	2	L	13
Value-impact Matrix (Scored or unscored) GIS	2	1	1	1	1	1	0	0	2	2	0	2	L	13
Influence diagram or cartoon	2	1	1	1	1	1	0	0	2	2	0	2	L	13
Fuzzy cognitive map	2	2	2	2	2	0	1	1	2	2	0	2	L	18
Qualitative process model	2	2	2	2	2	1	1	1	2	2	1	2	L	20
Expert Elicitation	2	2	2	2	2	2	2	2	2	2	1	2	M	23
Bayes Net	2	2	2	2	2	2	2	2	2	2	1	2	M	23
Statistical Model	2	2	2	2	2	2	2	2	2	2	2	2	M	24
Quantitative process model	2	2	2	2	2	2	2	2	2	2	2	2	M	24

Canonical Case 2: Direct

Method	Spatial	Alterations	Implied Link	Indirect Effects	Facultative	Masking etc	Non-Linear	Sequential Pressures	Multiple Pressures	Future effects	Uncertainty	Temporal Pressures	Data Requirements	Total
Unstructured list	2	1	1	1	1	1	0	0	2	2	0	2	L	13
Value-impact Matrix (Scored or unscored) GIS	2	1	1	1	1	1	0	0	2	2	0	2	L	13
Influence diagram or cartoon	2	1	1	1	1	1	0	0	2	2	0	2	L	13
Fuzzy cognitive map	2	2	2	2	2	0	1	1	2	2	0	2	L	18
Qualitative process model	2	2	2	2	2	1	1	1	2	2	1	2	L	20
Expert Elicitation	2	2	2	2	2	2	2	2	2	2	1	2	M	23
Bayes Net	2	2	2	2	2	2	2	2	2	2	1	2	M	23
Statistical Model	2	2	2	2	2	2	2	2	2	2	2	2	M	24
Quantitative process model	2	2	2	2	2	2	2	2	2	2	2	2	M	24

Canonical Case 3: Diffuse

Method	Spatial	Alterations	Implied Link	Indirect Effects	Facultative	Masking etc	Non-Linear	Sequential Pressures	Multiple Pressures	Future effects	Uncertainty	Temporal Pressures	Data Requirements	Total
Unstructured list	1	1	0	1	0	0	0	0	1	1	0	1	L	10
Value-impact Matrix (Scored or unscored) GIS	1	1	1	1	0	1	1	1	1	1	0	1	L	10
Influence diagram or cartoon	1	1	1	1	0	1	1	1	1	1	0	1	L	10
Fuzzy cognitive map	2	2	1	1	1	0	1	1	2	1	0	2	L	14
Qualitative process model	2	2	2	2	2	1	1	1	2	2	1	2	L	20
Expert Elicitation	2	2	1	1	2	2	2	2	2	2	2	2	M	22
Bayes Net	2	2	2	2	2	2	2	2	2	2	1	2	M	23
Statistical Model	2	2	1	2	2	2	2	2	2	2	2	2	M	23
Quantitative process model	2	2	2	2	2	2	2	2	2	2	2	2	M	24

Canonical Case 4: Feedback

Method	Spatial	Alterations	Implied Link	Indirect Effects	Facultative	Masking etc	Non-Linear	Sequential Pressures	Multiple Pressures	Future effects	Uncertainty	Temporal Pressures	Data Requirements	Total
Unstructured list	1	1	0	1	0	0	0	0	1	1	0	1	L	6
Value-impact Matrix (Scored or unscored) GIS	1	1	0	1	0	0	0	0	1	1	0	1	L	6
Influence diagram or cartoon	1	1	0	1	0	0	0	0	1	1	0	1	L	6
Fuzzy cognitive map	1	1	1	1	1	0	1	1	1	1	0	2	L	11
Qualitative process model	2	2	2	2	2	1	1	1	2	2	1	2	L	20
Expert Elicitation	2	2	1	1	2	2	2	2	2	2	2	2	M	22
Bayes Net	2	2	2	2	2	2	2	2	2	2	1	2	M	23
Statistical Model	2	2	1	2	2	2	2	2	2	2	2	2	M	23
Quantitative process model	2	2	2	2	2	2	2	2	2	2	2	2	M	24

3. NEXT STEPS

This report is based on consultations with GBRMPA, QLD State Government, and DAWE Environmental Standards. It (Part 1) describes the steps in the guidelines and their application into EIA and regional planning. It will be updated (Part 2) with a specific case study on a management question from GBRMPA and specific plain language summaries that link the guidelines to legislation and policy for GBRMPA, QLD State Government and DAWE.

4. CASE STUDY: QUANTIFYING CUMULATIVE IMPACTS ON CORAL REEFS

A case study was developed to demonstrate an application of this guidance to plan-of-management scale problem for assessing cumulative impacts from natural and anthropogenic sources of pressures on coral reef ecosystems of the GBR. Here we used field data on reef communities collected on shallow coral reef systems along the entire length of the Reef that was matched with spatial data on the distribution of pressures (extracted from Stuart-Smith et al. 2019). This analysis could be framed to assess the relative impact of fishing pressure against impacts from land use runoff, crown of thorns starfish and storms. The key value of interest investigated is bony fishes, which was subdivided into components of socio-economic value (the exploitable component of reef fish communities) and ecological value (two major groups of herbivorous fishes). Values associated with the benthic community were also investigated, primarily in relation to their influence on the fish community, but also as important components of the system which the GBRMPA manages.

The goals of the case study were to:

1. Determine whether the spatial distribution of these values reflects the spatial distribution of key pressures along the GBR, in a way that is consistent with current ecological understanding (and as reflected in conceptual models of the GBR shallow reefs);
2. Provide insight on whether the cumulative impacts of pressures on reef fish values primarily reflect the accumulation of direct impacts, or indirect effects through impacts on the benthic habitat; and
3. Assess the spatial footprint of cumulative pressures acting at local to regional scales and evaluate whether this is likely to be a persistent feature of the seascape through time, through broader scale acute disturbances such as the 2016 mass coral bleaching event.

4.1 Step 1: Understanding pressures

Data were available from the full length of the GBR, allowing inclusion of different combinations of pressures in the far north to be considered, which are not possible to investigate with any other standardised dataset.

Pressure data layers came mostly from the dataset compiled by Matthews et al. (2019). From a number of correlated environmental variables, those used for these analyses were nitrogen inputs (CRS_NO3_SR, or the standard deviation of monthly nutrient values) and sediment (Primary river plumes). Crown of Thorns sea star (CoTS) impacts were incorporated through the GBR-wide interpolated scores of accumulated CoTS densities (all_cot_sum). Impacts were attributed to cyclone-generated waves based on a fetch-based wave height model developed by Puotinen et al. (2016), in the form of the number of cyclones predicted to generate >4 m waves at a given site since 1998. Two methods of accounting for fishing impacts were trialled, GBRMPA zoning and an angler isolation index. The GBRMPA zoning did not have a significant effect in preliminary models, so was excluded in order to increase power of the final model. The isolation index was developed by P. Dunstan (unpublished) and represents predicted attenuation of potential fishing effort based on the number of registered boats in each council area, location of boat ramps and assumed maximum distance travelled for each boat based on size.

Below are answers to the checklist of criteria for pressures. The assessment of pressures in the case study was based on a modelled data layers spanning the entire GBR and available over time scales that encompassed the span of reef survey data. There was, however, no estimate of the uncertainty associated the pressure data included in the analysis. Moreover, the analysis of impacts was based on the mean values of pressures, and not a full distribution or maximal values, thus the results should attract a level of precaution in their interpretation.

Characteristics	
Is the available data sufficient to map pressures?	Are available data on comparable spatial and temporal scales? *Yes, data were available across the entire length of the GBR and for time periods that encompassed biological sampling.*
	Are empirical data available or are the data inferred, modelled, or based on expert option? *Data is largely derived from modelling outputs but based on well documented data layers.*
	Are baseline data available? *Yes, in most cases there are baseline data available for the pressure data.*
	Do available data have comparable data resolutions? *Yes*
If the presence of the pressure is inferred from models or expert opinion the following additional characteristics should be considered.	
Is it possible to obtain an estimate of the uncertainty at the relevant scale?	Does the model incorporate uncertainty into the pressure estimate? *No.*
	What is the confidence in the spatial prediction (if appropriate)?*NA*
	What is the confidence in the temporal prediction (if appropriate) *It varies but was not considered in this analysis.*
Does the model generate measurable outputs that can be tested?	Does the model generate measurable outputs or scores that can be compared with observed pressure status? *Yes*
What level of complexity does the model address?	What type of interaction does the model account for (additive, synergistic, antagonistic, masking)? *Additive*
Does the model support a precautionary approach?	Does the model consider the maximum potential value of pressures? *Not really, It spans values across entire GBR, but models based only on mean effects of pressures, and not maximal values or a distribution of values.*
	Does the model consider the maximum potential impact of activities/pressures? *No (same as above).*
Does the model reflect the complexity of the environment?	Does the model estimate impact categorically or continuously numerical? *Continuous, numerical*
	Does the model benchmark pressure levels for impact estimates? *NA*

4.2 Step 2: Understanding Values

Reef fish, the primary values analyses here were obtained from Reef Life Survey data. The data has broad spatial coverage of co-located data on reef fishes and corals from the same transects, and the taxonomic coverage of all reef fish species. The RLS data are collected on 50 m transect lines in shallow reef (<17 m), with fishes recorded in duplicate 5 m wide blocks and corals and algae scored from 20 photo quadrats taken every 2.5 m along the transect line. The methods are described in detail in an online methods manual (www.reeflifesurvey.com) but are specifically related to the GBR dataset in Stuart-Smith et al. (2018).

The exploitable fishes value was calculated as the total biomass of species from particular families large enough to be caught and kept recreationally or commercially by hook and line or spear (>20 cm), whether legally or illegally. All species in the families Carangidae, Carcharhinidae, Haemulidae, Lethrinidae, Lutjanidae, Rachycentridae and Scombridae were included, as were a subset of Serranids from the genera Cephalopholis, Epinephelus, Plectropomus, Variola, and a subset of labrids from the genus Choerodon, plus Cheilinus undulatus (which is protected in QLD, but may be taken by poaching or suffer mortality following catch and release). The herbivorous fishes were split into scraping herbivores (Scarines other than the excavating Bolbometopon, Chlorurus and Cetoscarus) and browsing and detrivorous herbivores from a range of families (mostly Acanthurids and Siganids).

Below are answers to the checklist of criteria for values. The data available from Reef Life Survey has a high level of resolution across the GBR and compares well with the criteria.

Characteristics	
Is the available data sufficient to map values?	Are data available on comparable spatial and temporal scales? *Yes*
	Are empirical data available or are the data inferred, modelled, or expert option? *Empirical*
	Are baseline data available? *Yes*
	Do available data have comparable data resolutions? *Yes*
If the presence of the value is inferred from models or expert opinion the following additional characteristics should be considered.	
If the presence of the values is inferred from models or expert opinion, is there an estimation of the likelihood of the presence of the desired value (*e.g.,* species occurrence/ abundance/ biomass)?	Can the model capture the functional form of the relationship between the covariate and the response (*e.g.,* the occurrence of the desired value)? *Yes*
	Is there sufficient data to obtain a good estimate of the occurrence of the desired value? *Yes*
	Are the models assumptions data type appropriate for the observations (*e.g.,* Point Process for presence only data, Binomial for presence absence data, Negative Binomial for abundance data)? *Yes*
Is it possible to obtain an estimate of the uncertainty at the appropriate scale?	Does the model incorporate uncertainty into the risk score? *Yes*
	What is the confidence in the spatial prediction (if appropriate)? *High*
	What is the confidence in the temporal prediction (if appropriate)? *High*
Does the model generate measurable outputs that can be tested?	Does the model generate measurable outputs or scores that can be compared with observed environmental status? *Yes*
What level of complexity does the model address?	What type of interaction does the model account for (additive, synergistic, antagonistic, masking)? *Additive*
Does the model support a precautionary approach?	Does the model consider the maximum potential impact of activities/pressures? NA
Does the model reflect the complexity of the environment?	Does the model estimate impact categorically or continuously numerical? *Continuously numerical*
	Does the model benchmark pressure levels for impact estimates? *Yes*
	Is it possible to robustly estimate how many multispecies groups there are (e.g. the number of assemblages, communities)? *Yes*

Can multivariate (e.g., multispecies) predictions be accounted for?	Can the spatial distribution of multispecies groups be estimated? *Yes*
	Can the uncertainty in group membership and the spatial distribution of each group be estimated? *Yes*
	Can the species composition within each group be estimated? *Yes*
	Can the environmental characteristics of each group (i.e. the functional form of the relationship between the group and the environmental covariates) be estimated? *NA*

4.3 Step 3: Conceptual models of Key Habitats

Conceptual models for coral reefs within the GBR Reef were obtained from existing reef conceptual models described in Dambacher et al. 2012, 2013, Anthony et al. 2013, and Kuhnert et al. 2014 (Appendix A Conceptual Models). Figure 3 is an example of one such model developed for inshore reefs near Gladstone Harbour. These models were used to inform the structure of the analysis of cumulative impacts and risk. These models met all of the criteria listed in Section 2.3.2.

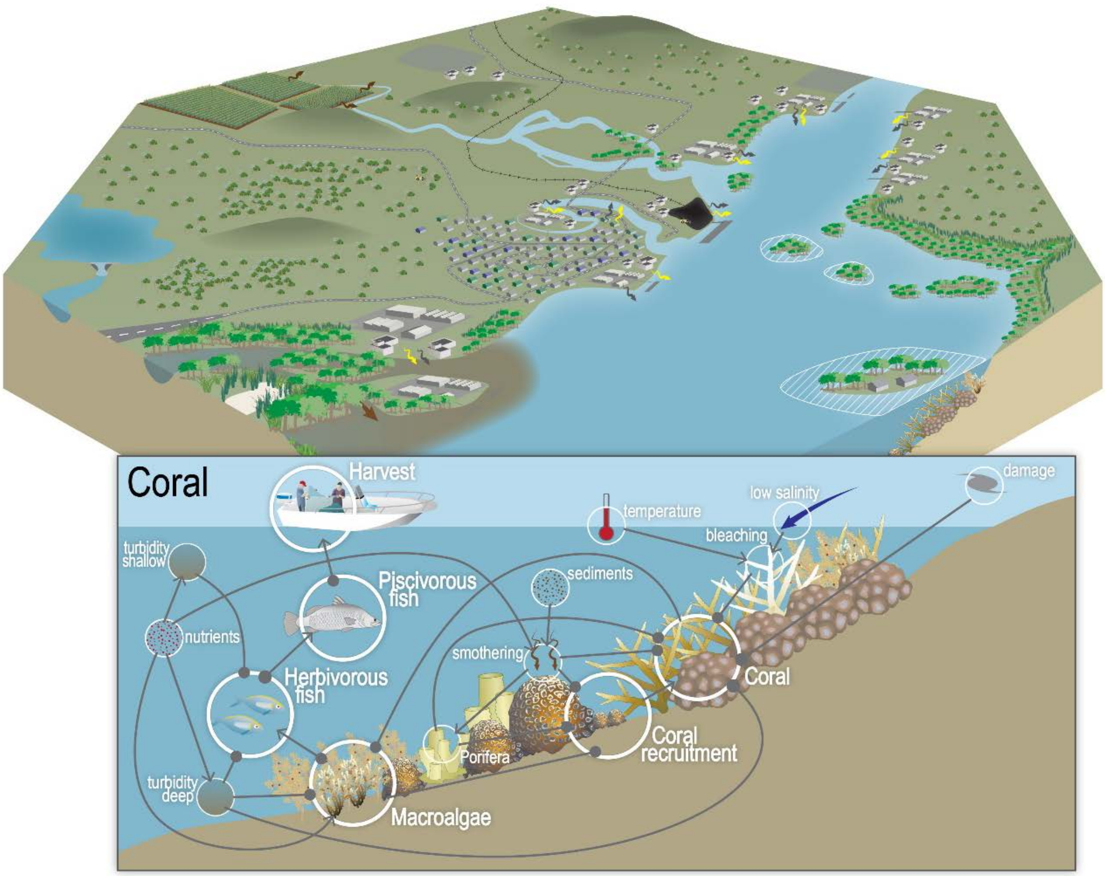


Figure 3. Conceptual model of coral reef ecosystem and anthropogenic and natural pressures; from Dambacher et al. (2013).

4.4 Step 4: Zone of Influence

The distribution of pressures at each of the reef sites was calculated from the data sources listed in Step 1. Each of the pressures was overlaid against the sites sampled and intensity of the pressure recorded. Along with the observation data this was used to estimate the impacts on the system and the species identified as values (Figure 4). This case study was a retrospective assessment of cumulative impacts, and thus did not assess the potential for future impacts against management or response thresholds, thus there was no formal analysis of a zone of influence.

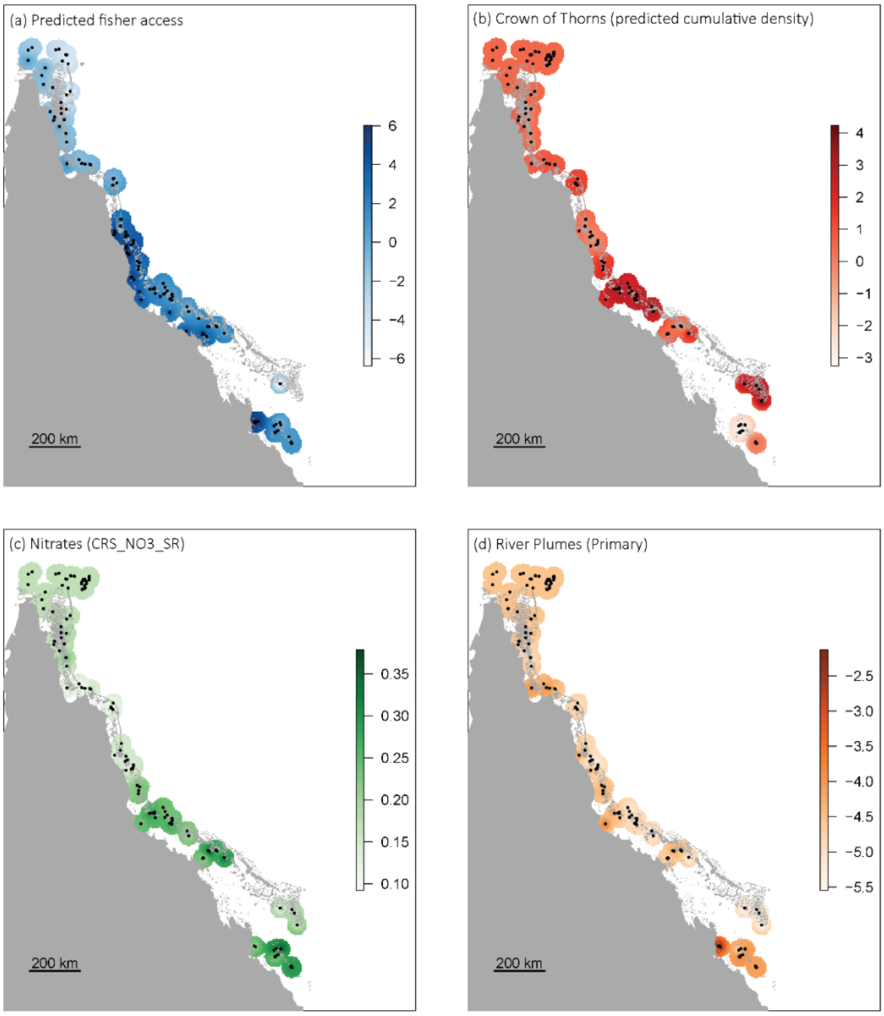


Figure 4. Zone of influence for multiple pressures on coral reefs in the Great Barrier Reef and Coral Sea. Interpolated pressure values across reef sites surveyed by Reef Life Survey along the Great Barrier Reef and northern Coral Sea. Fisher access (a) is predicted from an index relating the density of boat registrations in each region and estimated travel distance based on their sizes. It is thus used as a proxy for access by recreational fishers. The scale represents the natural log of the predicted number of boats per cell. Crown of thorns sea stars (b) represents the total densities from the model Matthews et al. (2019), accumulated across years (All CoT sum) and log-transformed. Nitrates (b) show the standard deviation of annual nitrates (CRS_No3_SR), and river plumes (d) the primary plume values (Primary), also log-transformed. Details of pressure calculations and modelling are provided in Matthews et al. (2019).

4.5 Step 5: Risk Assessment and Uncertainty

Structural Equation Models (SEMs) were used to evaluate the significance and strength of paths in the hypothesised ecological network, as described in multiple GBR reef conceptual models (derived from expert workshops).

In each SEM pathway fitted, the depth (grouped into bins of <5 m, 5-10 m, >10 m) and region (northern, central and southern GBR) were included as random variables, to account for spatial and depth-related variation before testing the pathway of interest. Two SEMs were fitted, one using only spatial RLS data collected prior to the 2016 mass bleaching event (data from 2010-2015), and a second using only data collected at sites surveyed after the 2016 bleaching event (2016-2018).

The ecological system assessed in this case study in one with feedbacks that involve multiple species and pressure. The tools used to assess cumulative impacts in this case study ranked high against the criteria (i.e., structural equation models scored 14 and qualitative process models scored 12 for canonical case 4), thus they can be considered sufficient to address the level of complexity of the ecosystem.

Below are answers to the checklist of criteria for risk assessment and uncertainty.

Criteria		
1. Is the method sufficient to address the complexity of the system being assessed?	a)	Causality: does the method attempt to determine causality - i.e. cause and effect pathways between pressures and response? Can it differentiate between additive and synergistic effects? How well can the links between the pressure and values (or accepted indicator) in the cause effect model be estimated from the model? *Yes, the qualitative process model was used to inform the links within the structural equation model.*
	b)	Structure and process: is the method able to identify alterations to ecosystem components and processes such as nutrient cycling, predation, habitat modification, sedimentation, light penetration? *Yes, both biotic and abiotic processes are included in the qualitative and statistical models.*
	c)	Time: to what extent does the method consider the frequency and duration of impact? Does it incorporate an extended time horizon to detect long term response, and also allow for time lags? *The data incorporated some consideration of time scales* (*i.e., before and after bleaching event*), *but pressure data incorporated only as mean values, thus no explicit treatment of variability over time.*
	d)	Space: does the method recognise the geographic sale of human pressure and set its spatial boundaries accordingly? Does it include a spatial dimension that acknowledges spatial variation in both pressure and response? *Yes, scale of data whole-of-reef.*
	e)	Pressure: can the method recognise and detect the effect of multiple pressures acting simultaneously or sequentially on components and processes of the ecosystem and identify the links between pressure? *Yes*
2. Does the method generate measurable outputs that can be tested	f)	Uncertainty: How well does the method empirically estimate quantitative uncertainty for both likelihood and consequence? *Yes, however, this was a retrospective study, but it can be used to predict future changes in state of fish and corals with quantitative estimates of uncertainty.*
	g)	Estimation: How well can the links between the pressure and values (or assessment or measurement endpoint) in the cause effect model be estimated from the risk model? *The cause-effect relationships are treated explicitly within the modelling framework.*
3. Is there sufficient data available to generate a prediction of risk for the given method?	h)	What are the data needs of the method? *High data needs for numerical estimates of pressures and values.*

4.6 Identified Cumulative Impacts

Patterns in reef fish and coral cover groupings prior to the 2016 bleaching event reflected the distribution of cumulative pressures along the GBR to a degree, with particularly strong impacts of cyclones and CoTS on the cover of more fragile tabular and branching corals (Fig. 5). The effect sizes of CoTS and cyclones on tabular and branching corals were the greatest of all the significant linkages shown in the final model, and the overall explanatory power of the model was greatest for patterns in the cover of tabular and branching corals as a result (Fig. 5). Turf cover was higher where cyclone impacts were greater and tabular and branching coral cover lower and was also positively related to foliose algal cover. Sediments and nutrients were negatively associated with foliose and turf cover, respectively, but a weak positive effect of nutrients was detected on tabular and branching corals.

The bony fish values were not strongly associated with either pressures or habitat values in this model, although weak positive direct effects of cyclones were evident on browsing herbivores and exploitable fishes, and weak benefits of massive corals were evident for browsing herbivores. Fishing pressure did not have a significant pathway in the SEM, mostly due to high site to site variability in exploitable fish biomass. Despite a lack of a significant pathway using the linear modelling techniques applied here, high exploitable fish biomass and high predicted boat access using the isolation index were mutually exclusive, suggesting the limitation of exploitable fish biomass at all but the most isolated sites (i.e. reduced boat access predicted by the index).

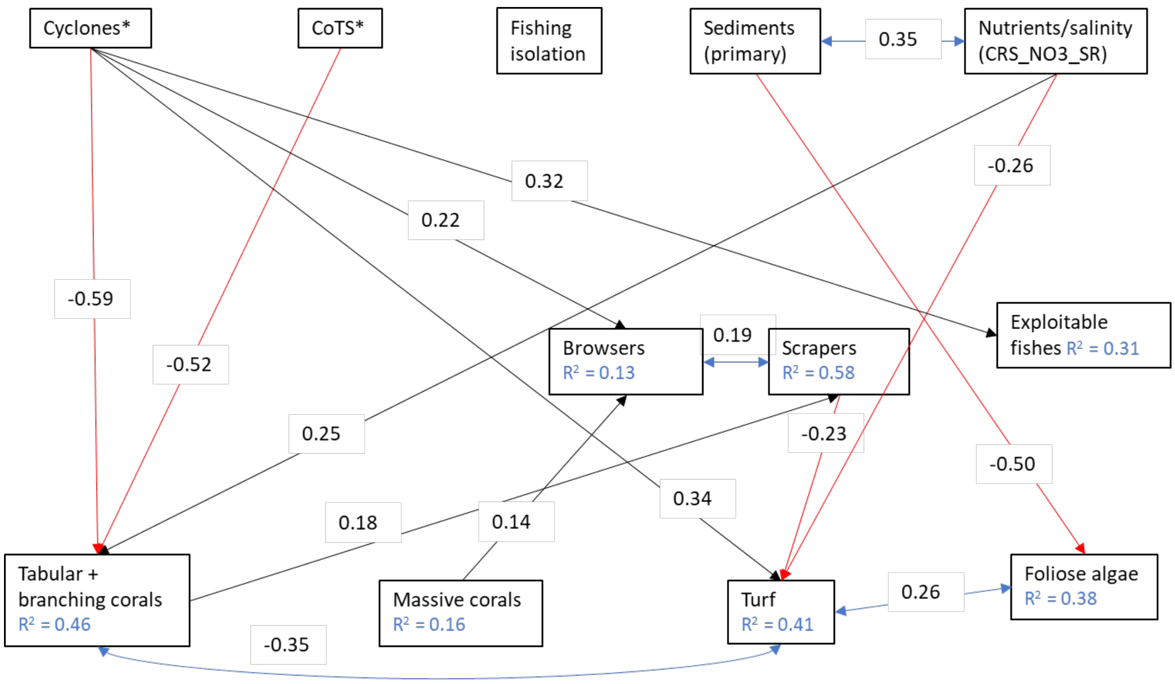


Figure 5. Structural equation model fitted to spatial data on pressures, fish biomass and coral cover data along the entire length of the Great Barrier Reef, prior to the 2016 bleaching event. Standardised effect sizes are shown for each linkage to allow comparison between linkages within the model. Red arrows represent significant negative effects in the directions shown, while black arrows represent significant positive effects.

Based on the RLS data collected after the mass bleaching event in 2016, few of the same pathways shown in Fig. 5 remained significant (Fig. 6). In particular, the strong negative associations of cyclones and CoTS on tabular and branching coral cover were no longer included in the final model. The post-bleaching model generally provided lower explanatory power than the pre-bleaching model for the effects of pressures on the habitat values, but greater explanatory power for the fish values, primarily due to stronger links between the corals and fish values (Fig. 6).

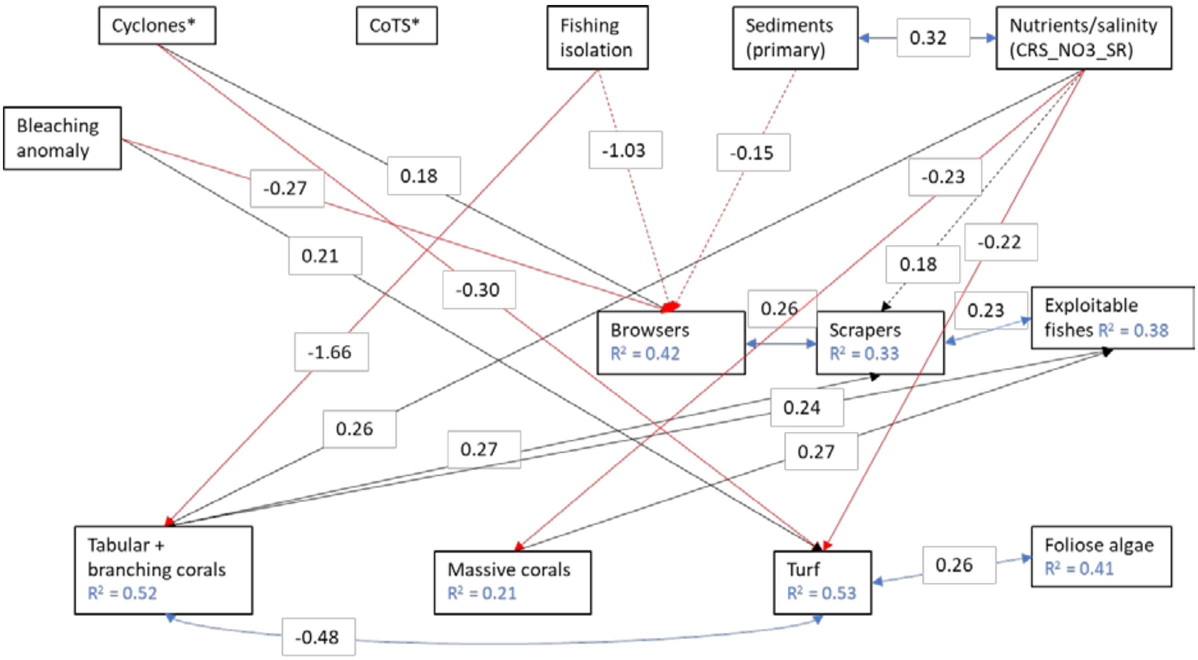


Figure 6. Structural equation model fitted to spatial data on pressures, fish biomass and coral cover data along the entire length of the Great Barrier Reef following the 2016 bleaching event. Standardised effect sizes are shown for each linkage to allow comparison between linkages within the model. Red arrows represent significant negative effects in the directions shown, while black arrows represent significant positive effects. Dotted lines are shown for linkages which were marginally non-significant.

The primary conclusions of the case study include that signals of localised impact from cumulative pressures may be masked by broader regionally-acting pressures, and indirect effects may be weak and highly context-dependent. The implications of these for dealing with cumulative impacts in a practical sense include preparing for the high probability that important impacts will be missed by standard assessment procedures, effectively through a lack of true 'controls'. This points to a critical role of long-term monitoring data and not just the use of spatial designs to test for impact.

An important question in the context of this case study is whether a new development is likely to have (or has had) impacts on identified values of the GBR relating to the bony fishes. Based on conceptual models and current ecological thinking, one may expect that any new development which impacts on the cover of structurally complex corals will have some sort of indirect impact on the fish community. The results of this case study reveal some particular nuances to these pathways of impact. Firstly, damage to corals may actually benefit some herbivorous fishes. For example, cyclones appeared to directly benefit browsing herbivores (which were positively linked with scraping herbivores) in both SEM models. Although not empirically demonstrated here, it is plausible that the disturbance of a cyclone could stimulate algal growth and provide increased food production for herbivorous fishes (even if not detectable in changes of the standing crop or percentage of foliose or turf algae). In such a case, a trade-off may exist between prioritising coral values vs prioritising ecological value associated with fish herbivory, although presumably prioritising corals would be the preferred management option, given the rationale for the ecological value of herbivores is to putatively promote coral recovery.

A second nuance relates to the strength and context-dependence of habitat cover on exploitable fish biomass. The exploitable component of the fish community investigated here, although dominated by predators of fishes and invertebrates, includes a huge range of ecological diversity. The dependence of each species on complex habitats for shelter and outcomes for their feeding efficiency will vary considerably. In some cases, loss of complex corals could have extreme effects on the biomass of exploitable fishes, while in other circumstances, negative effects may be greatly diminished through prey switching mechanisms and compensatory dynamics where small herbivorous fishes and grazing invertebrates may fill the niches of the prey. Such complexities will make detection of indirect impacts of habitat loss on fish values extremely difficult, and likely resulted in weak or no relationships in our SEM models. Caution must be exercised in assuming no impact is likely as a result of a development. Ongoing monitoring programs with high site-level replication, covering large regions and the full fish community are needed to provide the best ecological context possible, but a precautionary approach is also highly recommended.

The case study example presented here met the characteristics for a robust assessment well for almost all criteria. The structural equation modelling incorporates an analysis of uncertainty expressed as R2 values for the state variables. However, these results are based on the mean values of pressures, and as previously identified, the full distribution of pressure intensity and maximum values were not incorporated in this case study. Thus, there should be a level of caution in interpreting and applying these results.

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APPENDIX A – BACKGROUND CONCEPTS

1. MAPPING PRESSURES

Most studies on pressures focus on impacts of single activities or pressures (Ban et al. 2010), as pressure interactions are often difficult to predict (Crain et al. 2008). Understanding of these interactive effects between pressures is limited, but currently serves as the basis for cumulative assessments and mapping. In mapping the spatial extent of pressures, a linear decay model from the source is generally used (assuming that pressures diffuse equally in all directions), where a precautionary approach has been used to score pressure based on maximum potential intensity and impact. In reality, the pressures at the temporal and spatial scale of the assessment may be much lower than the precautionary maximum and varying distance decays are likely associated with different pressures.

In pressure datasets, the main assumptions relate to the spatial extent of pressures from their sources, quantification of the pressures (often based on scoring the underlying activities), and the normalisation of pressures (Korpinen and Andersen 2016). Existing cumulative impact mapping projects have documented specific examples of modifications for assessing and mapping cumulative impacts.

Activity category	Examples of modifications for mapping cumulative impacts
Vessel traffic	Mapped using a noise propagation model (because noise was considered the predominant pressure) (Clarke Murray et al. 2015b)
Coastal and land-based activities	Treated as a point source impacts and subjected to kernel density decay. Highest intensity assumed to be associated with rivers with large stream orders with a marine outlet. Relative intensity value for each activity calculated (binned into high, medium, low) and used to seed the kernel density decay at the mouth of each estuary for the watershed. The radius of the kernel density decay set by the maximum size of the freshwater plume for that stream from published literature and satellite images (Clarke Murray et al. 2015b).
Fishing	Fishing and associated activities (used the closest equivalent to a fishing vessel) assumed to impact the both deep and shallow water pelagic habitats regardless of depth of fishing gear (Clarke Murray et al. 2015b)
	Single score for fishing, despite pelagic fishing at three depth zones. Each fishery is a different layer (Halpern et al. 2008; Ban et al. 2010)

1.1 Choosing an appropriate scale

Selecting an appropriate spatial and temporal extent is generally recognized as a challenge for assessments of cumulative impacts and the management of multiple activities (Dubé 2003; Duinker and Greig 2006). Assessments of cumulative impacts are frequently limited by spatial and temporal scope. For example, how pressures occurring today might interact with existing or historical pressures, and to what extent have historical pressures already altered the environment (Stelzenmüller et al. 2018).

The most common spatial scales for cumulative assessments include: the proposed project footprint, the political unit (often a county, state, or province), or a watershed in which a proposed project is located. Assessments are rarely at the scale of an eco-region/area containing distinct natural communities despite this spatial scale being considered more useful for cumulative impact assessments (Ma et al. 2009). A review of cumulative impact assessment tools conducted by Stelzenmüller et al. (2018) highlighted that GIS and overlay analysis is very useful to reveal scale mismatches between existing management measures and areas with an increased risk for cumulative impacts.

The majority of cumulative impact assessments focus on the current condition of the area or ecosystem as a baseline against which to measure future disturbances from a proposed project. Past impacts from anthropogenic and natural disturbances are usually factored into the assessment of current level of risk (Johnson 2016) and can be factored in as a description of the desired environmental condition. However, the cumulative impact of these proposed and past projects, along with long-range pressures, such as climate change, and the potential interactions with other proposed projects are generally ignored. Including all potential activities or potential projects both within and outside of the study area is critical for identifying emerging issues or risk (Johnson 2016).

1.2 Uncertainty

Uncertainty is inherent in any cumulative impact assessment and can occur at several stages throughout the process: quantifying the amount of an individual pressure produced by an activity; the extent to which that pressure impacts the ecosystem; how single pressures interact with one another and how these interactions vary across space and time (factors of exposure); and how the ecological component is affected. Uncertainty can occur from inadequate knowledge, low predictive ability of ecosystem behaviour, natural variability, measurement error, or changing policies (Halpern and Fujita 2013; Opdam et al. 2009; Stelzenmüller et al. 2015). This results in high uncertainty in the interactions between the human activities and the resulting cumulative impacts on an ecological component (Clarke Murray et al. 2014).

Uncertainty is one of the most challenging issues facing cumulative impact assessments because of the difficulty in designing statistically appropriate tests to assess effect magnitude beyond two or three interacting pressures (Clarke Murray et al. 2014). Uncertainty is accounted for in cumulative impact assessments using a range of techniques, most commonly Bayesian models, expert opinion, Monte Carlo simulations (O et al. 2015; Batista et al. 2014), and sensitivity analyses.

Cumulative impacts are frequently determined indirectly based on the assumption that the interactions are additive by combining studies on single impacts from several studies (Clark et al. 2002; Clarke Murray et al. 2014). As an extension of this assumption, additive models tend to assume that cumulative impacts are roughly equivalent to the sum of impacts on single species (Clarke Murray et al. 2014).

Recommendations to address uncertainty when assessing cumulative impacts include:

- Conduct additional field experiments to identify cumulative impacts of multiple disturbances and distinguish between single and cumulative impacts by (Crain et al. 2008).
- Conduct additional controlled laboratory experiments explicitly testing a small number of significant pressures and their interactions to gain knowledge of the underlying mechanisms is crucially required (Clarke Murray et al. 2014).
- Conduct research on how multiple pressures interact to evaluate the relative impact of different pressures and the cumulative impacts of their interactions; an important component of this will be account for non-additive interactions (Crain et al. 2008).
- Develop and refine methodologies that allow for the explicit incorporation of uncertainty into models and management decision-making frameworks (Batista et al. 2014, DFO 2012, O et al. 2015, Samhouri and Levin 2012).

1.3 Climate change

The effects of climate change are expected to interact with both current and historic impacts to severely alter the structure and function of marine ecosystems (Clarke Murray et al. 2015a). Incorporating climate change considerations at all stages of the cumulative impact assessment, especially at regional scales, is important for effective impact prediction and forecasts (Agrawala et al. 2012; Duinker and Grieg 2006).

When incorporated into cumulative impact assessments, Clarke Murray et al. (2015a) found that the biggest change in potential cumulative impacts was due to climate change pressures. In their assessment of cumulative impacts, they found that climate change was the dominant impact at the coast-wide scale in British Columbia and land-based activities had a higher potential impact at local scale (Clarke Murray et al. 2015a).

Weitzman (2016) proposes three actions to help governments better incorporate climate change considerations into the environmental assessment process. These actions include:

1. Strengthen legislative foundation for incorporating climate change in environmental assessment;

2. Standardise guidelines, lists, and project-level requirements;

3. Implement regional-level and strategic considerations for climate change, especially in vulnerable areas.

1.4 Data and knowledge gaps

1.4.1 Data gaps

Understanding the potential cumulative impacts in a specific area is reliant on the quantity and quality of data available on pressures and habitats (Clarke Murray et al. 2015b), as well as the risk of harm to these habitats from pressures. Common data limitations include: limited information about future developments (*e.g.,* commercial fishing, recreational boating, etc.); older data; imprecise data (commercial fishing is a commonly listed example of both older and imprecise data); differing data resolutions; differing timescales and ranges; and lack of baseline information.

In the absence of empirical data, expert opinion is commonly used as a way to derive baselines for conceptualizing the magnitude of the cumulative impacts or quantifying the effectiveness of management measures (Stelzenmüller et al. 2018). General industry trend information may be available at a regional scale (*e.g.,* projected increases in recreational boating), but is not applicable at the fine resolution needed for cumulative impact models. Similarly, climate change data is relatively coarse and does not represent projected future change (Clarke Murray et al. 2015b). The result of coarse data is offshore ecosystems tend to be better represented than inshore impacts where local oceanography and conditions modify the impacts, particularly for climate change pressures (Halpern et al. 2008). These issues tend to result in both under and over-estimation of cumulative impacts and makes it difficult to have current and consistent cumulative impact estimates (Clarke Murray et al. 2015b).

A lack of spatial and temporal data adds to the challenge of untangling cause-effect pathways for most cumulative impact assessments (Stelzenmüller et al. 2018). The temporal scale of most systematic monitoring rarely spans the past few decades and fails to encompass the life spans of many species or environmental disturbances (*e.g.,* El Nino-Southern Oscillation) (Stelzenmüller et al. 2018). As a result, setting meaningful-benchmarks or tipping points is difficult and compromises the quantification of pressure-state relationships.

1.4.2 Knowledge gaps

While there is a growing body of research focusing on single pressures associated with several activities, there is a paucity of information on multiple pressures associated with multiple activities where the interactions between each pressure and impact is determined. Additionally, many studies focus on single ecosystem components, as opposed to defining the risks to ecosystem functions or services (Stelzenmüller et al. 2018).

Understanding the relationship between a single activity that produces a single pressure and its impacts on the marine environment can prove difficult (Clarke Murray et al. 2014). Tracing the source of the pressure back to an activity can be challenging, as many pressures are diffuse (*e.g.,* noise) and may originate from multiple activities. Additionally, research and monitoring of activities tend to focus on direct impacts, ignoring indirect impacts (Clarke Murray et al. 2014).

While the base assumption of mapping cumulative impacts is that the interactions between pressures and ecosystem components is additive, experimentation is necessary to predict non-additive interactions between pressures and ecosystem components (Clarke Murray et al. 2015b).

2. UNDERSTANDING VALUES

2.1 Mapping of valued components of system

There are many ways of valuing coastal and marine areas, including ecological (*e.g.,* biodiversity, productivity), economic (*e.g.,* economic benefits from harvesting and regulation) and socio-cultural values (*e.g.,* spiritual fulfilment, aesthetic enjoyment and recreation). The values that are identified in any survey will reflect the questions asked, the stakeholders involved and their priorities. It is important that the value ascribed to a particular area or asset reflects the importance stakeholders with different spatial outlooks give to these assets – local communities may value an inshore area for fishing, national governments might value the same area for mining rights, while Traditional Owners would have values intrinsic to their cultural heritage.

Conservation values have been defined by the Australian Government as Matters of National Environmental Significance (MNES). MNES are the assets in the environment that have been defined under the EPBC Act as being important for the continued functioning of marine ecosystems. Australian Marine Parks will also have values linked to local flora, fauna and conditions that need to be protected at a higher level than the surrounding waters. Within the GBR world Heritage area there are also outstanding universal values as defined by the World Heritage criteria.

Assessing interactions between the ecological, cultural and economic values and different uses of the marine environment will help identify scenarios that support mutually compatible activities and provide management options to avoid, mitigate (or offset) activities that are not compatible with the different values identified. For example, activities such as aggregate mining might be incompatible with many ecological values and other uses such as ecotourism. The mix of value and use will be driven by the context of the area, its potential, and the objectives of managers and other stakeholders.

2.2 Habitats in the GBR: the containers for values

In the GBR, MNES are meant to reflect the key values of the Reef. The characteristics of many MNES are well described but their distribution of often not. In many cases, however, the MNES are can be associated with habitats that sufficiently describe their locations. This offers the potential to use the distributions of habitats to (1) describe the distribution of values and (2) describe the ecosystems that support these values and the pressures that may impact them. The distribution of many of these habitats (Table A4.1 GBRMPA Cumulative Impact Management Policy) have been identified (from state and federal data sets) and can be mapped for the entire GBR Management region (Figure 7).

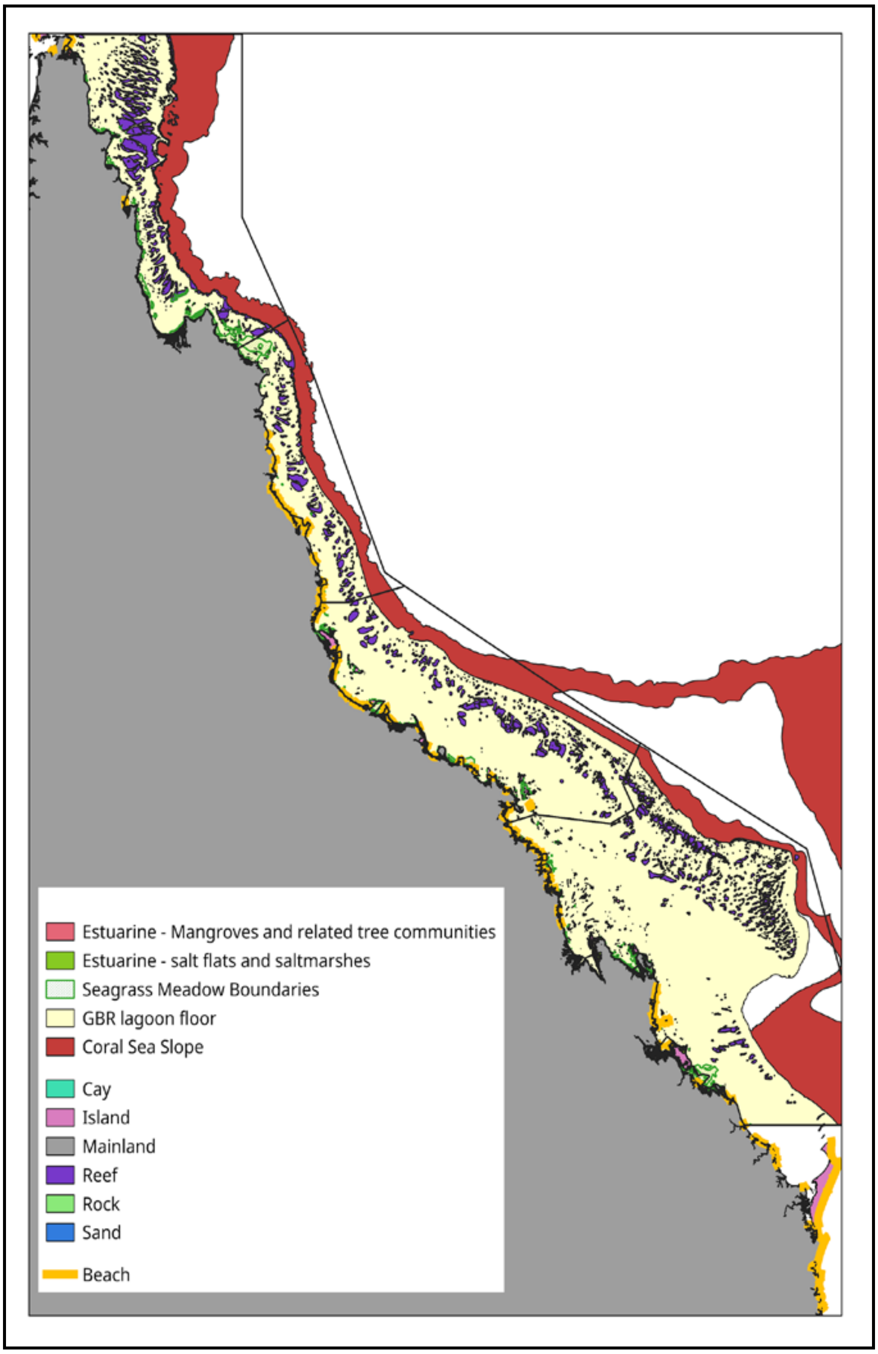

Figure 7. Distribution of Habitats listed within Table A4.1 of the GBR Cumulative Impact Management Policy.

2.3 Integrating Social Values

Environmental managers are increasingly seeking guidance and strategies to integrate social and cultural values into the sustainable management of ecosystems (Satterfield et al. 2013, Satz et al. 2013, Fish et al. 2015). This is key information to support decisions where the economic values can be well described through standard economic valuation practices but where the social values are less clear. How people value natural resources is key information for environmental managers needing to identify what needs to be protected and for whom (Ban et al. 2013, Bennett et al. 2017, Klain et al. 2014, Loc et al. 2018). By measuring and understanding the values that different stakeholders within the one ecosystem hold for that ecosystem, resource managers are able to see what values are shared across stakeholder groups and need to be protected for the benefit of all (Marshall et al. 2018). Divergent values indicate what to protect for the benefit of particular stakeholder groups. Of the nine values that Marshall et al. (2018) assessed (identity, pride, place, aesthetic appeal, biodiversity, lifestyle, heritage, and agency), all were important for all stakeholders within the context of the Great Barrier Reef. Interestingly, the most highly rated values across all stakeholder groups included reef aesthetics, biodiversity and pride in the World Heritage Areas designation. In the South Australian Murray Darling Basin region, the most highly valued ecosystem services were recreation and tourism, bequest, intrinsic and existence, fresh water provision, water regulation and food provision (Raymond et al. 2009).

The term ‘values’ is commonly used to refer to many related but different concepts. We provide a simple framework, drawing on Brown (1984), to help distinguish and relate three core value concepts:

Held values: the nature of that relationship is shaped by the values they hold within themselves: for example, their moral compass.

Relational values: primarily, the importance or value of a thing derives from how people experience the thing; the relationship between people and the thing.

Assigned values: things are often described in very specific ways for particular purposes: example to reflect their importance in a value relationship or connect them to a decision making process.

Example 7. SELTMP case study on approaches to social and cultural values

The Social and Economic Long Term Monitoring Program (SELTMP) for the Great Barrier Reef is gathering long-term data specific to Reef users, communities and industries, and providing new insights into relationships between people and this iconic natural resource. SELTMP synthesises existing socio-economic data from a wide range of sources and addresses key knowledge gaps by conducting large-scale surveys of Reef user groups.

The first of such surveys, in 2013, questioned 8,300 people (commercial fishers, tourism operators, tourists, and coastal and national residents) about their dependence, usage and affinity with the Reef, as well as their perceptions, values, experiences, attitudes and behaviours.

In order to determine the value of a number of different environments within the Great Barrier Reef (beaches, creeks and estuaries, islands and cays, inshore reefs, mid-shelf and outer reefs, open water, and shipwrecks), survey questions were designed to ascertain the values that people held for each environment. Eight values were sought (pride, identity, biodiversity, lifestyle, heritage, economics, wellbeing, and aesthetics). SELTMP participants (*n*=1,034) were asked to agree or disagree with each survey statement on a ten-point scale where a rating of 1 represented “very strongly disagree” and 10 represented, “very strongly agree”. One question asked participants to describe their resource use: “Thinking about all of your visits to the Great Barrier Reef in the last 12 months, what proportion of your time was spent at each of the following GBR environments” (beaches on the coast, creeks and estuaries, islands and cays, inshore reefs, mid shelf and outer reefs, open water, shipwrecks).

Results suggested that most reef users spent the majority of their time on beaches, which are typically the ecosystems closest to where people live. People that tended to use the beach the most were sunbathers, people collecting shells, and sightseers. People that used creeks and estuaries the most were net/trap fishers, spearfishers, and line fishers. Islands and cays were used mostly for spearfishing, motorised watersports, and sailing. Inshore reefs were used mostly by spearfishers, net/trap fishers, and motor-boaters. Mid and outer reefs were used mostly by spearfishers, net/trap fishers, and SCUBA divers. The open water was used mostly by net/trap fishers, spearfishers, and people using motorised watersports. Shipwrecks were used mostly by net/trap fishers, spearfishers, and line fishers (Fig. 8). That is, spearfishers and net fishers used inshore reefs, mid and outer reefs, open water and shipwrecks than other reef users.

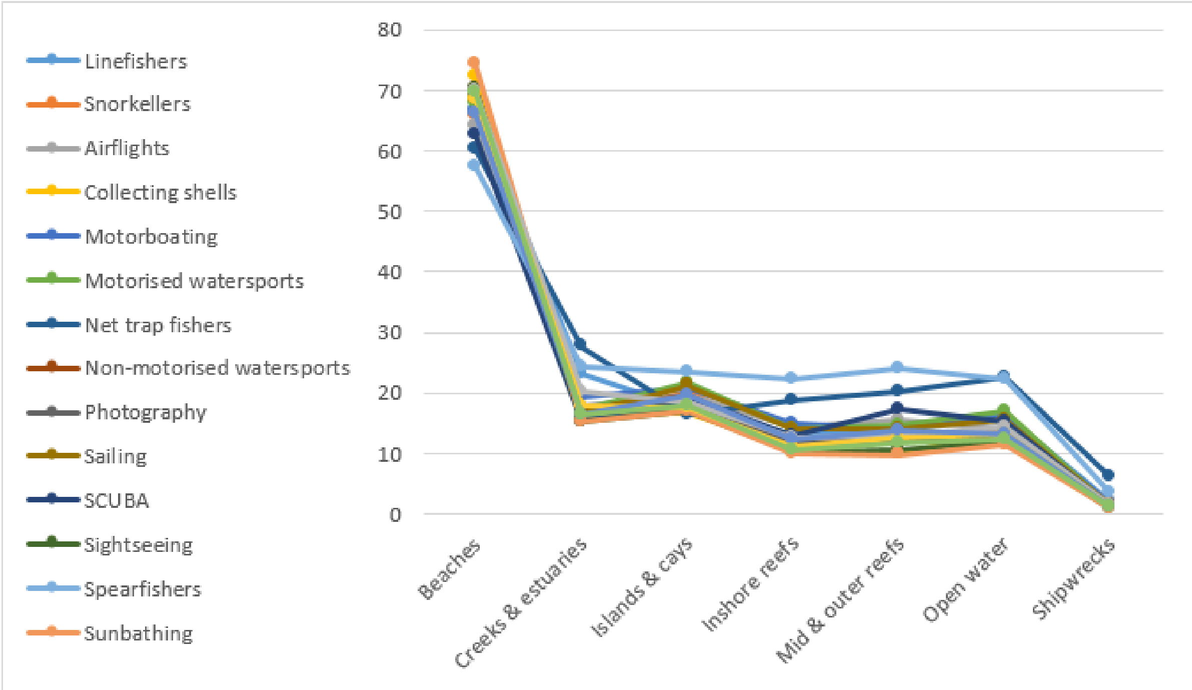

Figure 8. Habitat uses and users within each of the seven ecosystems of the Great Barrier Reef. Survey participant's responses to the question: "Thinking about all of your visits to the Great Barrier Reef in the last 12 months, what proportion of your time was spent at each of the following GBR environments?

3. CONCEPTUAL MODELS

Conceptual models play a foundational role in the risk assessment process. Their most basic function is to represent a collective understanding about how an ecosystem works. They should: a) identify the important components and processes in the system; b) document assumptions about how these components and processes are related; c) identify the linkages between these components/processes and anthropogenic pressures; and d) identify knowledge gaps or other sources of uncertainty (Manley et al. 2000, NPS 2012, Hayes et al. 2012). It is important that the formulation of a conceptual model occurs early in the risk assessment process, as it drives the collation of system knowledge and understanding about how the system works and how it might respond to anthropogenic pressures, and thereby ensures that relevant components are included in the scope and design of the assessment.

Maddox et al. (1999) recognise three general roles of ecological modelling:

- to summarise the most important ecosystem descriptors, spatial and temporal scales of biological processes, and current and potential threats to the system
- to identify identifying aspects of the ecosystem that should be measured for the purpose of assessment endpoints and monitoring
- to interpret monitoring results and explore alternative courses of management.

It is important to recognise that while the goal of a conceptual model is to document current understanding about an ecosystem, the model itself cannot represent an objective "truth'. It should be considered as a working draft in need of updating as errors are identified and understanding is advanced; moreover, it is not expected to be complete or include all aspects or components of an ecosystem.

Construction of conceptual models can include a broad range of tools, including simple narrative descriptions, schematic diagrams, box-and-arrow flowcharts, or even cartoons that pictorially illustrate physical and biological processes and the effects of anthropogenic pressures. Despite their varied form that they can take, they will include common elements and be built through a common set of steps.

Gross (2003) provides a series of nine steps in constructing conceptual models:

1. Clearly state the goals of the conceptual models.
2. Identify bounds of the system of interest.
3. Identify key model components, subsystems, and interactions.
4. Develop control models of key systems and subsystems.
5. Identify natural and anthropogenic pressures.
6. Describe relationships of stressors, ecological factors, and responses.
7. Articulate key questions or alternative approaches.
8. Identify inclusive list of indicators (i.e., assessment and measurement endpoints) and prioritise them.
9. Review, revise and refine.

Conceptual models need to portray the ecological system at a level of resolution that is useful to the purposes of the risk assessment, striking a balance between simplicity and complexity. They should not seek to represent the entire system with myriad components and processes; rather the goal should be to encompass the relevant subsystem (Dambacher et al. 2009, 2015), which includes the components of the system that are the focus of the risk assessment, the associated processes and variables that act to maintain and regulate them, and the natural and anthropogenic pressures or concern. For assessments within the GBR, conceptual models may be narrowly focused on site specific values, and thus be limited to isolated components of the system with few pressures, or they may need to represent a large number of interacting components with complex relationships. For the latter application, the modelling exercise may have a broad focus that can be represented through the functioning of critical habitats (e.g., corals, seagrass). For any application and scale, however, the role of the conceptual model is to convey how pressures acting on a system can conceivably impact valued components of the ecosystem and provide a spatial and temporal context relevant to the proposed project or plan of management.

Going beyond narratives and cartoons, mathematical models that can be used to address ecosystems with greater complexity in their physical and biological processes. These can include population viability models, spatially explicit population- community- and landscape-level process models, and regional-scale whole-of-system models (Maddox et al. 1999).

While these models have greater sophistication, they come with a greater cost to develop and maintain. Moreover, if their inner workings and output are overly complex, they can be difficult for managers to understand and act upon and they run the danger of alienating the public (Lindenmayer and Likens 2010). It will thus be important to find a useful level of model complexity that strikes a workable balance between model generality, reality and precision (*sensu* Levins 1966,1998, 2006).

One form of mathematical models are qualitative models, which have been used to guide monitoring programs in the GBR (Dambacher et al. 2012, 2013, Kuhnert et al. 2014) and assessing cumulative impacts and aid structured decision making (Anthony et al. 2013). A basic feature of qualitative models is the development and analysis of sign directed graphs, or signed digraphs (see Example 5). These can be used to describe the main interacting variables within a system, linking elements and values to their surrounding ecosystem and also to the pressures of concern. While model links are qualitative, such that they represent only the 'sign' of the effects (i.e., positive, negative or nil), they nonetheless provide a rigorous means to formally assess a system's dynamics, predict its response to disturbances and explore the potential outcome of management interventions.

3.1 Examples of conceptual models of key habitats in the GBR

Where applicable, assessments can make of use of existing conceptual models; for example, conceptual models have been developed to examine the relationships of pressures and values for seagrass, coral reefs and inshore plankton (Figs 9-16). These models were developed as qualitative process models through workshops with experts in coral reef and seagrass biology and water quality of pelagic ecosystems (Anthony et al. 2013; Dambacher et al. 2012, 2013; Kuhnert et al. 2014).

The below models detail the main variables and effects at a relatively general level of resolution and exclude minor species groups and weak effects. There were a number of links that were uncertain or contentious, which provide the basis to consider alternative model structures; see source material for detailed explanation of the causal understanding underpinning each model.

3.1.1 Seagrass

Pressures included in seagrass models include:

- Fresh water
- Nutrients
- Ocean warming
- Root disturbance
- Sediments
- Structural damage
- Suspended solids
- Toxicants

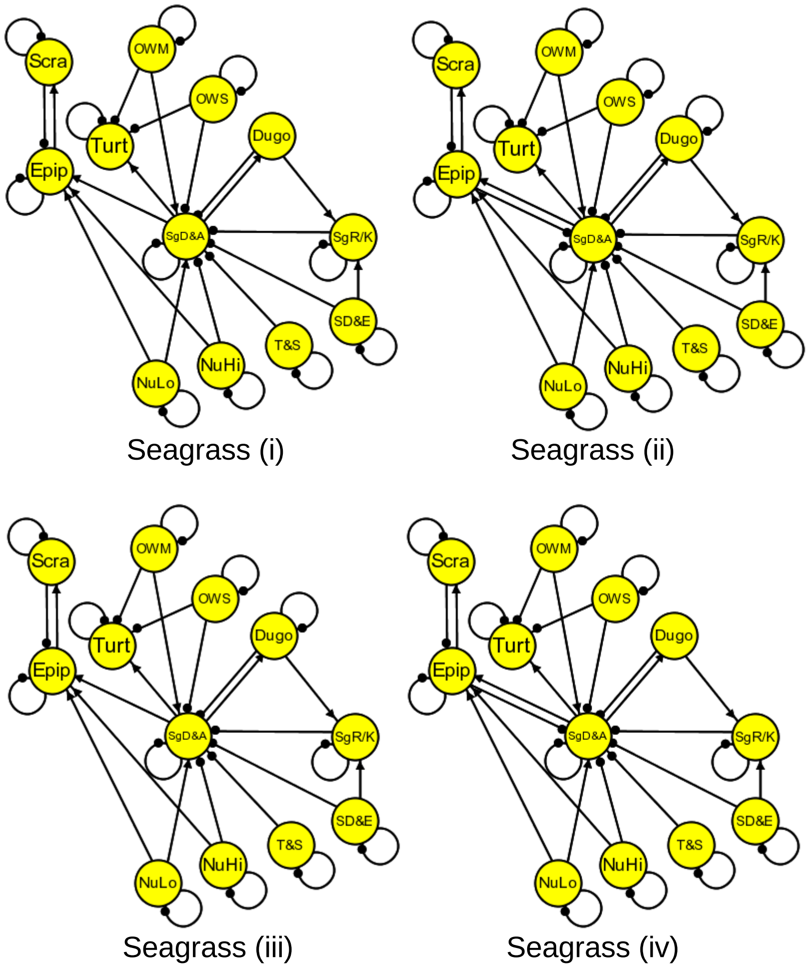

Figure 9. Alternative signed digraph models of seagrass ecosystems (Anthony et al. 2013); Dugo: dugong, Epip: epiphytes, NuHi: nutrients high, NuLo: nutrients low, OWM: ocean warming mild, OWS: ocean warming severe, Scra: scrapers (prawns and fish), SD&E: structural damage and erosion, SgD&A: seagrass distribution and abundance, SgR/K: seagrass *r* versus *K* life-history strategy, T&S: turbidity and sedimentation, Turt: turtle. Alternative models based on presence-absence of links from Epip to SgD&A, and negative self-effect of Dugo.

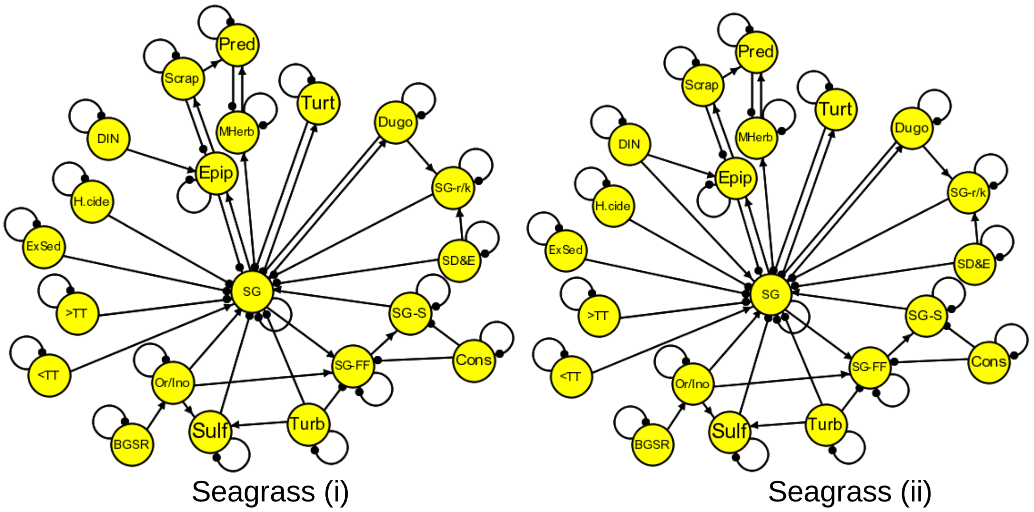

Figure 10. Signed digraph models of seagrass ecosystems of the GBRWHA (Kuhnert et al. 2014); variable names are BGSR: background sediment regime, Cons: consumers of seagrass fruits and seeds, DIN: dissolved inorganic nitrogen, Dugo: dugong, Epip: epiphytes, ExSed: excessive sediment, H.cide: herbicide, MHerb: mid-sized herbivores, Or/Inorg: organic-to-inorganic sediment ratio, Pred: predators, Scrap: scrapers, SD&E: structural damage and erosion, SG: seagrass, SG-FF: seagrass flowers and fruits, SG-r/k: ratio of *r* and *k* seagrass growth form or species, SG-S: seagrass seeds, Sulf: sulfides, Turb: turbidity, Turt: turtles, <TT: temperature below critical threshold, >TT: temperature above critical threshold. Alternative models based on presence-absence of links from DIN to SG.

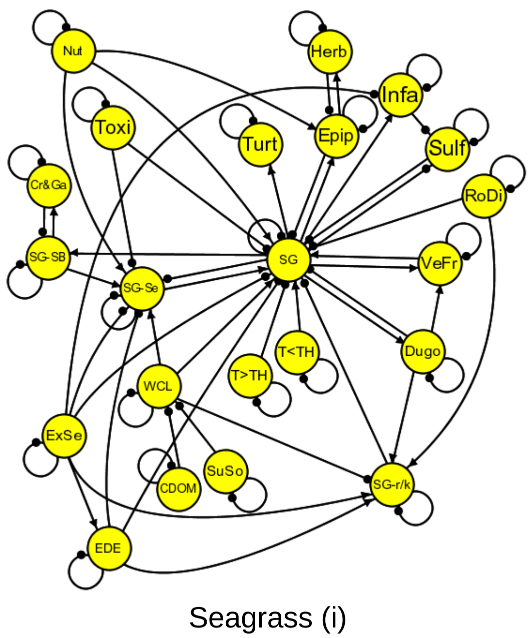

Figure 11. Signed digraph model of seagrass life stages in Gladstone Harbour (Dambacher et al. 2013); variables names are CDOM: coloured dissolved organic matter, Cr&Ga: crustacean and gastropods, Dugo: dugongs, EDE: excessive daytime exposure, Epip: epiphytes, ExSe: excess sediments, Herb: herbivores, Infa: infauna, Nut: nutrients, RoDi: root disturbance (i.e., storms, animal burrows, boat and shipping impacts, erosive currents, dredging), SG: seagrass, SG–r/k: seagrass ratio of r and k growth form or species, SG–SB: seagrass seed bed, SG–Se: seagrass seedlings, Sulf: sulfides, SuSo: suspended solids (i.e., from storms, flooding, boat wakes, shipping, change in currents, dredging, waves, spring tides), T<TH: temperature below threshold, T>TH: temperature above threshold, Toxi: toxicants (i.e., from shipping and runoff from industry, urban, and agricultural sources), Turt: turtles, VeFr: vegetative fragments, WCL: water column light.

3.1.2 Coral reefs

Pressures included in coral reef models include:

- Crown of thorns starfish
- Dissolved inorganic nitrogen
- Fresh water
- Nutrients
- Ocean warming
- Pesticides
- Storms
- Suspended solids
- Turbidity and sedimentation

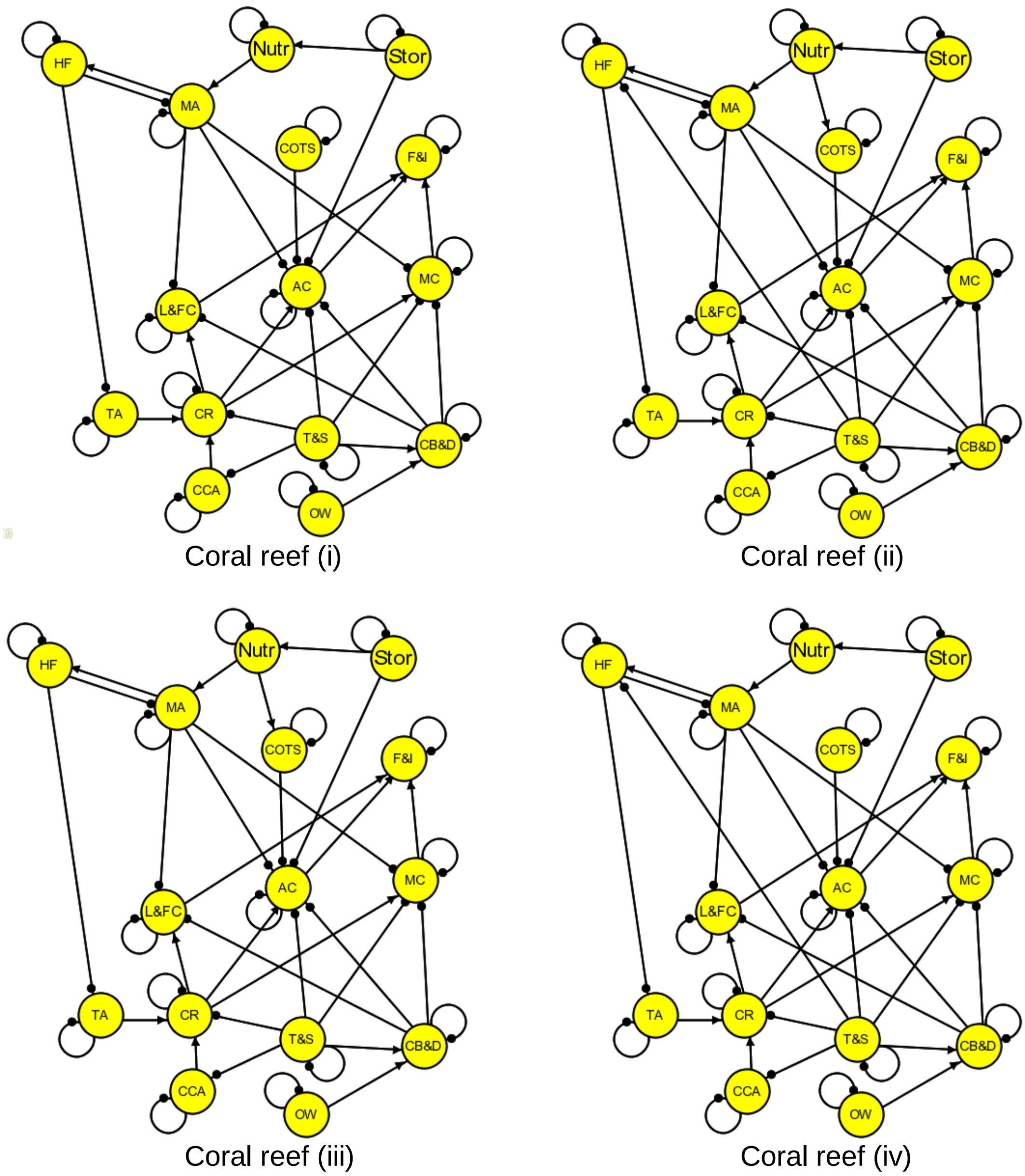

Figure 12. Alternative signed digraph models of coral reef ecosystems (Anthony et al. 2013); AC: *Acropora* corals, CB&D: coral bleaching and disease, CCA: crustose coralline algae, COTS: crown of thorns starfish, CR: coral recruitment, F&I: fishes & invertebrates, HF: herbivorous fishes, L&FC: laminar and foliose corals, MA: macro algae, MC: massive corals, Nutr: nutrients, OW: ocean warming, Stor: storms, TA: turf algae, T&S: turbidity and sedimentation. Alternative models based on presence-absence of links from Nutr to COTS, and from T&S to HF.

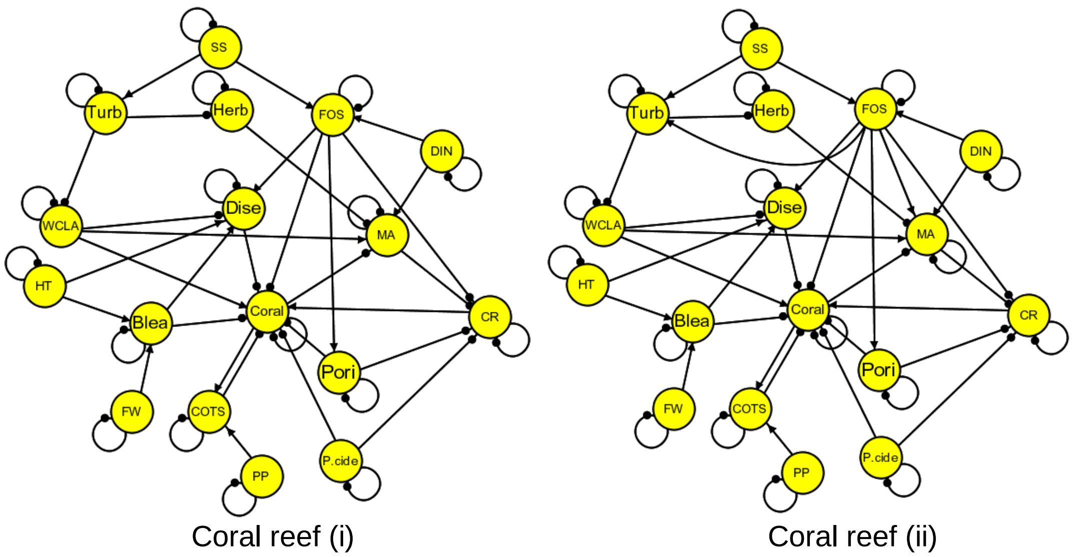

Figure 13. Signed digraph models of coral reef ecosystems of the GBRWHA (Kuhnert et al. 2014); variable names are Blea: bleaching, COTS: crown of thorns starfish, CR: coral recruitment, DIN: dissolved inorganic nitrogen, Dise: disease, FOS: flocculated organic sediments, FW: fresh water, Herb: herbivore, HT: high temperature, LZP: large zooplankton, MA: macroalgae, P.cide: pesticides, Pori: porifera, SS: suspended solids, Turb: turbidity, WCLA: water column light availability. Alternative models based on presence-absence of links from FOS to Turb and MA.

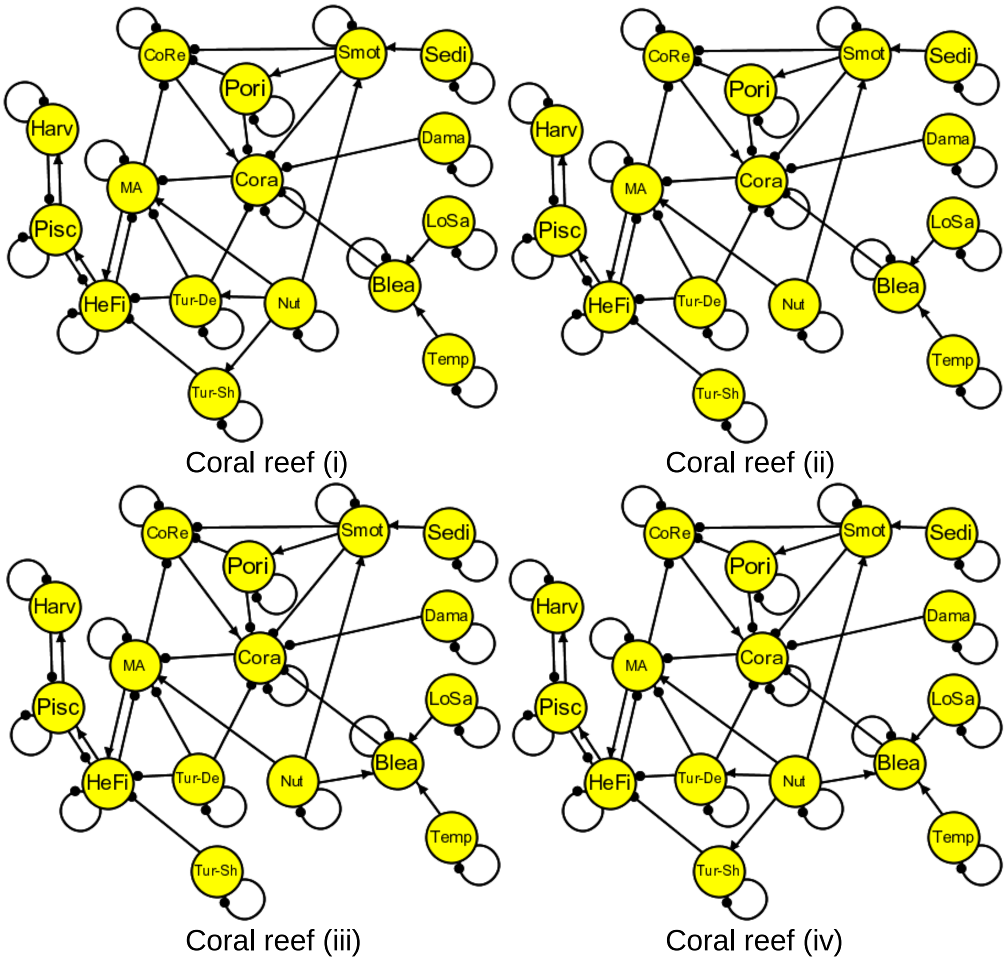

Figure 14. Signed digraph models of coral reef ecosystems in Gladstone Harbour (Dambacher et al. 2013); variables names are Blea: bleaching, Cora: coral, CoRe: coral recruitment, Dama: damage, Harv: harvest, HeFi: herbivorous fishes, LoSa: low salinity, MA: macro algae, Nut: nutrients, Pisc: piscivores, Pori: porifera, Sedi: sediment, Smot: smothering, Temp: temperature, Tur–De: turbidity deep (>5m depth), Tur–Sh: turbidity shallow (<5 m depth). Alternative models based on presence-absence of links from Nut to Tur-De and Tur-Sh, and from Nut to Blea.

3.1.3 Inshore Plankton

Pressures included in inshore plankton models include:

- Nutrients
- River runoff
- Suspended sediments

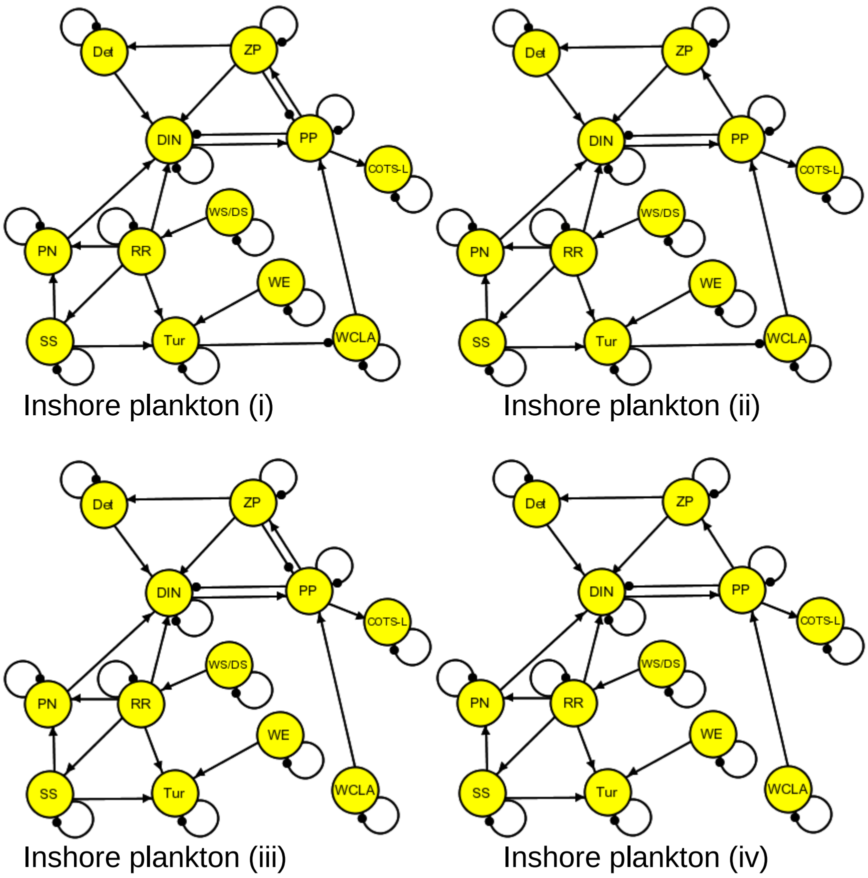

Figure 15. Signed digraph models of inshore plankton community of the GBRWHA (Kuhnert et al. 2014); variable names are COTS-L: crown of thorns starfish larvae, Det: detritus, DIN: dissolved inorganic nitrogen, PN: particulate nitrogen, PP: phytoplankton, RR: river runoff, SS: suspended solids, Tur: turbidity, WCLA: water column light availability, WE: wave energy, WS/DS: wet season versus dry season, ZP: zooplankton. Alternative models based on presence-absence of links from ZP to PP, and from WCLA to PP.

3.1.4 Islands (reefs and cays) ecosystems

Pressures included in island (reefs and cays) models include:

- Acidification
- Sea level and storm intensity
- Temperature

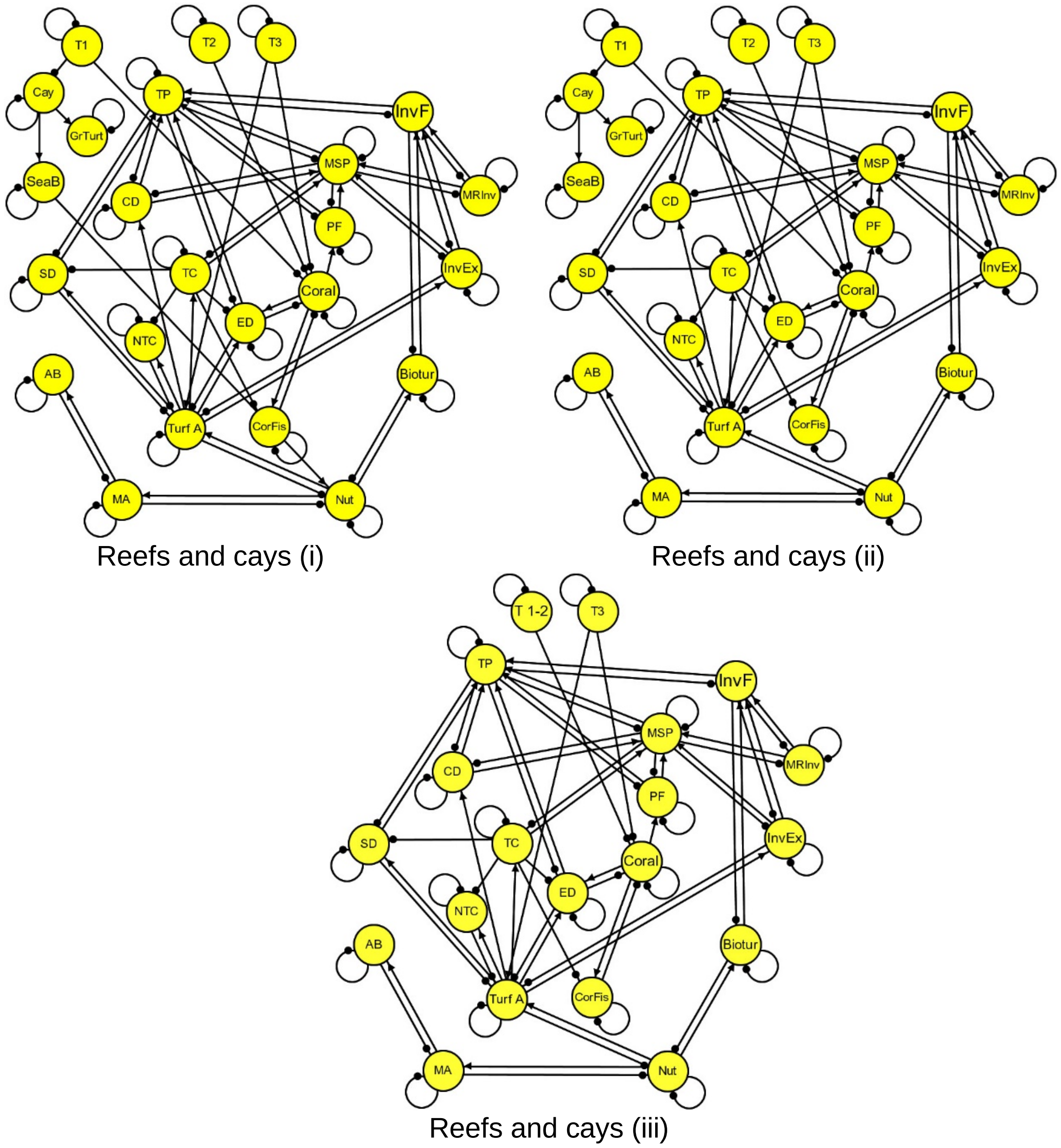

Figure 16. Signed digraph models of Reefs, Cays and Herbivorous Fishes (Dambacher et al. 2012); model variables are Biotur: bioturbators, Cay, CD: combing detritivore, Coral, AB: algal browsers, CorFish: coralivore fish, EC: excavating detritivore, GrTurt: green turtle, InvEx: invertebrate excavator, InvF: invertivorous fish, MA: macroalgae, MRInv: mobile reef invertebrates, MSP: mid-sized predators, NTC: non-territorial croppers, Nut: nutrients, PF: planktivorous fish, SD: scraping detritivore, SeaB: seabirds, TC: territorial croppers, TP: top predators, and TurfA: turf algae. Pressures (threats): T1: increased sea level and storm intensity, T2: acidification, T3: increased sea surface temperature.

4. ZONE OF INFLUENCE

4.1 Effect of pressure or activity on ecosystem

To adequately disentangle direct and indirect effects of a pressure in complex ecosystems, it is imperative that ecosystem component(s) that are *directly* affected by the pressure or activity first be identified. The next step is to then identify potential impacts to other components that represent MNES. This latter step is aided by an examination of conceptual models of the system and identifying the causal pathways of interaction that link the pressure or activity to ecosystem values. For instance, in Fig. 17b, nutrient runoff from a catchment is shown as a pressure that has a direct effect on epiphytic algae. Indirectly, however, it can also affect seagrass, juvenile fishes and dugongs, all of which are MNES. It would be less informative to approach an assessment of risk to dugongs from increased levels of nutrients without first establishing by which component nutrients directly affect and the causal relationships of intervening variables.

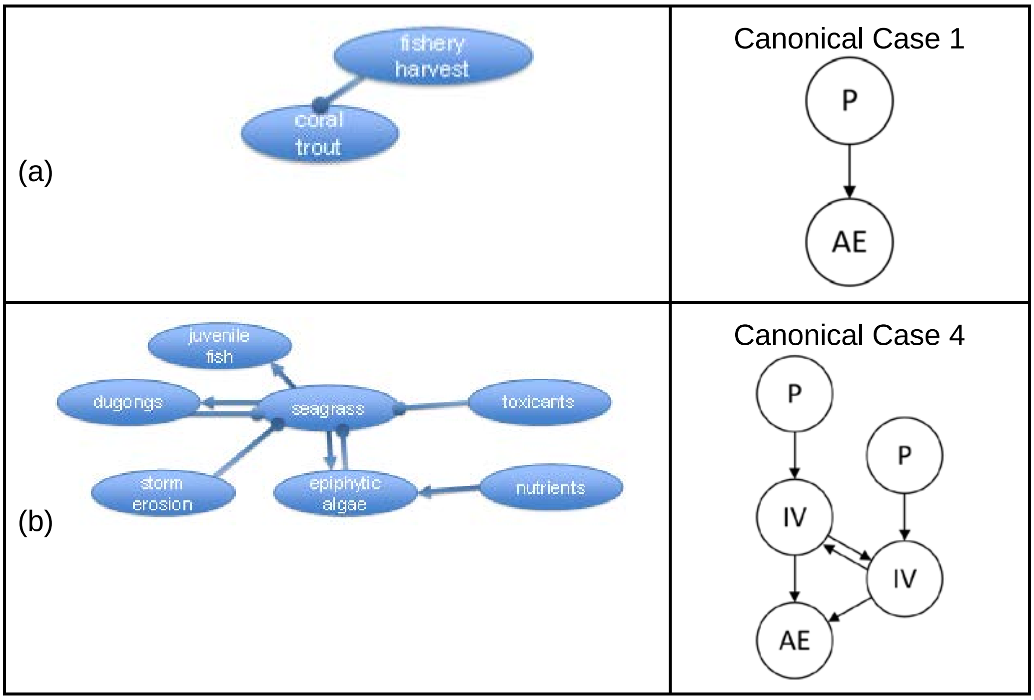

Figure 17. Simplified conceptual models of ecological systems; links ending in an arrow denote a positive direct effect, negative direct effects are denoted by link ending in filled circle. The system in (a) conforms to a most simple cause-effect relationship (Canonical Case 1 of Fig. 2) and in (b) is a more complex system with feedback and multiple pressures (Canonical Case 4 of Fig. 2).

4.2 Assessment and measurement endpoints

Assessment endpoints will typically be a MNES. They are intended to be clear manifestation of a value that is to be protected and may also have multiple attributes that are of value (e.g., a population of coral trout can be valued for its contribution to biodiversity, its contribution to healthy reef functioning through the process of predation or its contribution to catch in recreational fisheries). Measurement endpoints are aspects of a MNES that are 1) accepted as an informative indicator of the condition or state of an associated assessment endpoint with respect to its value, 2) measurable, 3) are sensitive to a pressure or activity, and occur at different levels of organization.

A general list of different types of ecological endpoints, adapted from USEPA 2003, can include:

Organism-level endpoints

- Gross anomalies
- Kills and mortality events
- Rates of survival, growth and reproduction

Population-level endpoints

- Abundance
- Distribution
- Extirpation
- Production

Community-level and ecosystem-level endpoints

- Abundance
- Area
- Distribution
- Function
- Physical structure
- Production
- Species or taxa richness
- Succession stage

Habitat endpoints

- Area
- Quality
- Succession stage

Natural and cultural heritage endpoints

- Characteristics of designated sites
- Status of designated sites

To establish a zone of influence for a given pressure, it is desirable that there is a well-defined relationship describing its impact on individual measurement endpoints (i.e., dose-response type relationships or loss functions). These relationships are also central to establishing meaningful calculations of risk and actionable acceptance criteria, thus the availability of pre-existing knowledge and data will be an important consideration in the selection of measurement endpoint for a given pressure. Where possible, measurement endpoint should also be selected to minimize the number of intervening variables between the pressure and the assessment endpoint, thus limiting the degree of inference required to address the impact of pressures on values. Additionally, to maintain the relevancy of the risk assessment to management concerns and decision making, the nature of the measurement endpoint should be aligned as closely as possible with the value that the assessment endpoint is meant to represent. For instance, in Fig. 17a the pressure of harvest mortality impacts coral trout directly with no intervening variables. If coral trout are selected as an assessment endpoint to represent biodiversity of bony fishes, then population size could be the most useful measurement endpoint, but if selected to represent the process of predation on coral reefs, then average size may be more relevant.

In complex ecosystems, it may often be the case that some MNES are too difficult to measure directly, although their state may be sufficiently described by another highly correlated component of the system. For example, in Fig. 17b, if dugong populations cannot be effectively monitored, then either the abundance or growth rate of seagrass, a critical food resource for dugongs, may be an acceptable and useful measurement endpoint. Similarly, seagrass has been identified as a critical habitat for juveniles of some populations of bony fishes, which may also be difficult to monitor. In the examples of Table 3, the degree of inference required for assessing impacts of toxicants on juvenile fishes is less than that for assessing the impact of nutrients on dugongs, and involves only one, as opposed to two, intervening variables.

Table 3. Assessment and measurement endpoints for simple and complex systems (Fig. 17) with intervening variables between pressure and assessment endpoints.

Pressure	Assessment endpoint	Measurement endpoint	Intervening variables
Harvest mortality	Coral trout	Coral trout population size Coral trout average size	None
Toxicants	Juvenile fishes	Seagrass distribution and abundance	Seagrass
Nutrients	Dugong	Seagrass distribution and abundance Seagrass growth rate	Epiphytic algae Seagrass

4.2.1 Dose-response relationships

Spatial boundaries for a zone of influence are determined and mapped according to threshold values defined in a dose-response type relationship. Where applicable, threshold values can be based on accepted water quality guidelines for specific pressures (i.e., GBRMPA 2009), empirically derived relationships from the literature or expert elicitation or opinion. Uncertainty in the dose-response relationship should ideally be assessed as a probability derived from empirical data, modelling studies or formal expert elicitation. The resolution of the spatial data describing the pressure or measurement endpoints introduces another form of uncertainty, and courser levels of resolution should attract a more precautionary or conservative threshold value. The number of threshold demarcations used (i.e., low-high, versus low-medium-high versus continuous gradient) is somewhat arbitrary and can be adjusted to meet the needs and methods of the risk assessment but will also depend on the granularity of data layers. At the very least, there should be a designation of a concentration or intensity value beyond which a pressure will have an impact that is likely to be observable.

4.2.2 Mapping zones of influence

Based on the threshold values established in a dose-response relationship, the zone of influence is defined as the area where a pressure that exceeds a predetermined threshold value overlaps with a MNES, as represented by a specified measurement endpoint. A key challenge for developing zones of influence is the attribution of a pressure intensity or concentration to different sources. For instance, in Example 6, a zone of influence for turbidity originating from a catchment is shown to overlap with turbidity emanating from a port development, both of which combine, to varying degree, and overlap with seagrass beds. Assigning probabilities for pressures from different sources will require a combination of survey and remote sensing data and results of modelling studies (*i.e.,* eReefs, see sections for mapping pressures and for mapping values).

In some instances the impacts from a given pressure can extend beyond the region where it has an immediate and direct impact on a MNES. These impacts will require consideration of the causal knock-on effects and how these can potentially propagate to other areas of the Reef; possible examples include:

- Nutrient runoff from catchments may have a direct impact on pelagic ecosystems that is limited to nearshore areas. The impact on plankton communities, however, has been implicated in causing or amplifying COTS outbreaks, which can have subsequent impacts to coral reefs extending to large regions of the marine park well outside the area of immediate and direct impact of nutrients.

- Port developments have a relatively small footprint associated with their infrastructure. However, the associated activities such as dredging and dredge spoil management, and increases in ship anchoring areas, shipping lanes and shipping traffic can all lead to secondary impacts well outside the immediate port area.

5. RISK AND UNCERTAINTY

5.1 Types of cumulative impact assessments

Existing work on cumulative impacts largely fit into two categories: environmental assessment or observational/experimental research studies. Environmental assessments largely focus on the activities and pressure produced by the project being assessed, i.e. a single activity produces multiple pressures, while observational and experimental research studies tend to focus on a single pressure produced by multiple activities, e.g. noise. Ultimately, what is required is the assessment of multiple pressures from multiple activities on multiple components (Clarke Murray et al. 2014). To fully account for the cumulative impacts of multiple activities on coastal and marine ecosystems, scientists and managers must be able to understand: (1) which activities cause which pressures; (2) the magnitude, frequency, and spatial scale at which the activities occur; (3) what the resulting direct and indirect cumulative impacts will be on the ecosystem; and, (4) how multiple ecological components at different levels of organization (e.g., individuals, populations, species, communities, and ecosystems) will respond (Clarke Murray et al. 2014).

Under the EPBC Act EIA assessment (as defined by the Significant Impact Guidelines 1.2) the definitions of potential impacts are a:

Direct impact: are the those what are a direct consequence of the action, and

Indirect and offsite impacts include:

1. ‘Downstream’ or ‘downwind’ impacts, such as impacts on wetlands or ocean reefs from sediment, fertilisers or chemicals which are washed or discharged into river systems

2. ‘Upstream impacts’ such as impacts associated with the extraction of raw materials and other inputs which are used to undertake the action, and

3. ‘Facilitated impacts’ which result from further actions (including actions by third parties) which are made possible or facilitated by the action. For example, the construction of a dam for irrigation water facilitates the use of that water by irrigators with associated impacts.

However, as has been noted (Abbot Point CIA 2013, Dunstan and Dambacher 2017 , Hayes et al. 2015, Hayes et al. 2012, Holsman et al. 2017, Minerals Council Australia 2015; Uthicke et al. 2016), these do not cover the full suite of possible cumulative impacts. Additive, Synergistic, Antagonistic impacts are not included and there is no identification of impact pathways through the ecological system.

There are a wide variety of different tools that can be used to assess impact and cumulative impact (Dunstan and Dambacher 2017, Hayes et al. 2015, Hayes et al. 2012, Holsman et al. 2017, Minerals Council Australia 2015, Uthicke et al. 2016). Dunstan and Dambacher (2017) and Holsman et al. (2017) both suggest a hierarchical approach to cumulative impact assessment is appropriate, which could build off the successes of the Ecological Risk assessment for the Ecosystem Effects of Fisheries (ERAEAF, Hobday 2011). This latter approach was designed to address impacts of from a single activity or pressure (fisheries) and expanding it to a more general case will require consideration of multiple methods and the means to assess levels of uncertainty and precaution required by managers.

5.2 Environmental assessment & cumulative impact assessments

Ecosystem based management (EBM) approaches cumulative impacts on an ecosystem level and include intrinsic ecological values. EBM provides a holistic framework for managing multiple activities and preserving ecosystem health (Clarke Murray et al. 2014). EIAs can be project-based (most common), regional, and/or strategic-based (Dubé 2003; Johnson 2016). Project-based assessments typically focus on multiple pressures from a single activity or a single pressure from multiple activities (Noble 2010). Most are a response to regulatory review and approval for an individual project and are at the federal level of screening assessments and the most basic level of assessment (Noble 2010). Project-based EIAs are generally restricted to the geographic footprint of the project; therefore, the spatial and temporal scales of the impacts must be defined carefully (Johnson 2016). Regional EIAs focus on an area of interest and assess cumulative impacts from all projects within an area, usually focusing on Values (Clarke Murray et al. 2014). Regional EIAs represent the recognition that assessments should extend beyond the scope of any one project or proponent (Dubé 2003). Regional EIAs consider broader spatial and temporal scales and a wider scope of ecosystem components and are more closely aligned with broad-scale sustainability targets (Johnson 2016). Strategic-based EIAs are not common but are currently the most comprehensive assessment of cumulative impacts (Clarke Murray et al. 2014). Strategic-based EIAs focus on a specific area but are designed around strategic decision making to support sustainable development or planning (Clarke Murray et al. 2014).

There are four main components to most EIAs:

1. Scoping the type of impacts that will be included in the analysis.
2. Designating a baseline to compare ecosystem impacts with/without the proposed project.
3. Constrain the assessment by bounding the spatial and temporal extent of potential impacts.
4. Determine if the project is expected to significantly impact the ecosystem (Foley et al. 2017).

5.3 Observational and experimental research

Observational and experimental research studies tend to focus on a single pressure that is produced by multiple activities and the impact on suites of ecological components (Clarke Murray et al. 2014). These studies generally do not link the impacts they are studying to the original activity, and instead discuss the range of existing activities that are likely to have produced the pressures (Clarke Murray et al. 2014). This lack of connection between pressures and their sources only gives part of the picture and contributes to the challenge of managing the production of pressures from those activities (Clarke Murray et al. 2014). Capturing cumulative impacts by mapping out the pathways from activity to pressures to impacts is a critical first step.

5.4 Assessment methods and tools

Below are examples of models and tools commonly used for visualization, assessment, and management of cumulative impacts, and their specific research and management goals (adapted from Clarke Murray et al. 2014).

Type	Goal	Models and Tools
Visualisation	To visualise the cumulative impacts of human activities	Pathways of effects models (Grieg and Alexander 2009). Causal-network frameworks (also referred to as cause-effect pathways). Supported by a number of conceptual frameworks, e.g. DPSIR, which provide guidance on how to link driving forces to generic pressures and to physical, chemical, and biological attributes and then translate the impacts into policy responses (Stelzenmüller et al. 2018).
	To identify areas of intense human use from multiple pressures and activities	Spatial analysis (Halpern et al. 2008 (first example, developed Cumulative Effect Index (CEI) global map of impacts; the areas at greatest risk are identified by summing the severity of unique types of pressures (log-transformed and scaled) that coincided per pixel in space); Halpern et al. 2009 (California Current effects mapping); Ban et al. 2010 (cumulative effects mapping in British Columbia); Maxwell et al. 2013 (risk maps); Johnson et al. 2013 (Great Barrier Reef cumulative exposure map); Clarke Murray et al. 2015a (cumulative effects mapping analysis)) Mach et al. 2017 (cumulative effects mapping of California's network of MPAs)). Regional area assessment examples: Hawaiian MPA (Selkoe et al. 2009), the Mediterranean Sea (Micheli et al. 2013), the Baltic Sea (Anderson et al. 2015), Western Canada (Ban et al. 2010) or the California Current (Halpern et al. 2009). Also referred to as 'cumulative risk maps' (Uthicke et al. 2016). Cumulative effects mapping is a relatively new scientific endeavour with extensive data requirements. These models highlight areas of high and low potential cumulative effects, but mostly only investigated current, not projected, pressures. Clarke Murray et al. (2015a) was the first documented attempt to incorporate planned development in cumulative effects mapping analyses. However, scenario analyses and evaluations of trade-offs in ecosystem services have been done that incorporate planned activities (e.g. InVEST tool; Tallis et al. 2011). An important assumption of cumulative effects mapping is that pressures interact additively (Halpern and Fujita 2013). Past studies assign a single pressure for each activity, when multiple pressures can result from each activity. Additional pressures associated with each activity, not included in the analysis, means that the existing methodologies probably underestimate of the cumulative effects experienced by ecosystems (Clarke Murray et al. 2015b). Multipurpose Marine Cadastre (Bureau of Ocean Energy Management and NOAA Coastal Services Center).
	To explain the cumulative effects of past activities	Strength of evidence tables (Clarke Murray et al. 2016). Multiple regression (Clarke Murray et al. 2015).

Type	Goal	Models and Tools
Assessment	To estimate cumulative effects on a region from multiple human activities	Statistical models, e.g. Linear and non-linear regression (Dauer et al. 2000). Risk assessment (Clarke Murray et al. 2016; DFO 2012; Hannah et al. 2018; Hobday et al. 2011; O et al. 2015; Rubidge et al. 2017; Thornborough et al. 2018). Redundancy analysis (Perry and Masson 2013). Cumulative Effects Framework (CEF) (British Columbia Government). Regional Strategic Environmental Assessment (R-SEA) (Noble 2010). As a strategic approach, R-SEA has different features to other types of environmental studies and assessments for cumulative effects. R-SEA is intended to be an integrative, regionally based assessment process.
	To assess cumulative effects from multiple pressures and activities on a single species or population of concern	Simulation models (e.g. "bow-tie" graphical model as discussed in Stelzenmüller et al. (2018)). Population models (Poot et al. 2011). Ecological models (Spaling and Smit 1993).
	To assess the impact of a specific event (e.g. oil spill, hurricane) on the ecosystem	Regression (Irons et al. 2000; Peterson et al. 2003).
Management	To estimate the cumulative effects from a single proposed project with consideration of other nearby projects	Environmental Impact Assessment/Cumulative Effects Assessment. These frameworks include the stages listed in the NESP proposal, i.e. identification of VCs (in this context VCs are project specific and are only considered a VC if they are impacted by the project); determination of other human activities (outside of the project) that may also impact the VCs, etc. NB: Papers describing cumulative effects assessment methods abound in the literature, but most are not particularly helpful to practising professionals. The method must be able to incorporate the effects of all the relevant human activities that might contribute to the impact being studied (Ross 1998). Project-based cumulative assessments should align with strategic and regional assessments and plans (Uthicke et al. 2016).

Type	Goal	Models and Tools
	To assess the trade-offs among ecological and socio-economic components from global change or management scenarios	Ecosystem models (Atlantis; EcoPath with Ecosim). Development scenario models (Greig and Duinker 2007). Multi-scale Integrated Models of Ecosystem Services (MIMES). Assessment and Research Infrastructure for Ecosystem Services (ARIES). Integrated Valuation of Environmental Services and Tradeoffs (InVEST). Ocean Health Index (Halpern et al. 2008; 2009). British Columbia Environmental Assessment Office assessment.
	To plan activities for a region of interest that allows sustainable development	InVEST Spatial analysis (Halpern et al. 2009) MARXAN Atlantis

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