Northern Australia Environmental Resources Hub

National Environmental Science Programme

Integrated models, frameworks and decision support tools to guide management and planning in Northern Australia

Final report

Natalie Stoeckl, Daniel Grainger, Michelle Esparon, Marina Farr, Silva Larson, Mark Kennard, Jorge G Álvarez-Romero, Lorenzo Cattarino, Vanessa Adams, Michael Douglas, Bob Pressey and David Pannell

James Cook University Australia · Griffith University · The University of Queensland Australia · Charles Darwin University · The University of Western Australia

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Front cover: Irrigated agriculture in northern Australia (photo Michael Douglas).
Back cover: Part of the decision tree created from this project.

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Executive Summary

There is a lot of interest in developing northern Australia while also caring for the unique Australian landscape (Commonwealth of Australia 2015). However, trying to decide how to develop and protect at the same time can be a challenge. There are many modelling tools available to inform these decisions, including integrated models, frameworks, and decision support tools, but there are so many different kinds that it's difficult to determine which might be best suited to inform different decisions. To support planning and development decisions across northern Australia, this project aimed to create resources to help end-users (practitioners) to assess:

1. the availability and suitability of particular modelling tools; and
2. the feasibility of using, developing, and maintaining different types of modelling tools.

First, to scope our work, we conducted a very broad-scale literature review on the numerous different models and modelling approaches, determining which types should be included in our analysis and clarifying what we mean by the phrase *integrated decision support tool (IDST)* (Section 2.1). For the purposes of this project, an IDST must:

- integrate data from both the natural and the human realms;
- do more than simply describe, visualise, collate or disseminate information; it must generate its own sets of predictions and/or decisions; and
- have been used in applied settings and populated with regionally relevant data (i.e. the IDST must be more than a conceptual diagram or a method such as a particular type of statistical analysis).

Model availability and suitability. Using insights from the literature, we identified three broad categories of IDSTs: those originating from within (1) the biophysical sciences, (2) the social and economic sciences, and (3) the mathematical/computing sciences (Section 2.2). Continuing our analysis (Section 2.3), we further identified three sub-categories within each of the three broad categories. They could be differentiated according to a range of factors such as the focus of the model (e.g. on aquatic species, hydrological systems, economics, or interactions between systems), the spatial and temporal scale of data used within the models, and the techniques used to analyse data within the models (Table 2). We discussed each of those sub-categories in more detail, critically evaluated and assessed their strengths and limitations, and summarised the technical specifications of each of these nine different sub-categories of IDSTs (Appendix 1).

Feasibility of using, developing and maintaining models. For each of the nine sub-categories of IDSTs, we identified *case study* examples of their application in northern Australia (Appendix 2). Where we were unable to find examples from northern Australia, we sought examples that had been applied elsewhere in the world but in contexts similar to that of northern Australia (i.e. with relatively intact ecosystems, significant Indigenous populations and development that is largely focused around industries that are reliant upon natural resources).

We then developed questionnaires, and interviewed relevant northern stakeholders (creators of, and potential users of, IDSTs) (Section 3). Using a snowball sampling technique where interviewees referred additional stakeholders to take part, we interviewed 40 current and potential IDST users (30 of whom had used an IDST) and 17 model builders. Amongst other things, these interviews highlighted that decision-makers use a variety of different methods to collate information, with IDSTs being rated as generally more useful than public meetings and internet surveys, but often less useful than private consultations, negotiation and consensus-seeking approaches. Modelling tools that displayed outputs visually were considered to be the most useful, particularly for influencing policy. Most importantly, our interviews with model builders highlighted the considerable time (several years) and resources (several millions of dollars) required to build the larger (coupled) systems models. It was also noted that a number of “off-the-shelf” models exist, that could be tailored for a specific region, landscape or industry within less time and with much less resources.

Overall, our project highlighted that a useful way to think about which type of model to use is to first consider one’s primary objective and then use that objective as a first-round ‘filter’. For example, the primary goal of many of the early IDSTs developed by biophysical scientists was to protect key species at minimum ‘cost’. So practitioners who have a primary goal or a legislative requirement to protect aspects of the natural realm (e.g. conservation of a species) may find these models to be the most useful. That said, our detailed discussion of IDSTs (Sections 2.3.2.1 to 2.3.4.3), highlights that each sub-category of IDST is most suited to different decision-making contexts. It is important that the primary objective itself should drive the choice of model, rather than choosing a model just because it originated in the same field in which the researcher or practitioner operates. For example, hydrological models and bioeconomic models often involve deep integration, thus helping to foster understanding about the way in which different parts of the human system interact with the natural system—it is not only the systems models which can do this. Similarly, although hydrological models focus primarily on the biophysical (hydrological) system, their objective is often largely anthropogenic—namely to determine how much water it is ‘safe’ to extract for use in an economic system. So, primary objectives that are linked to the environment (such as wanting to conserve a species) are not necessarily best met with models from the biophysical sciences. Likewise, objectives that are primarily linked to society are not necessarily best achieved by models from the social and economic sciences.

To guide decision-makers through the complex labyrinth of model choices discussed in this report, we developed a stylised flowchart of the types of questions addressed by each of our nine sub-categories of models (Figure 17). This flowchart shows how those questions link to the primary objectives of decision-makers, while also synthesising stakeholder perceptions and experiences regarding the ease of understanding of model outputs, and the likely resources (human, financial and time) required for model development or application.

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Acronyms

ABM .... Agent Based Model

ABS……………... Australian Bureau of Statistics

ABARE… .... Australian Bureau of Agricultural and Resource Economics

ACCSP .... Australian Climate Change Science Program

ANN................. Artificial Neural Network

BBN................. Bayesian Belief Network

BCR………… .. Benefit-Cost ratio

CBA .... Cost -Benefit Analysis

CA………......... Cellular Automata

CSIRO……… .. Commonwealth Scientific and Industrial Research Organisation

GA…… .... Genetic Algorithm

GBR................. Great Barrier Reef

GDP................. .Gross Domestic Product

GRP……........... Gross Regional Product

CGE................. Computable General Equilibrium (model)

GIS…… .... Geographic information system

CPM................. Conservation Planning Model

IDST .... Integrated Decision Support Tool

IT………… .... Information technology

IO..................... Input-Output (tables and models)

MCA…………..... Multi-Criteria Analysis

N………….......... Nitrogen

NBM .... Network Based Model

NERP .... National Environmental Research Program

NESP .... National Environmental Science Program

NGO .... Non-governmental organisation

NPV……… ...... Net Present Value

NPF……........... Northern Prawn Fishery

NRM .... Natural Resource Management

NSW…............. New South Wales

NT…................ Northern Territory

P……… .... Phosphorous

QLD……........... Queensland

SDM................. Species Distribution Model

SROI… .... Social Return on Investment

SA… .... South Australia

SM .... Systems Model

TERM .... The Enormous Regional Model

UK…… .... United Kingdom

USA……… ...... United States of America

VIC………....... Victoria

WA………....... Western Australia

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1 INTRODUCTION

1.1 The National Environmental Science Programme

The National Environmental Science Programme (NESP) will build on its predecessors, the National Environmental Research Programme (NERP) and the Australian Climate Change Science Programme (ACCSP). Like its predecessors, NESP aims to generate world-class biodiversity and climate science to environment decision-makers and other stakeholders. Research must have a strong public good focus, and importantly, be capable of delivering public good outcomes.

NESP comprises six research hubs, each with their own specific research priorities: Clean Air and Urban Landscapes; Earth Systems and Climate Change; Marine Biodiversity; Northern Australia Environmental Resources; Threatened Species Recovery, and Tropical Water Quality Hub (see the NESP website for a detailed description of each hub). The research about which this report is written was undertaken as part of the Northern Australia Environmental Resources Hub, which addresses issues associated with the sustainable development of the unique northern environments.

This report is associated with one of the core themes of that hub, to: *Develop and trial spatially explicit tools to guide planning and management decisions that support a mix of multiple uses and protected areas while maintaining environmental values.*

1.2 Context and aim of project

There is much interest in 'developing' northern Australia with a parallel commitment to "caring for the unique Australian landscape" (Department of Prime Minister and Cabinet 2014). However, trying to decide how to 'develop' and 'protect' simultaneously is a non-trivial task: the complex interactions that exist between and within natural, social and economic systems means that small changes in even one part of one system may have far reaching and unexpected impacts elsewhere – perhaps tomorrow, perhaps five years from now. Since we do not fully understand the complex links between and within our natural, social and economic systems, we are not equipped to assess the desirability of, or to make predictions about the likely consequence of different types of 'development' (e.g., growth in agriculture which requires the extraction of underground water; growth in tourism which increases traffic and risk of weeds spreading). Hence the need for modelling tools: integrated models, frameworks, and decision support tools that can help us understand what the social, ecological and/or economic consequences of different actions or decisions might be, and for planning tools which help guide decision-makers when pursuing multiple objectives simultaneously.

There are numerous different types of modelling tools, several of which have been developed and trialled in Northern Australia. These contribute to planning for multiple objectives and include, for example, species distribution models, conservation planning models, and management strategy evaluation tools – see, for e.g. Pantus et al. 2011, Chan et al. 2012, Hermoso et al. 2012, Stoeckl et al. 2013a, Adams et al. 2014a, Adams et al. 2014b).

Internationally, many examples of integrated modelling tools exist. However, the variety of available models, and the complexity of some (in content, and/or in presentation), makes it difficult for end users to assess *a priori* the likely suitability of different models to inform different types of management choices/decisions in different contexts. The development of different types of models given varying resourcing abilities is also a challenge. Further, as commented by Briscoe:

> *A wise observer of the practice of water diplomacy was once asked how research in conflict resolution affected actual negotiations.*
>
> *Ah! he replied, — you have to understand that researchers don't practice and practitioners don't read.*
>
> *Briscoe 2011, p 2*

The aim of this project was thus to create a resource to help current and potential 'end users' (practitioners) to assess

- the availability and suitability of particular tools and/or
- the feasibility of using, developing, and maintaining different types of tools

to support planning and decision-making regarding development across Northern Australia.

We therefore produced this report which:

- Documents the different modelling tools that have been developed and trialled in Northern Australia;
- Documents some of the different modelling tools that have been developed and trialled elsewhere, but with potential to be applied in Northern Australia;
- Characterises these different modelling tools;
- Identifies the strengths and weaknesses of different modelling tools;
- Provides guidance about how to choose a tool that is best fit for purpose; and
- Documents ways in which modelling tools could be made 'more useful' from the perspective of key Northern Australian stakeholders.

NB: the project proposal had, as a goal, that of identifying potential future research trials/opportunities that could be considered for research plan Version 2 – this was done directly, given the involvement of Profs Pressey, Panell, and Douglas and Drs Adams and Álvarez-Romero in both this project and in projects 1.1 (RPV1, identifying research priorities) and 1.6 (RPV2)

1.3 Structure of the report

An overview of integrated decision support tools (IDSTs) is presented first, in Chapter 2. We begin this section with a brief and very broad-scale review of literature on the numerous different models, modelling approaches, and frameworks that generate information which could be used to 'support' decision-makers when needing to think about, assess potential 'impacts' of, assess trade-offs and make decisions about different types of 'development' relevant to Northern Australia. We use insights from this review to 'scope' our work: determining which types of tools should be included in the review and clarifying what we mean by the phrase *integrated decision support tool (IDST)*. Based on the literature, we then identify three broad categories of IDSTs (Section 2.2), each with three sub-categories with inherently different 'modelling' characteristics (such as 'realms' considered, algorithms/analytics used, outputs generated, etc.).

In Section 2.3 we discuss those sub-categories of IDSTs in more detail, using insights from the literature to critically evaluate and assess their strengths and limitations and to identify key 'technical' characteristics of each broad category of IDST – very succinctly summarised within Table 2, and given more detail in Appendix 1. We also collate examples of their applications across Northern Australia, providing *case study* descriptions of at least two applications for each of the nine different sub-categories (Appendix 2). We were unable to find examples of Northern Australian applications for some (sub) categories of IDSTs. For these, we sought examples that had been applied elsewhere in the world – specifically looking for examples where the IDSTs had been used in contexts similar to that of Northern Australia (i.e. with relatively intact ecosystems, significant Indigenous populations and 'development' largely focused around industries that are reliant upon natural resources).

In Chapter 3 we report on the findings of a survey that we conducted with relevant northern 'stakeholders' (creators of, and potential users of IDSTs). We developed two questionnaires that could be used to learn more about IDSTs, compiled a list of people who had developed, used, or were likely to benefit from the use of IDSTs in the context of Northern Australia (hereafter, northern stakeholders), and interviewed them to document applications of these modelling tools.

In Chapter 4 we provide a summary of key findings and guidance on how to select a model that is fit for purpose.

2 OVERVIEW OF INTEGRATED DECISION SUPPORT TOOLS (IDSTs)

2.1 Definition of an IDST (used in this report)

If one wishes to 'develop' Northern Australia while "caring for the unique Australian landscape" (Department of Prime Minister and Cabinet 2014), one needs to think about 'development', (a socio-economic phenomenon driven from what is often referred to as the 'human' realm), within 'landscapes' which are part of the 'natural' realm. One is thus making decisions about what to develop and/or what to protect within a complex socio-ecological system in which humans are embedded in nature (Berkes and Folke 1998). It is exceedingly difficult to understand the potential implications of development across multiple linked systems. Hence the need for tools which provide information about the way in which changes (e.g. decisions about development) in one part of the socio-ecological system might impact other parts of the system (hereafter *realms)*. Our review thus focuses on models (a.k.a decision support tools or systems) that consider both the 'natural' and the 'human' realms, where we define:

the 'natural' realm as including

a. Aquatic systems (freshwater, estuarine and marine ecosystems, including species, habitats, communities, etc.)
b. Terrestrial systems (as above for terrestrial ecosystems)
c. Hydrological systems (including surface and ground water)
d. Geophysical systems; and

the 'human' realm as including

e. Economic systems
f. Social systems.

Since the dawn of civilisation, humans have been observing, trying to better understand and trying to make predictions about what might happen to them (and their world) in various situations in an effort to make 'better' decisions. Two stylised examples of problems faced by hunter-gatherers helps describe the context, highlighting three key uses to which models can be put (Kelly et al. 2013):

1) For system understanding. One must observe (and describe) the environment/ situation to, for e.g.
   a. find out what types of plants are edible, and to determine how to spot them
   b. learn about how (where and why) animals are likely to move.
2) For forecasting and prediction. One can use observations to draw inferences, to, for e.g. predict,
   a. where to find edible roots
   b. where an animal might be heading.
3) For policy and decision-making. One can use predictions to help decide what to do, e.g.
   a. which tree to dig under in search of edible roots
   b. which animal to track in which direction.

We do not generally have written records of the traditional knowledges that hunter-gatherers collected over tens of thousands of years and passed down through the generations, so details of many of the decision support tools that people have developed to help guide decisions are lacking. But, there have been several recent reviews of the modern scientific literature that focuses on modelling approaches for use in coupled natural-human systems. These reviews clearly highlight the depth and breadth of related literature and the speed with which that literature is growing (see, for example, Blair and Buytaer 2016; Filatova et al. 2016; Fulton et al. 2016; Polhill et al. 2016; Turner et al. 2016; Kelly et al. 2013; Croke and Nethery 2006).

The variety of models that are currently available provide different levels of 'support' to decision-makers, in that: (1) some only 'describe', (2) some 'describe' and 'predict', and (3) some 'describe', 'predict' and 'decide' (not in the literal sense of the word, but in so much as they identify a 'best' option). Models which only 'describe', provide less support to decision-makers concerned with issues such as 'development' in Northern Australia, than models from categories (2) and (3). As such, we do not consider models of type (1) in this report. We could also have restricted our discussion to include only models/tools within the third category, but such a restriction pre-supposes that decision-makers are only interested in models that identify 'best' options for them, thus directly helping them to make decisions. We are aware that some decision-makers generally prefer to see options/predictions laid out before them and then also use other tools, ideas and systems to help them make their own decisions given those options. Accordingly, this report concentrates on models which 'predict' and/or help to 'decide'.

Many of the models which focus on coupled natural-human systems use mathematical, theoretical and other conceptual ideas but they are not always fitted with (or even designed to be fitted with), empirical, context relevant, data. Whilst the contributions that these models make to our understanding of the world are profound (Polhill et al. 2016), this report is primarily concerned with empirical models that have been populated with contextually relevant data to support decision-makers in 'real world' situations/applications.

Thus, when determining whether or not a particular tool was, for the purposes of this project, an Integrated Decision Support Tool (IDST), we determined that it must satisfy all of the following criteria

1) It must integrate data from both the 'natural' and the 'human' realms (defined above). Following the lead of Liu et al. (2008), we note the difference between a model which is truly integrative (in that the decision support tool explicitly models interactions between/across realms) and one that is comprehensive but lacks integration (e.g. describing data from multiple realms, but not explicitly modelling interactions across realms).
2) It must do more than simply describe, visualise, collate or provide information; it must generate its own sets of 'predictions' and/or 'decisions'.
3) It must be populated with empirical data that is contextually relevant – i.e. it must be a working model that has been populated with regionally relevant data (not just a conceptual diagram or a particular type of statistical analysis such as regression).

Decision support tools help to make the decision-making process transparent, documented, reproducible, robust, and contribute to a coherent framework to explore the options available

(Sullivan 2002). The decision support process typically involves a number of stages which can then enable decision-making (Figure 1).

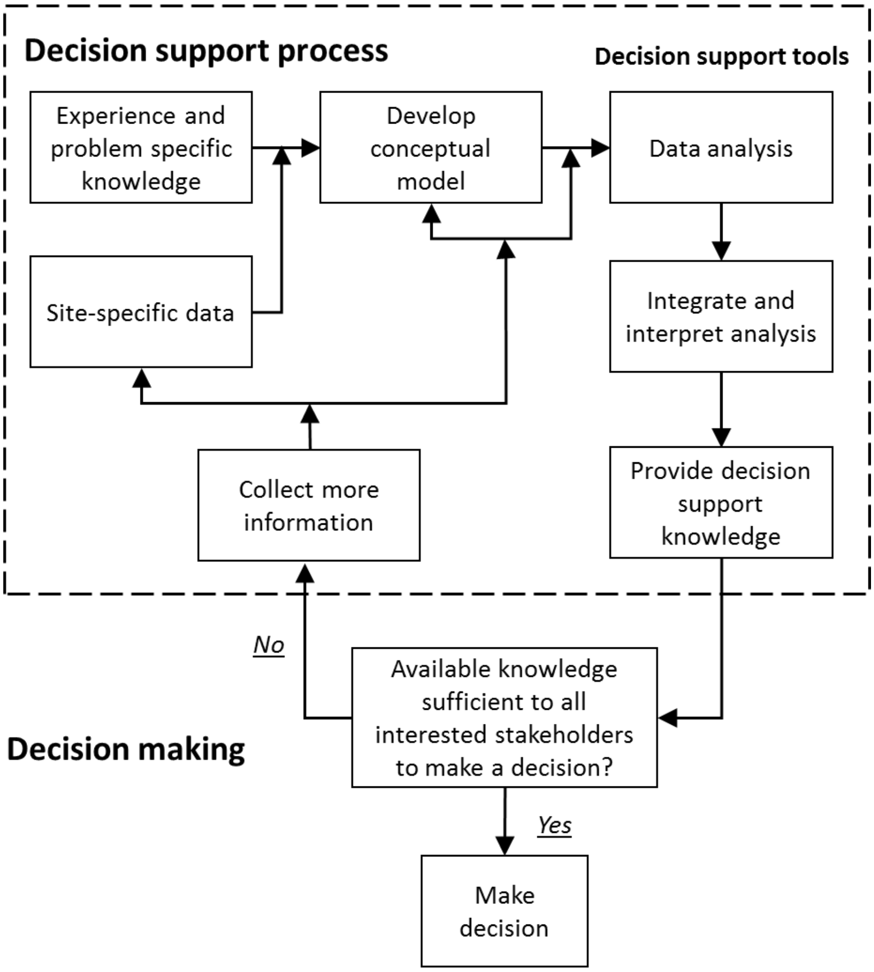

Figure 1: Flow chart outlining essential steps in the decision support process, involving the use of decision support tools to inform decision-making

(modified from Sullivan 2002)

These stages include assembly of experience, knowledge and site-specific information to develop simple conceptual models of system behaviour. This informs the collation/collection, analysis and interpretation of data in terms of the decision variable. Decision support tools are critical in these data analysis and interpretation stages. It is important to ensure that the knowledge generated by decision support tools is transparent and readily understandable by different stakeholders, not just specialists. Assuming that knowledge is sufficient (if not, then more information may need to be collected), decision support tools can thus make a useful contribution to the decision-making process. It is, however, vitally important to recognise that decision support tools contribute to just one part of the decision-making process and are invariably used alongside other decision support processes (see Section 3.2.1 for a discussion of other processes deemed particularly important in Northern Australia).

2.2 Categories of IDSTs used elsewhere in the literature

The variety of different variables one could focus on within these models, and the variety of different ways one can analyse, predict, or decide the most/least 'desirable' outcome means that there are almost an infinite number of 'tools' that could be thought of as an IDST. This makes it difficult for end users to assess *a priori* the likely suitability of any particular IDST to inform different types of management decisions in different contexts, and the likely feasibility of being able to develop one with available resources. Perhaps at least partially with the intent of helping people navigate through the modelling literature, various researchers have sought to describe some of the characteristics, strengths and weaknesses of different modelling approaches. It is impossible to do this for each individual model, so most researchers approach this problem by firstly identifying broad categories of models, and then describing key characteristics of each broad category.

Table 1 provides an overview of categories defined in a subset of recent modelling reviews, highlighting that categories differ widely across reviews. At least some of these differences no doubt reflect differences in the disciplinary background of authors, but some also critically relate to differences in the intent of the review.

Table 1: Categories of models identified in various reviews of the modelling literature

Broad category of model / modelling approach identified in review	Kelly et al. 2013	Filatova et al. 2016	Blair and Baytauert 2016	Croke and Nethery 2006	Fulton et al. 2015
Systems dynamics	X	X	X	X	
Pattern oriented modelling			X		
Agent based models	X	X	X	X	
Bayesian networks	X		X	X	
Coupled component models	X		X		
Knowledge based models	X				
Statistical / econometric (including meta) models		X		X	
Equilibrium models		X			
Scenario modelling			X		
Hueristic/knowledge-based modelling			X	X	
Risk assessment approaches				X	
Conceptual					X
Tactical					X
Strategic					X

2.3 Categorising IDSTs used in this report

"*While scientists often complain that their input is ignored by decision-makers, the latter have also expressed dissatisfaction that critical information for their decision-making is often not readily available or accessible to them, or not presented in a usable form*" (Liu et al. 2008, p 846). We have thus developed our own classification system – with the primary goal being to help potential 'end users' of IDSTs (assumed here to be intelligent 'lay people', without indepth understanding of the underlying nuances of various models and modelling approaches) to navigate their way through the literature and to better understand which types of models are likely to be most able to provide the type of support required for the particular decisions they face. The following discussion describes our system in general terms; a more indepth discussion of the key characteristics (including some technical details) of each of these broad types of modelling approaches is provided in Appendix 1. Appendix 2 presents case-studies that describe applications of these IDSTs in Northern Australia and other relevant contexts (in situations where we have been unable to find applications in this region).

2.3.1 Background

Before researchers had ready access to high speed computers, empirical IDSTs had to, out of necessity, focus on just a subset of key relationships/interactions between a relatively narrow range of variables, using algorithms and modeling approaches that could be calculated by hand, or with rudimentary calculators and computers. Despite the fact that modern day IDSTs combine insights, ideologies, methodologies and algorithms from a wide variety of disciplines, the historical literature from which modern research has grown, thus originates from several relatively disparate disciplines. First, are models which have (predominantly) been developed from within the biophysical sciences with a focus on the 'natural' realm; second are those that have developed (predominantly) from within the social and economic sciences, with a focus on the 'human' realm; and third are those developed within the mathematical/computing sciences with a focus on technical aspects of the modelling problem.

This distinction is a useful one for 'end users' to consider, because these models often have different primary objectives that may (or may not) link to the objectives of end users. Many of the early IDSTs developed by biophysical scientists, for example, had as their primary goal, that of protecting (improving or maintaining) key species, with minimal disruption (or at minimum 'cost') to the human realm. So end users who have a primary goal (or even a legislative requirement) to protect aspects of the natural realm (e.g. conservation of a species), may find that the models which have been developed by biophysical scientists are likely to be most useful.

In contrast, early IDSTs developed by the social and economic scientists often had, as their primary goal, that of protecting (or improving) aspects of the human realm (e.g. increasing economic growth or maximising profit, reducing poverty or increasing wellbeing), with minimal disruption to the natural realm. End users whose primary goal/concern is a socio-economic one (e.g. promoting the wellbeing of a community) may thus find models that have been developed by the social and economic scientists to be most appropriate.

Finally, models developed by the mathematical/computing scientists often focused on the modelling problem per-se[1] and do not generally 'focus' or 'favour' either the natural or the human realm. Decision-makers who are not bound by legislation or role to favour either the natural or the human realm and are, instead, primarily interested in interactions between them, may thus find that these models have much to offer.

The technical capabilities of modern day computers and our rapidly growing cross-disciplinary understanding of the algorithms, statistical techniques and computational heuristics, means that most modern day IDSTs are now able to consider multiple objectives (within limits) and most also incorporate useful insights and approaches from an extremely broad range of disciplines and perspectives. The distinctions we have identified here, are thus somewhat 'blurred' – with many applied IDSTs having characteristics that do not make it easy to place into a neatly labelled category. Nevertheless, we feel that this high-level differentiation may be useful for people trying to determine which type of IDST is likely to be the best fit for their purpose.

Figure 2 provides a graphical overview of the broad categories and sub-categories of IDSTs considered in this review, giving two examples (for each sub-category) of applications of those approaches to problems relevant to Northern Australia. In the pages that follow we provide a more indepth discussion of the different sub-categories of models within each broad category, describing some of their strengths and weaknesses and further identifying situations/characteristics that may help end users determine when each is, or is not, likely to be most useful as a decision support tool. Most evident from that more detailed discussion of various IDSTs is that they differ in respect of:

- 1. The type of decision/problem addressed;
- 2 The primary objective, if any, considered by the model (e.g. to protect species at least cost; to maximise profits for least environmental damage);
- 3. The extent to which the tool is able to model complex and deep 'interactions' between or within different realms.
- 4. The type of data/information that is required/used by the model, e.g.
    - Where the data relates to biophyiscal, hydrological, ecological, social, economic or other 'realms';
    - The extent to which data are spatially &/or temporally differentiated
- 5. Whether or not one realm 'dominates' another (or is considered in more detail than another)
- 6. The mechanics of the way in which data/information is integrated, e.g.
    - Within a statistical model that explores relationships between observations
    - Within a predictive model that

[1] Some of which have been found to be so complex that they are considered computationally intractable hence the need for the development and adoption of heuristics to increase the chance that a model predicts/decides correctly.

    - Optimises an objective function (eg. maximises profits, maximises number of species saved, minimises costs)
    - Simulates stocks and flows and relationships between variables (e.g. predicts stream flows with different rainfall events and groundwater extraction regimes; predicts crop growth with different soil types, nutrients and irrigation regimes)
    - Characterises/converges to a general equilibrium.
- 7. The way in which the model addresses uncertainty, and whether or not the modelling approaches typically allow for, or include scenario analysis.

Some of these characteristics are summarised in Table 2; further technical details relating to each category (and sub-category) of IDSTs are provided in a series of tables in Appendix 1 (with one table per sub-category of models).

As a final note before proceeding to our more indepth discussion of particular types of IDST, we should emphasise that some of these tools can be (and in some cases have been) used in combination to improve decision-making. For instance, decision-makers might want to consider potential changes in the distribution of aquatic species (e.g. fish, invertebrates) modelled using Species Distribution Models (SDMs) based on predicted hydrological changes associated with land use changes (using hydrological models), and then use this information to parameterise a conservation planning tool that can help to optimise land uses to ensure the persistence of the aquatic species of conservation interest. Moreover *coupled* systems models use (mostly) quantitative methods to explicitly <u>couple</u> various models (from potentially any sub-category) within a single integrated framework and rapid advances in computing and analytical sciences are making this *coupling* easier. To thus reiterate a point made previously: while we have used the characteristics summarised in Table 2 to help identify separate categories (and sub-categories) of IDTS which are discussed in subsequent sections, the distinctions which we have drawn are in many cases 'blurry' and becoming increasingly more so with time.

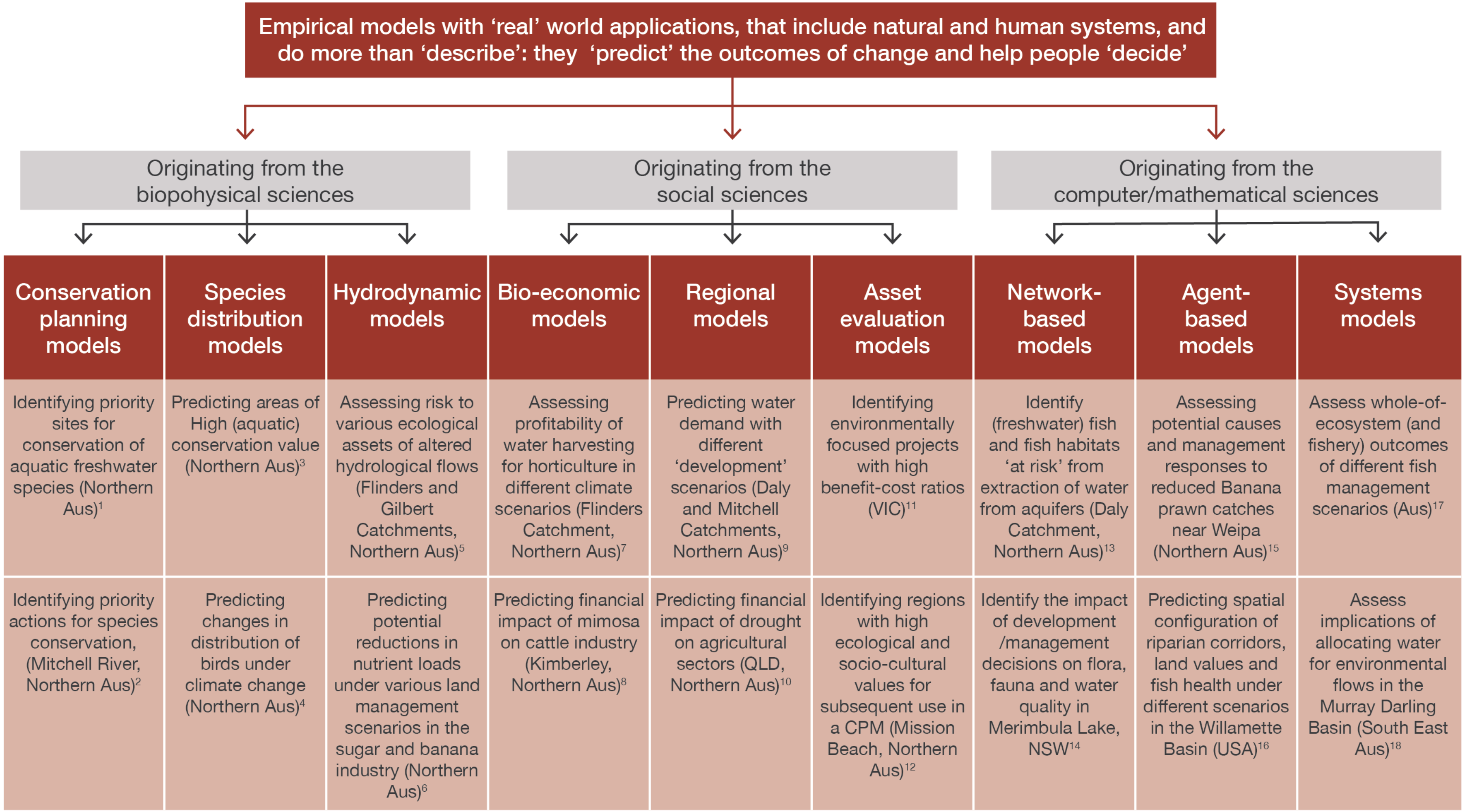

Figure 2: Broad categories and sub-categories of IDSTs considered in this review, showing regionally relevant applications of those models

1. Hermoso et al., 2012; 2. Cattarino et al., 2015; 3. Kennard et al., 2010; 4. VanDerWal et al., 2013; 5 DSITIA, 2014; 6. Armour et al., 2009; 7. Petheram et al., 2016; 8. Cook et al., 2015; 9. Stoeckl et al., 2013; 10. Horridge et al., 2005; 11. Pannell et al., 2012; 12. Pert et al., 2013; 13. Chan et al., 2012; 14. Ticehurst et al., 2008; 15. Dambacher et al., 2015; 16. Bolte et al., 2006; 17. Fulton et al., (2011); 18. Mainuddin et al., 2007

Table 2: Key characteristics of different types of IDSTs

Characteristic	Species distribution models (SDM)	Conservation planning models (CPM)	Hydrological models	Bioeconomic models	Regional models	Asset/Project Evaluation models	Network based models	Agent-based models (ABM)	Systems (SM) models
Purpose of model (decide / predict/optimise)	Predict species distribution	Decide best conservation policy	Predict impacts of 'change' on water resources	Optimise economic situation	Predict growth trajectories and impacts	Identify areas/projects of highest 'value'	Decide or predict	Decide, predict, or optimise.	Decide, predict
Dominant 'realm'	Aquatic and/or Terrestrial	Aquatic and/or Terrestrial	Natural for modelling. Human for objective	Economic	Economic	Human	No Dominant realm unless modelled	No Dominant realm unless modelled	No Dominant realm unless modelled
Aquatic or Terrestrial species or processes	Can be predictor or predicted	Can be an objective; few processes	Can be outcome; no processes	Can be, but if present often as a constraint	Rarely, if ever included, but could be	Value of state; no processes	Can be 'node'; simple processes	Can be an 'agent'	Can be an entire sub-component
Hydrological processes	Only if correlated with species; no processes	Rarely – if so, as a constraint; no processes	Always	Limited; if present often as a constraint (no process)	Limited; as an input & output (not a process)	Value of state; no processes	Can be 'node'; simple Bayesian processes	Can be boundary condition; no processes.	Can be an entire sub-component
Other biophysical variables or processes	Only if correlated with species; no processes	Rarely – if so, as a constraint; no processes	Often as influencing water dynamics	Limited; if present often as a constraint	Sometimes as an 'output' e.g. pollution	Value of state; no processes	Can be 'node'; simple Bayesian processes	Can be an 'agent'	Can be an entire sub-component
Economic agents or processes	Only if correlated with species; no processes	Almost always – typically as a constraint; no processes	Can be outcome; no processes	Always	Always	Core objective but; no processes	Can be 'node'; simple Bayesian processes	Can be an 'agent'	Can be an entire sub-component
Social agents, issues or processes	Only if correlated with species; no processes	Rarely	Can be outcome; no processes	Welfare effects on humans sometimes incorporated	Social indicators included in some models	Some attempt to value state; no processes	Can be 'node'; simple Bayesian processes	Can be an 'agent'	Can be an entire sub-component
Spatial resolution	Limited only by available data	Limited only by available data	Limited only by available data	Limited only by available data	Typically large	Challenged if values cross boundaries	Limited only by available data	Limited only by available data	Limited only by available data

Characteristic	Species distribution models (SDM)	Conservation planning models (CPM)	Hydrological models	Bioeconomic models	Regional models	Asset/Project Evaluation models	Network based models	Agent-based models (ABM)	Systems (SM) models
Interaction between scales[2]?	Potentially	No	Yes	Yes	Not normally	Yes	No	Yes, emergent features across scales	Yes, depending on choice of subcomponents
Temporal resolution[3]	Normally nontemporal	Normally nontemporal	Dynamic (often daily time-step)	Lumped, dynamic, or continuous	Nontemporal or lumped	Normally nontemporal or lumped	Normally lumped	Lumped, dynamic, or continuous	Lumped, dynamic, or continuous
Dynamic Feedbacks?	None	None	In most models	In some models	In some models	Very rarely	In some models	In most models	In most models
Convergence (point, cycle, chaotic)	Point estimate of probability	Best point estimate found	Typically point estimate of response to scenario	Typically point convergence.	Depends on model (typically multiple chaotic equilibria).	Point estimate	Typically converges to point solution.	Typically chaotic patterns	Typically chaotic patterns
Computational Complexity of problem and problem solving approach[4]	Computationally tractable. Statistical techniques used to predict	NP hard problem. Heuristics used to decide best policy	Computationally hard problems. Numerical heuristics used to predict water dynamics	Simplified optimisation with biophysical constraints. Brute force deterministic techniques to find best policy	Simultaneous equations, potential nonlinear equations. Iterative approaches to identify equilibria.	Complexity hidden in the background (methods for determining values); once determined, not complex to compare values	Complex problems (assumed learnable). Stochastic methods to parameterise; networks used to predict/decide	NP hard problems. Agents allowed parallel (brute force deterministic) computations to predict patterns	Tradeoff between breadth and depth of computation[5]
Sensitivity analysis undertaken?	Sometimes	Not usually	Not usually	Sometimes	Not usually	Sometimes	Usually for BBNs, difficult for ANNS	Sometimes	Sometimes
Scenario analysis included?	Sometimes	Sometimes	Almost always	Almost always	Almost always	Sometimes	Sometimes	Sometimes	Sometimes
Addresses uncertainty[6]?	If addressed, via scenario analysis or ensemble modelling	If addressed, via scenario analysis	If addressed, via scenario analysis	Addressed via scenario analysis	Addressed via scenario analysis	If addressed, via scenario analysis	Addressed in model design	Not usually	Not usually

[2] E.g. changes at the micro scale, impacting meso or macro scale
[3] After Kelly et al. (2013), differentiated as: nontemporal, lumped – big steps, dynamic – small steps, continuous – steps converge to zero
[4] Heuristic vs brute force approach / Deterministic vs stochastic methods / Decision problematic vs Optimisation problematic
[5] e.g. simple high level models which may lose important micro level feedback vs. low level exacting computations that lose macroscopic insights
[6] Unknown information – including information about data, model input and parameters

2.3.2 Models which have developed from within the biophysical sciences

The potential of biophysical models is well recognised for examining components and interactions of natural systems, estimating the changes and uncertainties of outcomes, and fostering communication between scientists, managers and the community (Bellocchi et al. 2009). Biophysical models vary according to their topic of focus (aquatic species, terrestrial species, hydrological systems), in the type of data used (qualitative or quantitative) in the spatial and temporal scale of data used (Hoosbeek and Bryant 1992) and in the way in which data are processed (mechanistic or empirical processes). Irrespective of their characteristics, all biophysical models are, by definition, an approximate reconstruction of actual phenomena that integrate natural processes into mathematical formulae or other model structures (Bellocchi et al. 2009).

Here, we focus on three broad classes of models that have been developed from within the biophysical sciences that are able to generate insights for those interested in natural resource management issues relevant to Northern Australia: species distribution models; conservation planning models; and hydrological models. We chose those three classes of models because they each focus on environmental issues of importance to Northern Australia (identified in the Northern Australia Environmental Resources Hub of the NESP). They are discussed in more detail below, but suffice to say here:

- Species distribution models allow one to look at the way a particular species is distributed through space and time, and at the way in which that distribution is, or could be affected by environmental (e.g. increase in temperature) or other changes (e.g. land use). These models are thus likely to suit decision-makers who need detailed spatial information about a particular species (or subset of species) – be it a species of conservation concern, and invasive species (e.g. weed) or a ‘threat’.

- Conservation planning models seek to determine the ‘best’ (e.g. most cost effective) way to achieve explicit conservation goals (e.g. persistence of threatened species or ecosystems). In most (but not all) cases, these models are spatial (or can be linked to specific areas), so determining the ‘best’ way to achieve a goal is equivalent to helping decision-makers identify regions in which conservation interventions (from strict protection to off-reserve management), would enable them to achieve a particular conservation goal at, for example, least financial cost. Decision-makers who must decide how to allocate scarce conservation resources (across space, activities and/or programs) may thus find these models particularly useful.

- Hydrological models focus on hydrological processes (i.e. movement, distribution and quality of water resources), amongst other things, allowing one to look at the way in which changes in the human system (e.g. land use changes, or water resource developments) could impact the hydrological system (e.g. modifying natural water flows, increasing pollutant/sediment river loads) and the broader environment that is dependent upon the hydrological system. These models are thus likely to suit decision-makers grappling with problems relating to water extraction, water development or land-use changes that are likely to affect water resources.

2.3.2.1 Species Distribution Models (SDMs)

Simplistically, species distribution models, hereafter SDMs (also known as ecological niche models, habitat suitability models or bioclimatic envelope models) are widely used to understand distribution patterns of species. They make predictions about the distribution of species across space, generally for a relatively large region/landscape or within a river catchment/network. The predictions are often presented visually – e.g. as a 'map' showing where particular species are likely to be most/least abundant within the region of interest. When generating these predictions, SDMs typically use explanatory and/or predictive statistical models that rely on observed co-variations between various 'predictor variables' (that describe environmental gradients) and the observed presence or absence of species (Elith and Leathwick 2009). Predictor variables are generally relatively coarse-scale and readily measured (e.g. variables describing climate, soils, vegetation, topography and flow regime), and correlate with the presence/absence of species. They can thus be used to make predictions about the likely distributions of species under past, present and/or future environmental conditions. Broadly speaking, SDMs use two different types of analytical approaches to generate predictions: correlative and mechanistic (deductive) – with numerous variants of each approach.

The earliest versions of SDMs were developed in the 1970s (Zimmermann et al. 2010) and generally relied on estimating statistical associations between species occurrences and environmental attributes at a set of sampling locations; these associations were then used to infer the distribution of species from environmental characteristics in unsampled locations (or time periods). The statistical approaches used in SDMs varies by model and may be based on species presence/absence data, presence-only data, or a mix of the two. Although species data from planned surveys that describe presence–absence are ideal for modelling distributions, most records are derived from *ad hoc* compilations of observations (e.g. from museums and herbaria) and are in a 'presence-only' form. There are many issues associated with the use of such data, many of which are also common to presence/absence data. These include bias, errors in identification of taxa and of locations, choice of appropriate grain size (spatial resolution), sparseness of records and the choice of appropriate modelling methods (for reviews, see Hermoso et al. 2013; 2015a,b).

In cases where data are sparse (e.g. for rare species), distributions can be inferred using simple convex or alpha hulls (i.e. polygons encompassing known records) or using expert opinion and rule sets (Elith and Leathwick 2009). However, correlative SDMs and simple mapping approaches using sparse data and/or expert opinion remain subject to criticism because they implicitly assume that species are in equilibrium with their environment, and they often fail to incorporate dispersal, demographic processes and biotic interactions (e.g., Dormann 2007; Jeschke and Strayer 2008; Olden et al. 2010). These assumptions are likely to be unrealistic in many circumstances. Potentially more ecologically realistic alternatives (yet more complex and data-hungry), include mechanistic niche models that explicitly incorporate mechanistic links between the functional traits of organisms and their environments into SDMs (Kearney and Porter 2009), or multi-modelling frameworks that combine species–environment relationships, landscape dynamics and population dynamics (Franklin 2010).

Like bio-economic models (Section 2.3.3.1), SDMs generally provide only a ‘partial’ picture of the natural system, but potentially a picture with great depth. The relationships (say, for example, between species presence and temperature) that are estimated by the models can be exploited to do much more than simply generate ‘maps’ showing distributions. They can, for example, be used in conjunction with extra information about predicted changes in temperature over the next 5, 10, 50 years, to predict species distribution in the future under different scenarios (Wilcox et al. 2013). These models have thus been used to explore a great variety of issues including: quantifying the environmental niche of species; testing biogeographical ecological and evolutionary hypotheses; assessing species invasion and proliferation; assessing the impact of climate, land use and environmental changes on species distributions; prediction of reference assemblages for bioassessment; mapping biodiversity and identifying conservation priorities; identifying remnant populations and uncovering species range extensions or gaps; and mapping suitable sites for species reintroduction (Booth et al. 2014; Rose et al. 2016). With more strategic integration into a structured decision-making framework, Guisan et al. (2013) argue that these models could provide even more effective support for those focused on conservation.

A defining characteristic of SDMs is, however, that the human realm is generally only represented by one or two variables (assumed to be exogenously given) and – like regional models (Section 2.3.3.2), the modelled relationship between the human and natural realms within SDMs is thus simplistic. So although these models are ‘integrated’ in that they include variables from both the natural and human systems, they generally have a very strong biophysical focus. SDMs contain much detail about a sub-set of the natural system (and relations within it), but relatively little about the human system; and (unlike bio-economic models, but similar to regional models and conservation planning models) relations between the natural and human systems are assumed to be relatively simple.

Applications of species distribution models are numerous and varied. Recent applications in Northern Australia include those that have been used to generate predictions about:

- The present-day distribution of numerous species of freshwater fish, turtles and waterbirds to identify potential areas of high conservation value (Kennard 2010; Hermoso et al. 2012).
- Likely changes in the distribution of birds under different climate scenarios (Van Der Wal et al. 2013).
- Regions where there may be a high risk of myrtle/guava rust (Elith et al. 2013).
- Regions where ghostnets pose a high threat to green turtles (Wilcox et al. 2013).
- Regions where the greater glider was at greatest risk of extinction from climate change (Kearney et al. 2010).
- Spatially-explicit individual-based spread model to predict the spread of invasive grass species in Kakadu National Park and Litchfield National Park, Northern Territory (NT) (Adams et al. 2015)

Elsewhere in the world, applications of species distribution models are all but innumerable (Guisan et al. 2013, for example, counted more than 2,500 SDM papers since 1990, which focused on: biological invasions, critical habitat, reserve selection and translocation; while Merow et al. 2013 reported that MaxEnt (a prominent SDM) can account for at least 1000 published applications). Interested readers are thus directed to Elith and Leathwick (2009); Guisan et al. (2013) and Booth et al. (2014) for recent, comprehensive reviews.

The decision-making context in which species distribution models are most useful includes situations in which the primary goal/interest of the decision-maker is the distribution of a particular species and the aim is to:

- Identify candidate sites for re-introduction or relocation of rare and threatened species
- predict reference assemblages for bioassessment and monitoring
- identify critical habitat attributes for management and rehabilitation
- assess potential human causes of historical changes in species distributions
- predict responses to future climate or restoration scenarios
- map biodiversity and identify species conservation priorities
- predict invasion potential of alien or translocated species;
- identify remnant populations and uncover species range extensions or gaps

And where

- The influence of the human realm (e.g. the influence of people or of economic activity) on a particular species can be appropriately modelled using simple ‘indicator’ relationships (e.g. one unit increase in the river disturbance indicator is associated with a ‘z’ unit increase/decrease in species abundance – all else constant), or can be inferred through other relationships (e.g. humans are contributing to climate change; this could increase temperatures; a one degree increase in temperature is likely to be associated with a ‘z’ unit increase/decrease in species abundance).
- If one is interested in more complex relations between the human and natural realm, other models may need to be considered (or ‘combined’ with SDMs in, for example, a coupled *systems model* – see Section 2.3.4.3).

2.3.2.2 Conservation planning models (CPMs)

Conservation Planning models or tools (CPMs) encompass a wide variety of approaches and frameworks aimed at identifying the optimal way to achieve explicit environmental objectives given limited resources (Moilanen et al. 2009b; Sarkar et al. 2006). In their simplest form, CPM may involve a conceptual diagram to guide the manager or the decision-maker through the key steps involved in making optimal decisions (Margoluis et al. 2013). However, conservation planning often has a strong spatial component, which stems from the need to consider where features of management interest (e.g. vegetation types, threatened species) are located in space (Sarkar et al. 2006). Therefore, in most cases, conservation planning is concerned with identifying the geographical areas where implementing one or more specific management actions, subject to ecological and socioeconomic constraints, can help to achieve specific objectives. These objectives are often, but do not have to be, environmental. So despite the fact that these models have been developed by natural scientists, many have an (implicit) objective which is predominantly socio-economic – and can thus provide information that is useful to decision-makers whose core objective is either 'natural' or 'human'.

Actions focused upon in CPMs are diverse. They range from strict reservation/protection (e.g. establishment of a nature reserve or protected area) to off-reserve interventions contributing to achieving the environmental objectives (e.g. managing fire, invasive species and grazing to protect native fauna; Carwardine et al. 2012; control erosion, restore riparian vegetation and restore natural river flows to protect aquatic biodiversity: Mantyka-Pringle et al. 2016).

Spatial CPMs come in a suite of different types. There are qualitative CPMs, which are fundamentally based on Multi-Criteria Analysis (MCA); others are more quantitative. Spatial MCA-based CPMs rank alternative strategies/actions (e.g., revegetation) based on a set of pre-specified rules, or criteria (e.g., enhanced social and community wellbeing, protection of threatened species, etc.) (Hajkowicz 2008). By linking the decision rules to a Geographic Information System, criteria can be used to weight different pieces of spatial information on features of interest (e.g., areas to revegetate, distribution of threatened species), which are combined to obtain maps of priority areas that indicate where to carry out required activities (Malczewski 2004). Spatial MCA models are widely used due to their ease of implementation and transparency, which allows stakeholder values and views to be incorporated right from the onset of the planning process (Pert et al. 2013; Straton et al. 2011; Zerger et al. 2011).

More quantitative CPMs make use of mathematical algorithms to solve a specific problem. A specific class of quantitative CPMs is that of spatial conservation prioritization models, which use mathematical optimisation techniques to achieve a specific objective, usually in the form of a mathematical equation, within some types of constraints (Moilanen et al. 2009b). According to Sarkar et al. (2006), this type of CPMs should, at the very minimum, be able to identify either (a) sets of complementary sites needed to achieve quantitative targets for biodiversity features or (b) the complementary contribution that individual sites make to biodiversity conservation within a region. Quantitative CPMs include classic reserve selection software, such as Marxan, Zonation, C-Plan and ConsNet (Ball et al. 2009; Moilanen et al. 2009a). These tools aim to find the most financially cost-effective set of sites in which to establish a nature reserve or a protected area, in order to achieve a specific conservation objective. Objectives can be formulated in different ways, depending on the tool (e.g. minimise costs of achieving a given conservation goal; or maximise conservation benefit for a given amount of expenditure). These two sets of tools exemplify two broad approaches in conservation prioritization, those based on threshold (e.g. Marxan) or on continuous benefit functions (e.g. Zonation)[7]. In most cases the mathematical optimisation techniques used by these models allow for 'complementarity' (noting that the efficacy of an action in one place, depends upon the actions taken in adjacent spaces)[8]. However, there are quantitative CPMs that do not consider complementarity. Most popular are those based on scoring approaches, which rank sites and actions based on how much they score against some key criteria (e.g., number of species present within the sites). Examples of quantitative scoring approaches are those based on return on investment framework and cost effectiveness analysis, where alternative sites and actions are ranked based on their benefit-cost ratio (Auerbach et al. 2014; Carwardine et al. 2012; Joseph et al. 2009; Wilson et al. 2007).

Classic reserve selection tools are useful when managers need to account for spatially-explicit issues (such as connectivity across the landscape[9]) in the planning processes. For instance, when planning for marine conservation, it is important that marine reserves allow the exchange of individual and/or propagules (e.g. larvae) to maintain the populations of species of conservation concern (Magris et al. 2014). Similar issues occur in terrestrial and freshwater conservation planning. Reserve selection software, such as Marxan and Zonation, can account

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[7] Threshold (or target-based) functions are based on predefined amounts or number of occurrences of selected conservation features (e.g. habitats, species) that need to be included within a conservation system (e.g. network of protected areas); these amounts could be arbitrary or based on ecological and/or socioeconomic criteria. Examples of objectives incorporated into threshold functions include: protect 30% of the current extent of each vegetation type or aquatic ecosystem; include a minimum number of individuals of each species within protected areas (e.g. to maintain functional populations); or include a given number of occurrences of each threatened species. The key characteristic of these functions is that they imply no further addition of value after the objective is achieved (increments of amounts of features beyond the threshold provide no further increments of value for conservation). On the other hand, continuous function as based on continuously increasing measures of value as amounts of selected features are added to a conservation system. In contrast to threshold functions, these indicate progressively increasing value as amounts of features are increased. The forms of continuous functions include linear, sigmoidal, and diminishing-returns. Effectively, this means that most sites have a value (e.g. for conservation) and can be sequentially added to a conservation system (e.g. network of marine reserves) to increase its overall value and to maximise the achievement of planning goals (e.g. biodiversity representation) within given constraints (e.g. budget). Methods based on continuous functions include return-on-investment, continuous surrogates derived from ordination space, and frontier curves defined by alternative balances between conservation and forgone revenue from natural resources.

[8] More formally: this means that when actions/sites are selected, ions and sites selected from the pool of all available, are those that add the greatest contribution towards achievement of species targets, relative to the actions and sites in the existing reserve network. This property, also known as complementarity, ensures that the prioritisation process finds the most cost-effective suite of sites and actions (which are the best at achieving the conservation objective within certain constraints, e.g. costs), while avoiding redundancy of effort (Wilson et al. 2009).

[9] Reserve selection software, such as Marxan and Zonation, accounts for connectivity by minimising the boundary length of the solution, which ensures creation of a compact reserve network. Accounting for connectivity creates a complex mathematical problem to solve (non-linear), more complex than a simple, a-spatial, reserve selection problem, and therefore requires purpose-built software with added capabilities. When ensuring connectivity does not constitute a key aim of planning, some other approaches, such as integer linear programming, represent valuable alternatives to more complex spatial conservation prioritization tools (Bryan et al. 2011; Star et al. 2013).

for connectivity by minimizing the boundary length of the solution, which ensures creation of more compact or connected reserve network systems[10].

Earlier versions of reserve section tools were only able to consider one action (commonly, siting protected areas or reserves). However, CPMs have been developed recently that allow selecting among multiple different actions or zones that contribute differently to the protection of conservation features and/or other management objectives (Watts et al. 2009) or different types of actions to mitigate different threatening processes to species (Mantyka-Pringle et al. 2016; Cattarino et al. 2015; Pouzols & Moilanen 2013; Carwardine et al. 2012).

CPMs typically only represent a picture of a particular system at one point in time. In other words, they do not consider dynamic processes, such as varying occurrence and intensity of threats through time or variation in costs of activities through time (but see Adams & Setterfield 2015; Visconti et al. 2010). Furthermore, CPMs are often criticised for the lack of transparency ("black boxes") and because they allow for limited stakeholder engagement (Auerbach et al. 2014). However, some CPMs were developed with the explicit intention and functionality to interactively deign conservation interventions with managers (e.g. C-Plan: Pressey et al. 2009) and others, such as Marxan, have added interfaces (e.g. Zonae Cogito: Segan et al. 2011) that facilitate on-ground interactive design with stakeholders (Game et al. 2011).

The use of quantitate CPMs as decision support tools has risen dramatically in the last 20 years, due to the availability of some of them as off-the-shelf software. Some applications of conservation planning models to Northern Australia include:

- Zoning for multiple land uses in the Daly River catchment (Adams et al. 2016)
- Optimal eradication and control of Gamba grass in the Northern Territory (Adams and Setterfield 2015)
- Incorporating different types of connectivity into freshwater conservation planning (Hermoso et al. 2012)
- Incorporating connectivity rules and condition assessment into river conservation planning (Linke et al. 2012)
- Prioritizing multiple actions for threat abatement (Cattarino et al. 2015; Fuentes et al. 2014)
- Defining water use management objectives, based on specific environmental, economic and social criteria (e.g., condition of water habitat, number of water bores allowed) (Straton et al. 2011)

[10] In the simplest forms, these tools can assume connections between notional reserves are only based on adjacency of areas or symmetric movement of species between reserves (Beger et al. 2010a), but these have been adapted to account for directional (i.e. asymmetric) connections between reserves and across realms (Beger et al. 2010a,b).

The decision-making context in which conservation planning models are most useful includes situations in which the primary goal/interest of the decision-maker is the conservation of a particular landscape or species and the aim is to determine which 'actions' (e.g. set aside an area as a reserve, eradicate a weed) should be taken to:

- achieve a given conservation benefit at least cost

OR

- to achieve the maximum conservation benefit for a given amount of expenditure.

This can be done at coarse scale (e.g. identifying a single action for a single region) or at finer scale (e.g. identifying some regions in which to undertake a particular action, and other regions in which to undertake a different action)

And where:

- There are no complex or dynamic links between the natural and human realms. If there are complex links – e.g. one felt that by undertaking certain 'actions', one might impact human values, thus changing conservation priorities – then it might be important to embed the CPM within a larger coupled *systems model* – see Section 2.3.4.3.
- It is valid to represent the costs (or benefits) of an action as simple indicator (e.g. cost of preservation is $x per hectare; benefit is y species per hectare). If costs or benefits vary across space, or in response to other factors, the CPM may need to be coupled to other models that can capture these more complex cost functions (see Section 2.3.4.3)
- It is reasonable to assume that there are few unobserved costs or benefits that have been overlooked (or that if one were able to measure these unobserved costs or benefits, their inclusion would not alter model choices). If there are numerous unobserved costs or benefits, *asset evaluation models* may need to be used to assess them prior to inclusion in the CPM.

2.3.2.3 Hydrological models

Simplistically, hydrological models explore the link between rainfall (precipitation) and ground and surface water flows – often also considering sediment and contaminant loads within those flows. They typically incorporate meteorological data (including annual, monthly, daily, or even hourly rainfall, as well as other information depending on the model such as evapotranspiration, wind speed records, etc) to help explain or predict ground and surface water-flows over different periods of time (e.g. over the course of the next month, next year, next decade). Most modern hydrological models explicitly consider water variability – for example, predicting flows using long-term historical rainfall records, and exploring the extent to which flows change under different climatic scenarios – thus contributing to debates about water security and 'risk' (Cook and Bakker 2012).

Many hydrological models were originally developed with the objective (implicit or otherwise) of determining how much water can be extracted (or captured) from a river basin (for economic 'development') subject to a set of biophysical or natural constraints (Chen 2008). So despite the fact that these models have been developed by natural scientists, many have an (implicit) objective which is predominantly socio-economic – and can thus provide information that is useful to decision-makers whose core objective is either 'natural' or 'human'. Modern day models typically also consider ways in which changes in hydrological systems are likely to affect other parts of the natural environment – e.g. sediment loads within river systems (Armour et al. 2009; Dougal et al. 2005) or various surface water dependent ecological 'assets' (McGregor et al. 2016; DSITIA 2014). So while assessing changes in water quantity is a major aim of hydrological models, these models are also frequently employed to explore management options to assess and improve water quality (Walling et al. 2011) since they help to link sources of land-based pollutants (such as sediment, nutrients associated with different land uses) to affected aquatic ecosystems. Furthermore, these models can help to identify dominant processes associated with production and delivery of pollutants (Drewry et al. 2006; Walling et al. 2011), and thus help to determine appropriate strategies to minimise impacts on aquatic ecosystems. Water-quality modelling applications include identifying erosion hotspots and estimating pollutant loads delivered to aquatic ecosystems.

There are at least three broad types of hydrological models: physics (process) based, empirical, and conceptual, which differ also according to the spatial and temporal resolution of the data used within them (Merrit et al. 2003). Some hydrological models provide much fine-grained detail about particular aspects of the system (analogous to the bio-economic models discussed in Section 2.3.3.1), whilst others are less detailed but provide more breadth (Liu et al. 2008) – e.g. information about connections between various parts of the system (somewhat analogous to the regional models discussed in Section 2.3.3.2). There is normally a trade-off in scale – generally the larger the region considered within a model (e.g. a continental scale model, versus one considering only a catchment, versus one considering a sub-catchment) the more coarse-grained will be its spatial and temporal resolution. Therefore many hydrological models work with what is often termed 'lumped' (aggregated) data. It is a non-trivial task to determine how best to convert data that has much spatial and temporal variability (e.g. rainfall at a single location) into aggregated measures (e.g. rainfall in a sub-catchment over a one-week, or longer period), with much controversy surrounding the 'best' way to do so (Jarvis et al. 2013). That said, advances in computing power mean that distributed models (with high resolution spatial and temporal processes) are becoming more common (Merrit et al. 2003) – even when developed for large regions; the complexity of the computing problem has increased, but problems associating with the 'lumping' of data are diminishing.

Simplistically, the physics-based models use a variety of mathematical equations, which describe individual, physical, processes. The equations are mostly derived at small scale, using observations from controlled experiments (Beven 1989). The difficulties of extrapolating results (equations) from these small scale experiments to larger scales are substantive (Lane et al. 1995; Pickup and Marks 2001; Seyfried and Wilcox 1995) – so substantive, in fact, that some researchers have called into question their ability to generate useful results at large scale (Beven 1989; Beven and Cloke 2012), although Fatichi et al.'s (2016) review highlights that these models are filling critical information gaps and providing predictions about the likely impact of a ‘non-stationary’ climate, and of land-use and land cover changes on hydrological processes.

Empirical hydrological models use statistical techniques to analyse relations between (data) observations; for example, regressing measures of sediment load, against measures of rainfall. They generally use just a small number of explanatory variables (Jakeman et al. 1999) – and perhaps for this reason, have been criticised for being overly simplistic representations of hydrological processes (Wheater et al. 1993), although they have been found, on occasion, to perform well compared to physics-based models despite their need for minimal information (Loague and Freeze 1985). They have been used in a variety of different contexts internationally (see, for example, Jarvis et al. 2013; Chang et al. 2011; Nu-Fang et al. 2011; Nadal-Romero et al. 2008; Alibert et al. 2003; Troutman 1983). It is relatively rare for empirical hydrological models to incorporate data from the human realm unless indirectly, as when variables capturing land use, or land management are incorporated, although there have been recent ‘proof of concept’ studies, explicitly modelling interactions between the natural and human realms (in this case, the effect of beef prices on sediment loads, affected through dynamic changes in cattle numbers/stocking rates) (Chaiechi et al. 2016).

Conceptual models sit somewhere between empirical and process-based models. They are mostly developed using top-down representations of interactions between key parts of the system – typically internal storages within a catchment, with links between the storages (flows), depicting transfer mechanisms (e.g. of sediment) and run-off (Merrit et al. 2003). They are often, but not always, populated with quantitative data, obtained from empirical and/or process-based models and/or using ‘expert information’. Complex inter-relationships between variables, which cannot often be modelled or quantified accurately, mean that conceptual models are not generally able to generate accurate predictions of particular states, or of determining ‘best’ outcomes (Jakeman and Hornberger 1993; Spear 1995); instead their strength is highlighted when used to compare scenarios – identifying which situation is likely to produce ‘better’ or ‘worse’ outcomes. Many of today’s hydrological models are extremely large (Kauffeldt et al. 2016). The models thus contain hundreds of parameters which leads to the “the curse of dimensionality where parameter estimation becomes a high dimensional and mostly nonlinear problem (Song et al. 2015, p 740), giving rise to a substantive, and growing body of literature focusing on sensitivity analysis within hydrological models.

As for other categories of IDSTs, applications of these types of models are numerous and diverse. Northern Australian examples include those which have been developed to:

- Identify (surface water dependent) ecological assets that could be considered to be ‘at risk’ from water resource developments (DSITIA 2014).
- Predict changes in sediment and/or nutrient loads with different catchment management (land use) plans (part of the eWater toolkit[11]); this has been done in the

[11] http://www.toolkit.net.au/tools/SedNet

Mitchell, Daly and Flinders catchments (Rustomji et al. 2010; Wasson et al. 2011; Caitcheon et al. 2012).

- Predict changes in stream-flow under different climates, with different water-extractions from associated aquifers, under different management regimes (Pantus et al. 2011). This model was also 'coupled' with ecological and economic models (see Section 2.3.4.3)
- Assess the likely impact of extreme events and price changes on sediment loads in the Burdekin (Chaiechi et al. 2016)

> The decision-making context in which hydrological models are most useful includes situations in which:
>
> - The primary goal/interest of the decision-maker is on water resources – either quantity (flows) or quality (e.g. sediment or pollutant loads).
> - The decision-maker is interested in the way in which changes in either
>   - the natural system (e.g. climate) or
>   - the human system (e.g. land use, water extraction, commodity prices) might impact hydrological systems.
> - will affect water resources
>
> And where
>
> - Variables that are excluded from the model (be it process based, empirical or conceptual) can be reasonably assumed to be invariant, or have little effect on model outcomes. If that is not the case, the models are arguably best interpreted as generating useful scenarios for comparison – highlighting the situations in which outcomes are likely to be 'better' or 'worse' (rather than generating quantifiable predictions of actual stream flows or pollutant loads).

2.3.3 Models that have developed from within the social and economic sciences

Polhil et al. (2016) highlight that many IDSTs have grown from within the economics discipline, referring to these types of models as equilibrium models. The original versions of these economic models, developed many decades ago, assumed equilibrium, but many of the restrictive assumptions (including, but not limited to 'equilibrium') imposed on those early models were required to ensure analytical tractability (with limited computing power). Technological, statistical/econometric and theoretical advances have enabled researchers to remove (or reduce) the number of underlying assumptions and restrictions, developing sophisticated models capable of modelling non-linear relationships (Wang et al. 2001), dynamic relationships (Leontief and Duchin 1986; Robinson and Duffy-Deno 1996) with short-run and long-run effects of numerous different types of changes (including large, 'supply-side' shocks, in addition to the small demand-side shocks which were the only ones early models could handle). These modern models do not require one to presume ‘equilibrium’. In fact, they can cater to systems that reach an ‘equilibrium’ or instead follow either a ‘repeating’ or a ‘non-repeating’ pattern/cycle. As such, most modern day models incorporate insights from a diverse array of modelling literatures, including ‘chaos’ theory (Ferreira et al. 2011; Bunch 2016). This is facilitated by the speed of today’s computers which makes it possible to run the models numerous times with different underlying parameters, thereby testing the sensitivity of final results to changes in assumptions.

Rather than using the (misleading) term ‘equilibrium’ to describe these models, we instead refer to three broad classes of models that are able to generate insights for those interested in issues relevant to Northern Australia: bio-economic models; regional models; and asset/project evaluation models. The last group, asset/project evaluation models, explicitly incorporates insights from other social sciences beyond economics. These models are discussed in more detail below, but suffice to say here:

- Bio-economic models tend to focus on a particular industry and that industry’s interaction with the natural realm. They are thus likely to suit decision-makers who need detailed information about one particular industry and related environment.
- Regional models look at the way different industries interact (financially) with each other and with different sectors of the community; they also consider fairly simplistic interactions with the natural environment (e.g. water demand, or CO_2 emissions, per extra dollar earned within an industry). These models are thus likely to suit decision-makers who are interested in obtaining a ‘big picture’ overview of the way in which ‘changes’ (or policies) are likely to impact different parts of the economy or environment.
- Asset/Project evaluation models seek to assess the ‘desirability’ of projects, programs, or ‘scenarios’ from the perspective of society in general. They typically consider a broad range of potential project/program ‘impacts’ (sometimes, but not always assessed in terms of dollar costs and benefits). These models are thus likely to suit decision-makers who need help when selecting projects or programs and who need to consider the interests of numerous individuals, businesses and community groups.

2.3.3.1 Bio-economic models

Bio-economic models are, in economic jargon, partial equilibrium optimisation models (subject, of course, to the comments above about no longer necessarily assuming equilibrium). The term ‘partial’ signals that these models focus on just part of the system – for example, providing information about the fishing, mining or agricultural industry. These models provide a very in-depth picture of that part of the human system – and of its interaction with the natural system. As such, these models are truly integrative in Liu et al’s (2008) sense of the word, and are, arguably, a type of coupled systems model (Section 2.3.4.3), albeit a type that focuses specifically on particular parts of the economic and natural system (a particular industry, and its relationship with the natural realm), neglecting other key parts of the socioecological system (Schulter et al., 2012).

The term 'optimisation' signals that these models do more than just predict – they also help '*decide',* by, for example, determining which of several actions are likely to generate the 'best' results (e.g. highest profit, or lowest cost). The name bio-economic highlights that these models include variables and insights from both the natural and anthropogenic realms, although their goal almost always has an anthropogenic bias (e.g. attempting to achieve highest profits for the agricultural sector while minimising damage to the natural system, or assessing the costs and benefits of various pest or water management strategies). Although the goal is generally anthropogenic, these models blend quite sophisticated sub-models from both the natural and human (economic) realms – often allowing for complex interactions within and between modules. Costs/profits are normally complex functions of numerous variables, which include biophysical variables – and those biophysical variables are themselves represented using complex modelling approaches (that include other biophysical and also 'human' variables).

Some of the earliest bioeconomic models were developed by those interested in the problem of open-access fisheries (examining the economics of whaling, sealing and other pelagic fisheries, and seeking to determine the 'best' (optimal) way in which to control harvest for maximum economic yield at a whole-of fishery scale (Conrad and Smith, 2012)) although there were also numerous models developed from about the 1960s which focused on the economics of water (Booker et al., 2012), and which required researchers to consider complex interactions between the natural (in this case hydrodynamic) and human realms. The very first models were static and conceptual, but by the early 1970s the framework for thinking about resource exploitation (in fisheries and elsewhere – e.g. for forestry, water resources and mining) was invariably dynamic, and frequently grounded in optimal control theory. This required economists to start thinking about (fish / forest / mineral / water) 'stocks' and 'flows', over time, developing mathematical models of non-linear dynamic systems, that incorporated (interacting) biophysical and economic variables. The early versions of these models were generally non-spatial, but rapid advancements in the mathematical and computing sciences (and in IT) have facilitated the development of these models so that nowadays, bioeconomic models often provide much spatial detail. Termed spatial-dynamic models (Conrad and Smith, 2012), they can, for example, consider whether a no-take marine reserve, inserted into a fishery, would generate spill-over benefits (perhaps with the reserve operating as a breeding ground, essentially increasing stocks elsewhere for the fishery).

Not only are bioeconomic models now frequently used to assess marine environments, but their application in terrestrial systems is now common place. They mostly focus on particular parts of the system elements – e.g. on a fishery, an agricultural system (Janseen and Ittersum, 2007), invasives (Cook et al., 2013, 2015) or water resources (Petheram et al., 2016). As noted by Schuelter et al., (2010, p 230), "the single-species-oriented management philosophy has been increasingly replaced by an ecosystem approach and several recently developed models have sought to address the complexity observed in marine and terrestrial ecosystems". We discuss, those broader whole-of-ecosystem models in Section 2.3.4.3.

Applications of bioeconomic models are numerous and diverse, although less common in Australia's north than other modelling approaches (particularly so, when compared to SDM's or CPMs). Northern Australian examples include those which have been developed to assess:

- The likely profitability of a cropping industry, dispersed across the Flinders Catchment (Queensland (QLD)), based on water ‘harvesting’ for irrigation under different extraction regimes and with different stream-flow scenarios (Petheram et al. 2016);
- The potential economic costs (to the cattle industry) of the mimosa invasion in the Kimberley and estimates of how much should ‘optimally’ be spent on eradication/ control programs (Cook et al. 2015);
- The losses likely to be incurred in the Northern Australian banana industry from yellow Sigatoka under different management guidelines (Cook et al. 2013).
- The sustainability of yields in the northern Prawn Fishery, and to advise on management strategies to ensure sustainability (Pascoe et al. 2013);

Elsewhere in Australia, bio-economic models have also been used to explore trade-offs between irrigation extractions and environmental values in the Murray Darling (Grafton et al. 2011; Mainuddin et al. 2007), to estimate the potential costs (to the grazing and sugar industry) of achieving water quality targets in the Burnett-Mary Region, QLD (Beverly et al. 2015) and to consider trade-offs between the costs and benefits of different weed eradication programs (Hester et al. 2013).

Some international applications which also address issues relevant to Northern Australia include an analysis of the outcomes of various management strategies and marine reserves in the pacific halibut industry (Linh-Son et al. 2014), and an assessment (combining a bio-economic and a general equilibrium model) of the likely impact of water-use controls on different sub-sectors of the agricultural industry in a large river basin in China (Li et al. 2015).

The decision-making context in which bio-economic models are likely to be most useful includes situations in which:

- The primary goal/interest of the decision-maker is human / socio-economic (this includes having a desire to demonstrate the importance of the natural realm to the human realm).
- The decision-maker is interested in a single industry (e.g. its likely profitability) and its interaction with the environment. If s/he is interested in the way in which changes in that industry affects other parts of the economy or society, then a regional model may be more appropriate (although that will provide more information about the intra-economy interactions at the expense of information about complex relations between the industry and the environment; an alternative is to consider systems model).
- The relationship between the industry and the environment is a complicated one with numerous interactive feed-backs (e.g. growth of biomass a function of biophysical processes and also harvest rates; spread of disease dependent upon biophysical processes and also human intervention strategies). If the relationship can be approximated using simple relations (e.g. X units of extra production generates Y units of extra CO_2), then it may not be necessary to use such a complex model (a simple economic one, with extra environmental variables could suffice).

2.3.3.2 Regional models

These models originated from a sub-branch of economics that sought to model entire economies – the main aim being to learn about ways in which changes in one part of the economic system would affect other parts. There is a strong and well-established literature on these models (see for example, Dixon and Jorgenson 2012; Liu et al. 2016), including those generating spatially relevant data (Brocker 2015). There are numerous examples of applications of this modelling approach where investigators have extended their economic-focused models to explicitly allow for linkages between the anthropogenic and natural systems (Cumberland 1966; Huang et al. 1994; Hawden and Pearson 1995; Gustavson et al. 1999; Eder and Narodoslawsky 1999), relying on simple 'indicators' to model those links (e.g. average CO_2 emissions, or average ML of water used per dollar earned in various sectors of the economy).

Regional models do not contain the rich 'detail' of the bio-economic models; their compensating strength being their breadth. While these models provide much detail about the way in which various parts of the human (economic) system interact, they do not model interactions within the natural system; the natural system is incorporated through a simple indicator (e.g. CO_2 emissions) which is modelled as a simple function of economic activity. In some sense, these models are thus a 'mirror image' of species distribution models (Section 2.3.2.1) and conservation planning models (Section 2.3.2.2), which contain much detail about the natural system, but relatively little about the human system.

Unlike bio-economic models, these models do not 'optimise' (e.g. find the 'best' solution), rather they are used to predict trajectories of change. They show, for example, how changes in one part of the economy might affect other parts of the economy, society and the environment, over defined time horizons (e.g. the next 5, 10, 20 years) under different scenarios, described to inform particular management problems (e.g. with different rainfall patterns, water extraction rules, or rates of economic growth). Modern day applications of these models often include equations that allow for complex dynamic interactions between variables over time (thus allowing for an element of 'chaos' and non-equilibrium). Many modern applications also include insights from economic geographers and regional economists who extended their early, simplistic models, to better understand underlying factors that influence the physical flows, and the geographic dispersion of economic activity, and – by extension – some of the environmental 'impacts' of changes in economic activity across space (Hoekstra and Van Den Bergh 2002; Knudsen 2000; Murata 2003; Roberts and Stimson 1998).

Internationally, there are innumerable applications of these models. Most popular are applications which focus on the link between economic activity and environmental pollutants (e.g. CO_2 and SO_2 emission)[12]. They have also been used in many other settings; for example, Lenzen and Foran (2001), Kondo (2005) and Guan and Hubacek (2008) all examined links

[12] "[I]ndicators with [a] complex natural science background such as water stress or biodiversity loss are hardly represented … [and] social indicators stand out for very weak coverage" (Böhringer and Löschel 2006).

between the economy and water consumption; O'Doherty and Tol (2007) examined water use, SO_2, CO_2 emissions and solid waste. Meyer et al. (2013) also provide examples of cases where these models have been used to assess the potential economic impact of natural disasters.

Many of these models are multi-regional, providing spatially differentiated data and information. They are normally built using industry specific data (e.g. gross value of production) that has been collated by central data collection agencies (such as the Australian Bureau of Statistics (ABS)); as such, the 'regions' included within these models are often quite large.

Australian applications of the models include numerous examples which consider the country as a whole and focus on issues relating to CO_2 emissions and the carbon tax (see, for example, Meng et al. 2013; Burniaux et al. 2013). We could find only two recent applications of this type of model which considered smaller regions in Northern Australia, explicitly incorporating variables from the natural realm. These include:

- One which assessed the potential impact of drought, providing results at the statistical division level for Queensland (Horridge et al. 2005); and
- One which looked at the ways in which growth in different sectors (e.g. agriculture, mining) could impact Indigenous and non-Indigenous incomes, and demand for water in the Daly and Mitchell River catchments (Stoeckl et al. 2013b).

We note also the significant potential of a model developed by the Centre of Policy Studies:

> *TERM (**T**he **E**normous **R**egional **M**odel) is a "bottom-up" Computable General Equilibrium (CGE) model which treats each region as a separate economy. The first TERM master database distinguished 144 sectors and 57 regions (nearly corresponding to the Australian Statistical Divisions). More recently, TERM has been extended to represent 182 sectors in 205 statistical sub-divisions: this allows us to split major cities into regions, and represent water catchment and tourism regions. The high degree of regional detail makes TERM a useful tool for examining the regional impacts of shocks (especially supply-side shocks) that may be region-specific.*
>
> (Centre of Policy Studies http://www.copsmodels.com/term.htm)

Most relevant to those interested in issues pertinent to Northern Australia are the following:

a) the claim that TERM is 'naturally suited' to simulating the effects of improving particular road or rail links – this might provide useful insights for the Northern Development Agenda.
b) there is a special version of TERM (TERM-H2O), which has been used to analyse the economic impacts of water shortage and of water trading focusing in particular on the Murray-Darling Basin (Wittwer and Griffith 2011; Dixon et al. 2011; Wittwer and Dixon 2013). TERM-H20 adds details of farm-water use. The most recent version provides information about 206 statistical sub-divisions, allowing the model to consider water-related issues at finer regional scale (within and across some catchments) considering farm, (semi)urban and tourism regions

c) TERM has been used to generate predictions about the potential economic impact of drought across various regions of Australia – although across Northern Australia, results were only available for statistical divisions within Queensland (Horridge et al. 2005).
d) TERM could also, potentially be extended to consider other issues relevant to Northern Australia – particularly focusing on ways in which to demonstrate environmental impacts/side-effects (water pollutants or water extraction) of the simulated changes to sectors of the economy within specific regions of the north.

This newer version of TERM represents a significant step forward from the previous version for those interested in Northern Australia (particularly since the model now separates out the towns of Darwin, Cairns and Townsville, so that the other regional models are not dominated by the economic activity of the larger centres). But as shown in Figure 3, Australia's statistical sub-divisions are still quite large, highlighting that these models are particularly good at providing information to support decision-makers concerned with cross-catchment/region issues, but unlikely to help those who are primarily focused on smaller scale within-catchment/region issues.

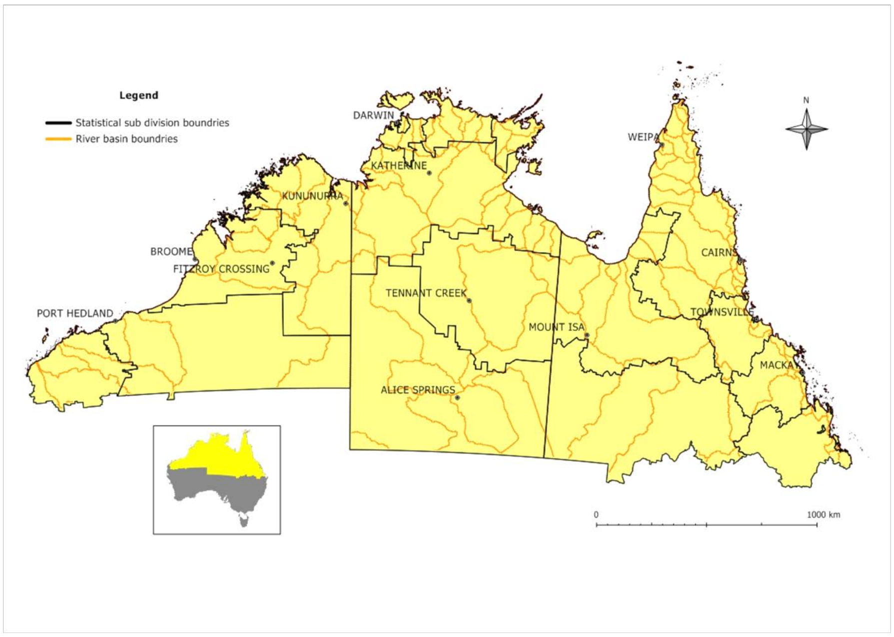

Figure 3: Statistical sub divisions and river basin boundaries across Northern Australia

The decision-making context in which regional models are most useful includes situations in which:

- The decision-maker does not need highly spatially disaggregated environmental/hydrological information.
- The decision-maker needs socially/economically disaggregated information.
- The region(s) of interest have multiple interacting economic sectors (e.g. households of different types, industries of different types) and the policy/decision-maker is interested in exploring:
    - Differences in potential 'impact' of changes on different sectors of the economy (e.g. determining if some sectors have more/less to lose from different development scenarios than others),
    - The potential environmental impact of change within the economy,
    - Ways in which the economic and environmental 'impacts' of change can be influenced by different management 'rules' (policies).

And where:

- 'Impacts' can be modelled with the use of simple heuristics (e.g. each additional 10 units of production in sector X, will likely be associated with an additional 12 units of nitrogen leaching into the ground water system). One would need to undertake additional (biophysical) research to determine how those first round 'impacts' (e.g. more nitrogen) would impact other parts of the natural realm; alternatively, one could couple the regional model within a larger systems model to adequately capture more complex interactions and dynamic feedbacks between the human and natural systems.

2.3.3.3 Asset/project evaluation models

Asset/project evaluation models originated from a sub-branch of economics that sought to estimate the monetary 'value' of non-market goods and services using, insights from that 'valuation' to help people decide whether a decision/change was likely to improve the current situation. Early examples of these models include approaches such as Cost-Benefit Analysis (CBA) and Social Return on Investment (SROI) analysis – which generally did not provide information for small geographic scales. Modern extensions of CBA and of related non-market valuation models include INFERR[13] and INVEST[14] which allow one to assess and compare the 'value' of multiple projects and/or which allow one to map 'values' across space; often incorporating such information within other IDSTs (such as conservation planning models). Not all of these approaches assess 'values' in monetary metrics.

Most of the methods, developed by economists, to assess the 'value' of environmental (and other non-market) assets in money metrics are complex, challenging to implement (well) and difficult to understand. Arguably, this complexity exists because, traditionally, economists have

[13] http://www.inffer.com.au/
[14] http://www.naturalcapitalproject.org/invest/

believed that (1) the 'value' of a good or service (irrespective of whether or not it is traded in the market place) is linked to the benefit (or 'utility') that an individual derive from it (e.g. how 'happy' it makes them); and that (2) 'utility' (happiness) cannot not be measured directly – at least not in an easy way that allows one to estimate 'value' or benefits directly (Kristoffessen 2010). So when economists have sought to measure the 'value' of a good or service, they have needed to assess value indirectly --- using the notion of 'income equivalent' compensations (after Hicks 1939). Simplistically, this means that economists draw *inferences* about the 'value' of a good (say an ecosystem, or a species of conservation concern) by simulating changes to it (e.g. degradation or improvements). They then work out how much money people would need to be given (or have taken away from them) to ensure there is no change to their overall utility (quality of life / wellbeing) as a consequence of the change to the environment. Determining how best to simulate the changes, and collect data to draw inferences about *income-equivalent* compensations can be difficult, but there are numerous different methods for doing so (Getzner et al. 2005; Bateman et al. 2002). Not all methods can be appropriately applied in all settings (Farr et al. 2016).

Cost Benefit Analysis (CBA) and assessments of the Social Return on Investment (SROI) are sometimes referred to as non-market valuation methods. Strictly speaking, they are not. Rather, they are structured ways of aggregating monetised data about benefits and costs – weighting them against each other according to specific rules (e.g., including discount rates). CBA and SROI studies thus often entail numerous non-market valuation activities, with 'value' estimates aggregated into a single value (e.g., the net benefit, or the 'return' on investment) [15] . In theory, a comprehensive CBA or SROI analysis should include monetised estimates of all benefits and all costs associated with the project/program being evaluated. But the difficulty of monetizing some values (particularly intangible values such as those associated with culture) means that these assessments often omit numerous values, instead concentrating on values (often associated with provision, or regulating services) which are more easily quantified (Farr et al. 2016). The aggregation process is also not uncontroversial; CBA is essentially a weighted voting system with weights determined by income. So when monetised estimates of 'value' are compared to inform decisions or prioritisation processes (within CBA or elsewhere), those comparisons will give greater weight to the preferences of the rich than of the poor (Adler and Posner 1999; Blackorby and Donaldson 1990; Loomis 2011). This may not be a problem if preferences do not vary systematically with income/wealth, but there is much empirical evidence highlighting statistically significant links between income and preferences (Jacobsen and Hanley 2009). Some governments endorse the use of 'weighted measures' within CBA to correct for this problem (e.g. in UK), including in developing economies where income inequalities are often extreme (Hanley and Barbier 2009).

Perhaps at least partially because monetary based approaches struggle to explicitly account for some types of goods and services (Turner et al. 2016), evaluation models which use non-monetised participatory type approaches and/or multi-criteria analysis to account for more

[15] See Costa 2013, Emerson et al. (2000) and Ryan and Lyne (2008) for further details on SROI. See Baker and Ruting (2014) for CBA.

complex ‘social values’ are becoming more popular (e.g. Pert et al. 2013). Some recent advances in this area have stemmed from the recognition that individual welfare (utility) is directly measurable (Brereton et al. 2008); if one is willing to accept that it is valid to compare the welfare of individuals (Frey et al. 2009) then one can (at least in theory) measure the ‘value’ of environmental goods and services in the pure economic sense of the word – by assessing the extent to which they contribute to individual welfare. The empirical difficulties of assessing ‘values’ in this way are non-trivial, but they do allow one to generate quantitative information about the contribution that different goods and services make to an individual’s wellbeing without imposing a significant cognitive burden on respondents (a problem common in contingent valuation and choice modelling studies), without forcing trade-offs, without requiring respondents to assess ‘value’ in monetary terms (often in hypothetical ‘markets’) and without requiring one to assume the existence of an underlying ‘market equilibrium’. One can simply observe the relationship between (individual) utility and the environment.

Asset/project evaluation models generally contain much detailed information from within the human realm – since they often require the use of complex methods for assessing asset/project values – but the links between human and natural systems are often, out of necessity, assumed to be relatively simple. For example, these models often adopt the assumption that the relation between the natural and human systems can be represented by simple ratios or indices: typically along the lines of "‘x’ hectares of woodland generates ‘y’ dollars’ worth of water purification services". They thus ‘estimate the net benefit (or benefit-cost ratio) of particular projects (Pannell et al. 2011; 2012; 2013a) or ‘map’ values across space (Ma et al. 2016) – although that can be challenging if ‘values’ do not directly correspond to particular points in space (most likely for some socio-cultural values; potentially also problematic for migratory species).

Most current evaluative approaches estimate the ‘value’ of different states of the natural system – either allowing end-users to select their preferred state, or providing heuristics to help decision-makers (e.g. selecting the state with the highest net benefit). Modern computers allow one to rapidly value and re-value different states of nature (using assumed, simplistic relations between nature and ‘value’), so it is possible to generate maps (or similar) which show a distribution of ‘values’ across time, and dependent upon different states of nature, which provide useful information to support decision-makers. Depending upon how many different goods and services are considered in these assessments they can be very comprehensive – ensuring that a broad range of assets are included in assessments. But the *interactions* that are modelled are generally only those *within* the human system, rather than between the human and natural systems. They are thus not truly ‘integrative’, as they do not explicitly model *interactions* between the human and natural systems. Birkhofer et al. (2015) and De Groot et al. (2010) identify some of the challenges facing those who wish to truly integrate evaluations within dynamic predictive models that explicitly model interactions between the human and natural systems.

Although examples of single-purpose non-market valuation studies abound, we could find no published examples of applications of comprehensive asset-based evaluation models across the savanna of Northern Australia. Relevant examples from elsewhere include:

- Pannell et al. (2012) who use INFFER to assess numerous environmentally focused 'projects' across Victoria (Australia), determining which are likely to generate the highest benefit-cost ratios, and are thus good candidates for funding; and
- Pert et al. (2013) who used participatory mapping to help identify 'values' in the Mission Beach area subsequently incorporating insights from the participatory mapping within a conservation planning model.
- Vogl et al. (2016) who combined the power of INVEST with hydrological models, to inform decisions on hydropower production in India.

The decision-making context in which asset/project evaluation models are most useful includes situations in which:

- The decision-maker has several different well-defined scenarios (choices/decisions) under consideration, and s/he wishes to select the 'best'.
- 'Best' is defined from an anthropogenic perspective, most often, but not necessarily, in dollar terms e.g.
    - The highest net benefit
    - The highest benefit-cost ratio
    - Highest individual or community wellbeing

And where:

- It is possible to assess most 'benefits' (impacts) in dollar terms, or to explicitly incorporate other 'benefits' using participatory (or other) approaches. If benefits are assessed using dollars, then one may need to use income-weights to redress potential biases if (a) the preferences of stakeholders vary systematically with income and (b) there are substantial differences in income/wealth of different stakeholders.
- The 'impacts' (of projects or of states of nature associated with the scenario) can be modelled with the use of simple heuristics (e.g. project X will likely protect an extra X units of forest, which will generate an extra Y units of 'value' in the form of water purification services). One would need to undertake additional (biophysical and economic) research to determine how those first round 'impacts' (e.g. more forests and better water) would impact other parts of either the natural or human realms.

2.3.4 Models which have developed from within mathematical and computing sciences

This group of models largely originated from the disciplines of mathematics and computer science. As such, they do not systematically bias one realm over another (e.g. protecting the environment at least cost to society versus protecting society at least cost to the environment); instead, their primary focus/goal is to understand more about the way in which parts of a system influences other parts.

Most reviews of these types of models differentiate between agent based models (ABM) – simplistically built from the 'bottom up' – and more 'top down' systems models (Kelly et al.

2013; Filatova et al. 2016; Blair and Baytauert 2016) although Croke et al. (2006) argue that systems modelling is a philosophical approach to modelling, rather than a unique and well-defined modelling approach. Researchers also regularly identify Network Based Models (NBM) – the popular Bayesian approach being an example of such – as belonging in a category of their own (Kelly et al. 2013; Blair and Baytauert 2016; Croke et al. 2006), with Blair and Baytauert (2016) introducing another category altogether, termed 'pattern oriented modelling', thought to represent a modelling approach that is part-way between the bottom-up Agent Based, and the top-down systems approaches. Some researchers also identify a separate group, termed coupled components models (Kelly et al. 2013; Blair and Baytauert 2016). In short, there is no universally agreed way of categorising these types of models (Kelly et al. 2013).

These computing/mathematical models can be conceptualised as being comprised of numerous 'boxes' that are connected in different ways (after Chan et al. 2012, in their discussion of Bayesian models). There are two different types of 'boxes' (*Nodes*[16] and *Sub-components*[17]) and two different types of 'connections' (fixed[18] and dynamic[19]). Here, we use differences in the way that the 'boxes' and 'connections' are defined to characterise and differentiate between three sub-categories of computing/mathematical models: Network Based Models (NBM); Agent Based Models (ABM); and Systems Models (SM). Below we provide a very short overview of each, with a more detailed discussion in the pages that follow.

- Network Based Models (NBMs) consist of a collection of nodes with (typically) fixed connections. At the risk of over simplifying, NBMs create 'maps' – powerful visualisations of the way in which different parts of a system (the nodes) are connected. These models are particularly useful for decision-makers who are considering implementing one or more changes (e.g. increased water extraction, increased fertiliser use) and who wish to identify which parts of their core 'system' of interest could be indirectly impacted by those changes (Chan et al. 2012). Unlike the other sub-categories of *computing/mathematical* models, NBMs are particularly well-suited to situations where uncertainty (about data) is the norm, rather than the exception (Kelly et al. 2015).
- Agent based models (ABMs) consist of a collection of nodes with dynamic connections. The connections typically describe the way 'agents' interact with each other – allowing patterns and behaviours to change and evolve over time. ABMs tend to present their projections visually – e.g. using dynamic charts or dynamic, spatially configured, maps to show how various parts of the system are likely to change over time, given initial starting conditions and the simple rules governing the behaviours of agents. These models are

[16] Nodes are processing units (which take inputs and provide outputs) and may or may not represent real world objects/interpretations e.g. in a Bayesian network the node may represent fish with the node output representing probability of survival (and with the input of node being such things as flow rate), in an agent based model, the node may represent a consumer or a fisher. In other cases (e.g. in an artificial neural network (ANN)) the nodes do not have a real-world object interpretation – they are simply equations/processes that convert inputs to outputs. These nodes are basic 'atoms' (building blocks) that cannot be reduced to sub-nodes.

[17] Subcomponents can be a collection of agents or nodes and as such may be reduce/broken down further. But they can be treated as a separate entity with well-defined inputs and outputs.

[18] 'Rules' (or relationships) between nodes or sub-components that are fixed over time (i.e. for the entire model-run)

[19] 'Rules' that can change over time (even arising or disappearing)

particularly useful for decision-makers who wish to explore the (potential) emergent outcomes of a key resource (e.g. fish stocks, stream flows, ecological habitat) given the choices that multiple interacting individuals make about that resource (e.g. to extract more fish or water) (Ostrom 1998).

- Systems Models (SM) consist of a collection of subcomponents with (typically) fixed connections. Sub-components can be defined at any scale and can even comprise (sub) systems models – hence why large SMs are often termed '*coupled components'* models. These models generally only consider a small handful of subcomponents (in detail) but their connections typically include dynamic feedbacks which means that outcomes, like those in ABMs can be *emergent*. SMs generate information that is useful to decision-makers working at a relatively aggregate (large) scale, who wish to explore the (potential) collective outcome on multiple (sub) systems of the complex interactions between them (e.g. a regional economy, embedded within the natural environment, with changes occurring to the both macroeconomy and to climate). The size and complexity of some SMs, means that they can take decades (and many resources) to develop from scratch and are thus often built first as sub-components, and then coupled in later years (Barzel et al., 2015; Boumans et al., 2002).

2.3.4.1 Network Based Models (NBMs)

While computer engineers focused on the mathematical metrics of networks and are, arguably, the 'fathers' of network based models, most modern day network models were also heavily influenced by insights from biologists and ecologists, well used to studying the impact of change on sub-components of complex interconnected systems – e.g. foodwebs (Mulder and Elser 2009) and central nervous systems. NBMs models often consider numerous (sometimes hundreds) of nodes and allow one to visualise the way in which a (mostly one-off) change in one part of the system can 'ripple through' to other parts of the system, travelling through various inter-connected nodes. They thus "show cause–effect relationships directly through a simple causal graphical structure" (Chan et al. 2010), so are particularly good at generating insights about the way in which seemingly unconnected parts of a system may, in fact, be crucially dependent upon each other. Mulder and Elser (2009) provide six particularly good, contrasting examples of the visualisations produced by network models. As such, these models provide crucial insights into the importance, redundancy and/or vulnerability of key nodes and connections within a system (Pocock et al. 2016) – analogous to identifying 'motorways' and/or dead-ends in a transport system.

The two most commonly used network based models are Bayesian Belief Networks (BBNs) and Artificial Neural Networks (ANN). BBN models consist of three elements: (a) a set of nodes representing the management system's key variables – these are usually representations of real-world objects (e.g. fish); (b) a set of links that represent the cause-effect relationship (Bayes' conditional dependence) between the nodes and (c) a set of probabilities representing the belief that a node will be in a certain state given the states of the 'input' connecting nodes (Chan et al. 2010). The 'connections' between nodes are thus representative of an underlying probability distribution, ascertained through scientific experiment/observations, using the expected values of statistical model, and/or using 'expert opinion'[20]. A network of BBN nodes is thus a simple 'conceptual map' of how a change in one node affects the chance of another node changing.

ANNs attempt to mimic the neural network of the brain. These models also have 'nodes', although the nodes do not have to represent a real-world object, they are better conceptualised as a set of equations that convert 'inputs' to 'outputs', using a series of 'weights' (Figure 4).

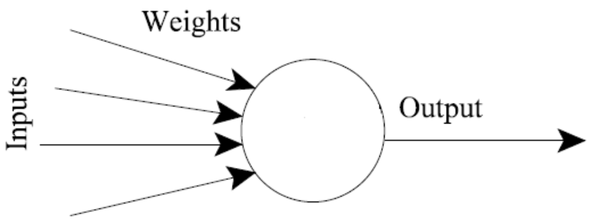

Figure 4: A 'Node' in an ANN

Key features of ANNs and BBNs are summarised in Table 3. Both ANNs and BBNs require expert input to build their network and data to train and test on. Typically, designers of these models use only some of their available data to parameterise the model; the rest of the data are then used (as if it were new data) to test the model's performance and to make predictions/decisions[21]. But the two models use different machine learning concepts for pattern recognition: the BBN have intrinsic meaning behind the structure, while ANN does not. The ANN uses a heuristic optimization method, so there is no guarantee that the ANN will find the most accurate model and while ANNs have the ability to learn complex patterns directly from observations, their reasoning process is inaccessible to human understanding and one cannot be certain what the ANN has learned. The BBN on the other hand, uses explicit representations of independence (and dependence) relationships between variables making the 'reasoning' behind the machine learning transparent (Zeng et al., 1999; Mitchell, 1997; Diederich, 1992).

For BBN's, the conversion of continuous to discrete data can cause instabilities in the model (Kelly et al. 2013), but the structure of network models means they can be 'easily constructed, extended and modified; BBNs in particular have a natural way to handle missing data; they explicitly incorporate uncertainty, and can show good predictive accuracy even with small sample sizes' (Mulder et al. 2015). That said, the uncertainty modelled by BBNs relates to uncertainty regarding data (probabilities) linking nodes; uncertainties surrounding model structure (which nodes are/are not included; which nodes are connected to other nodes; the

20 As such, the 'output' from each node is the probability of an event, given (or conditioned on) the 'input' (or state of) the parent node(s).

21 In most cases, the goal of network modellers is to minimise the number of nodes and connections required to explain data; the trade-off between parsimony and predictive ability is guided by information theory based techniques that usually value the information contribution (reduction in entropy) of a node; removing those nodes with little value.

uncertainty associated with the conditional probabilities parameterising a node) are less easily dealt with, although it is possible to do so, by comparing predictions across models with different structures (Kelly et al. 2013).

Table 3: Key features of BBNs and ANNs

Features	**BBN**	**ANN**
Optimisation method	Probabilistic	Simple heuristic
Explainable learning process	Yes	No
Flexibility in topology design	Yes	No
Weights inside the network	Computed or assigned	Trained
Possible data overfitting	No	Yes
Limitation on input data type	Yes (only discreet data)	No
Implementation	Difficult	Easy

Like Regional Models (Section 2.3.3.2), network models do not typically provide much fine-grain detail about the nature of interactions between nodes; their compensating strength being their ability to provide a 'big picture' overview of the input/cause and output/response dynamic. Network models considered in this review, do not generally incorporate feedbacks – instead considering a uni-directional mapping of a one-off change from 'top' of system to 'bottom' (although some network models do incorporate dynamic feedbacks (and 'learnings') very much blurring the distinction that we have drawn between network, and systems models (discussed in Sections 2.3.4.2 and 2.3.4.3).

There are numerous software platforms available for developing and applying 'standard' Bayesian Networks including: Netica[22], Analytica[23], GeNIe and SMILE[24] and Hugin[25]; BNT[26] and DBmcmc[27] handle dynamic BNs, and BUGS[28] supports continuous variables (rather than imposing discrete probabilities) (Kelly et al. 2013). Other source software platforms cited in Mulder et al. (2015) include 'Pajek' (Batagelj 1998), 'bipartite' (Dormann et al. 2008), 'Gephi' (Bastian et al. 2009), 'Cheddar' (Hudson et al. 2013), and 'Food Web Designer' (Sint and Traugott 2015). For Artificial Neural Networks, software is also numerous extending from MatLab and Excel plugins to Emergent.

22 Norsys Software Corp., www.norsys.com
23 Lumina Decision Systems, www.lumina.com
24 University of Pittsburgh, genie.sis.pitt.edu
25 Hugin, www.hugin.com
26 K. Murphy, bnt.googlecode.com
27 D. Husmeier, www.bioss.ac.uk/wdirk/software/DBmcmc
28 MRC and Imperial College, www.mrc-bsu.cam.ac.uk/bugs

Internationally, network models have been applied in hundreds, perhaps even thousands, of settings. Classic BBN reviews include McCann et al. (2007) and Ellison (1996); with Mulder et al. (2015) and Kelly et al. (2013) providing good reviews of Bayesian and other models - with Mulder et al. (2015) focusing on applications which consider Ecosystem Services (linking human and ecological systems) and Kelly et al. (2013) providing a comprehensive listing of applications that integrate human and natural systems throughout the world.

Chan et al. (2010) published example of a BBN applied in an 'integrated' (human-natural system) across Northern Australia (use of eFlow BBN to identify aquatic species 'at risk' from water resource developments). Several relevant applications from elsewhere in Australia (many selected from Kelly et al. 2013), include:

- Water allocation, access and pricing, Namoi River, Australia (Letcher et al. 2006)
- Declines in native fish, Goulburn Catchment, Australia (Pollino et al. 2007) -
- Salinity management, Macquarie River (Saloddin et al. 2005)
- Managing stocks of commercially important fishery species (Punt and Hilborn 1997)
- Farm irrigation, Shepparton Irrigation Region, Victoria, Australia (Wang et al. 2009).
- Prioritisation of flow and catchment restoration options, south-east Queensland, Australia (Stewart-Koster et al. 2010).
- Spawning and recruitment of fish species, Latrobe River in Victoria, Australia (Shenton et al. 2011).

> The decision-making context in which Network Based Models (NBMs) are most useful includes situations in which:
> - The primary goal/interest of the decision-maker is determining which parts of the system are most (least) likely to be affected by a 'change' elsewhere in the system – *i.e.* in identifying parts of the system that are *at risk.*
> - There is much too much uncertainty in the system to write a precise (deterministic) equation about the way in which a change to X could impact Y – this makes the use of a probabilistic (BBN) model or an ANN desirable
> - There are potentially many different complex interactions.
> - The decision-maker is primarily interested in the initial (first round) impacts of a 'change' – it is not necessary to understand how this plays out over time (albeit theoretically possible to reveal using NBMs).
>   - Although it is rare for these models to incorporate much spatial resolution, there is nothing preventing them from doing so in that one could define different 'nodes' for different points in space or time. This is possible in both BBNs and ANNs.

2.3.4.2 Agent based models (ABMs)

Rather than considering fixed connections between a large number of nodes (as per network models), agent based models normally focus on a relatively small sub-set of autonomous 'nodes' (in this case, termed agents) and at the dynamic (transient) interactions between the agents (in this case, the behaviours). ABMs typically present their projections visually – e.g. using dynamic charts or dynamic, spatially configured, maps to show how various parts of the system are likely to change over time, given initial starting conditions and the simple rules governing the behaviours of agents.

Nodes/agents are typically defined at a relatively small scale (e.g. an organism, an individual, or a small group of individuals) and are termed 'agents'. Although early ABMs depicted only humans as agents, an agent can represent elements from the natural system, so these models are truly integrative (e.g. animals (Drogoul and Ferber 1994), fish and fish predators – human and otherwise (Dambacher et al. 2015) or biophysical entities such as bodies of water (Servat et al. 1998)). Since there are an infinite number of different ways one could define agents and the 'rules' governing their behaviours, there are clearly no bounds on the variety of different ABMs one could devise. Researchers such as An (2012) and Blair and Baytauert (2016), however, distinguish between ABMs according to the types of 'rules' that are used to govern the behaviours of agents (e.g. if agents always seek to 'optimise', if agent behaviours are determined by 'experience' or by other variables in the model; if agent behaviours/rules can change over time as the agent 'learns' which behaviours work best). The computer code underpinning these rules uses Cellular automata, Genetic Algorithms or prediction/decision markets[29.]

ABMs allow for the fact that an initial change can generate an initial 'impact' (as for NBMs); in addition, they explicitly recognise that the 'impact' of that initial change may itself propagate further changes (impacts) in a dynamic (and potentially never-ending) cycle. These changes/impacts are normally depicted with simple deterministic equations or rules that describe connections between nodes over time (e.g. if X changes to Y, then in the next period Z will change to 2Y; or if X goes up then Y will go down during the next period[30]) . These connections are not necessarily fixed (e.g. they can turn on or off) and they are rarely uni-directional: X can change Y which can 'feedback' and cause X to change again. With strong links to general systems theory and to complexity theory (An 2012), these models are thus

[29] Many optimisation problems require searching a large solution set. GAs by their very nature start with a random collection of agents that cover that solution set, and after a short period of time the best/optimal solution is identified i.e. the large solution set is considered by the GA to find the desired global optima. For example, the optimal collection of planning units that achieve target biodiverse species targets may be obtained in this way. Cellular Automata (CA) has similar characteristics. But in contrast to the agents of GA (which are necessarily diverse to cover the solution set), the agents of CA are typically different groups of homogeneous agents e.g. rural agents and urban agents. Each CA agent has the same simple rules when interacting with other CA agents and simply put the interaction leads to the growth or demise of agents across time and space depending on the simple rules. These simple rules are informed by the real-world problem. For example, the location of agricultural land may suggest the CA rural agents populate closer to a water way and meet their demise further away. The urban CA agent may have a different rule. After some time and initial condition pattern of rural and urban agents will emerge into a different (and typically complex pattern). Prediction/decision markets aggregate real time information into market prices that represent probabilities of events e.g. a stock for "it will rain tomorrow" will be traded by human and computer agents: it pays $1 if it does rain tomorrow. One of the agents may believe that there is a 75% chance of raining so will bid around $0.75. All bids are averaged into a market price of say $0.80 which means the market believes there is an 80% chance of it raining tomorrow. There are prediction markets to track ecological processes eg flu epidemics and also for climate change etc (PMs thus aggregate real-time information to provide the best possible probability prediction).

30 Note the 'rules' do not have to be written as continuous equations; they can be simple on-off 'switches' – or written as -1 (negative impact), 0 (no impact), +1 (positive impact). See Dambacher et al. (2015), Dambacher and Ramos-Jiliberto (2007) and Carey et al. (2013)

typically 'chaotic' or 'evolutionary' – in that there is no pre-determined equilibrium/point of convergence. The models 'parallel process' (in the computational sense) and are thus particularly adept at exploring emergent behaviours and outcomes (Blair and Baytauert 2016) – specifically, learning more about the potential large scale (e.g. whole of community/region) outcomes of the behaviours of multiple agents. They do, however, require researchers to make numerous assumptions about individual behaviour (Kelly et al. 2013), and some may thus suffer from a "lack of analytic tractability and difficulties with extracting robust conclusions" (Levin et al. 2013).

There are several different software platforms which are particularly good if seeking to develop ABMs that allow one to explore different scenarios – most providing ways of visualising projected changes over time and/or across space, see, for example, Ascape[31], Cormas[32], Mason[33], NetLogo[34], and Repast[35] and Swarm[36] (LePage et al. 2012, Kelly et al. 2013). Perhaps at least partially because of the relative ease that these platforms allow one to develop ABMs, international applications are numerous (Blair and Baytauert 2016 and Kelly et al. 2013 review ABMs alongside other modelling approaches; An 2012 provides a particularly comprehensive review of ABMs; see also Le Page et al. 2012 and Bousquet and Le Page 2004 who review ABMs used to analyse ecosystem management, Berger 2001 who focuses on ABMs in agriculture, and Rounsevell et al. 2012 who focus on ABMs and ecosystem services); applications in a Northern Australian context are sparse, but include investigations of:

- Recreational fishing at Ningaloo reef (Gao and Hailu 2012)
- The northern prawn (commercial) fishery, at Weipa in the Gulf of Carpentaria (Dambacher et al. 2015)
- Forage growth and stocking rates in the rangelands of north-eastern Australia (Gross et al. 2006).
- Potential dispersal of mosquito-borne virus, harmful to cattle, from Timor across to Northern Australia (Eagles et al. 2012) - an example of an agent based model with no human 'agents'.
- Dispersal of fruit-fly across Queensland (Wang et al. 2015).
- The management of a screwworm fly invasion across mainland Australia (segmented into 20km x 20km grid squares) (Welch et al. 2014).

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[31] Developed by the Brookings Institute.
[32] Cirad, cormas.cirad.fr
[33] Developed in the USA at George Mason University
[34] CCL, ccl.northwestern.edu/netlogo
[35] Created in the USA at the University of Chicago and subsequently maintained by organizations such as Argonne National Laboratory, http://repast.sourceforge.net/
[36] Developed in the USA at Santa Fe Institute

A particularly interesting international application is one which embedded a hydrological model within an ABM (almost classifying it as a 'coupled' dynamic systems model), to explore water allocations/budgets (Martin et al. 2016).

The decision-making context in which Agent Based Models are most useful includes situations in which:

- The primary goal/interest of the decision-maker is determining how a common resource (e.g. fish stock, stream flow, aquifer balance, spread of a pest/weed) is likely to be affected by the behaviour of two or more 'autonomous' agents which share that resource.
- The actions of one 'agent' affect other 'agents' &/or the common resource.
- The decision-maker is interested in determining if some types of behaviours, or if some types of institutions that govern behaviours are likely to improve (or debase) the common resource.
- It is possible to characterise likely behaviours in relatively simple ways (ideally, in ways that can also be verified; although that is not necessarily if using scenario-type approaches to explore the way in which different types of behaviours might affect final outcomes).

2.3.4.3 Systems Models (SM)

Systems Models (SMs) are, simplistically, a macro-level variation of NBMs in that they generally consider subcomponents with fixed connections. In contrast to NBMs, however, they tend to focus on fewer connections and these connections almost always, like ABMs, include dynamic feedbacks. This is not to say that NBMs lack dynamic feedback; on the contrary NBMs with dynamic feedback are possible. These dynamic feedbacks introduce complex chaotic features even in a simple setting (as when, for example a logistic equation is used to model population growth, which introduces nonlinear chaotic feedback). When first developed by Forrester in the early 1960s (Kelly et al. 2013), these models often used simple rules and a computationally tractable number of 'subcomponents. The 'connections' between subcomponents were often written as difference equations explicitly quantifying links between stocks and flows (e.g. each day, 10% of the water contained within an aquifer (the stock), is extracted for agricultural use (the flow)). Over time, SMs have evolved with many researchers now developing them as a series of sub-models. That is, small SMs often serve as subcomponents to larger SMs, hence our decision to formally acknowledge the modern and very blurred distinction between what some researchers call [dynamic] systems models and what others call 'coupled components' models (Blair and Baytauert 2016; Kelly et al. 2013), treating them not as separate approaches, but as a single, albeit hybrid type of computing/mathematical IDST.

One of the strengths of SMs is that they allow one to simplify complex problems by firstly thinking about the larger system, and then considering how aggregated subcomponents of the system interact. In contrast to ABMs, these models thus involve an element of 'top-down' design (Blair and Baytauert 2016); requiring model developers to firstly create a big-picture overview of how various components of the system are connected, and to later, parameterise those connections. The process of developing a 'big picture overview' has itself evolved into philosophical modelling approach (sometimes termed mediated, participatory or group model building), where intended outcomes of model development are not solely focused on generating quantitative predictions of and visualisations of integrated systems, but rather on bringing diverse groups of stakeholders together, to better understand the way in which their actions/activities affect one another (see, for example, Boumans and Costanza (2007) and Belt et al. (2013) for applied examples relevant to integrated water resource planning). Easy-to-use software platforms such as ithink[37], Vensim[38] SIMILE[39], and Powersim Studio[40] make it possible for people with minimal technical background to develop dynamic models, (Kelly et al. 2013; Bouman and Costanza 2007). Moreover, "*because of the ease with which [these models] can be modified and run, [they are] especially useful for testing assumptions about connections. [They] can also be used to show how models of this type are sensitive to changes in parameters and specification, especially in the case of the technology term*" (Costanza and Gottlieb 1998, p 232). Perhaps at least partially because of the ease with which such models can be developed, some applications have been criticised for not being empirically grounded.

Whilst the development of some SMs have emphasised the participatory/mediating side of the modelling process, other SMs have instead focused on the task of generating (verifiable) quantitative predictions, from linked, quantitative models. These highly quantitative SMs often combine insights from ecology, chaos, psychology, econometrics, growth theory, business cycles theories, structural change and game theory into systems models that can deal with complex interconnections between various sub-systems across multiple scales (Liu et al. 2015), and can allow for 'bounded rationality' and endogeneity, can model transition paths and also complete regime shifts (Polhil et al. 2016; Filatova et al. 2016).

Depending upon the model (and the sub-models that are contained within), SMs are usually able to provide detailed information at multiple scales (micro, mezzo and macro), and about interactions between sub-systems (normally, but not necessarily, at the meso or macro scale). These models generate information that is useful to decision-makers working at a relatively aggregate (large) scale, who wish to explore the (potential) collective outcome on multiple (sub) systems of the complex interactions between multiple, connected, sub-systems (e.g. a regional economy, embedded within the natural environment, with changes occurring to the macroeconomy and to the climate). That said, the size and complexity of some SMs, means that they can take decades (and many resources) to develop from scratch (often first building the sub-components, and then coupling them).

There are innumerable examples of international applications of relatively small scale SMs, built on free (or relatively inexpensive) software platforms; not surprisingly there are fewer

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37 isee systems, http://www.iseesystems.com/
38 Ventana Systems, http://www.vensim.com/
39 http://www.simulistics.com/
40 Powersim Software AS, http://www.powersim.com/

examples of the very large coupled-models. Applications relevant to Northern Australia include:

- A relatively small coupled systems model, with hydrological, ecological and economic components, used to explore social and ecological implications of different types of economic growth, with different water extraction regulations in the Daly River, NT (Pantus 2011).
- A large and complex coupled systems model with hydrological and economic components to explore water trading in the Murray Darling Basin, Australia (Mainuddin et al., 2007; Yu et al., 2003).
- *Atlantis:* A 'whole of ecosystem' systems model (with biophysical and economic components), focusing on the South-East Australian fisheries, and used to assess potential impact of different management regimes (Fulton et al. 2011). See also Christensen and Walters (2004) for a description of Ecopath (an ecological model) that has been combined with Ecosim (a dynamic systems model) to consider impacts of fishing on ecosystems.
- The *Land-use Trade-off Model* (LULO) – "an integrated, environmental-economic model of land systems to project potential land-use and ecosystem services under intersecting global change and domestic policy combinations for Australia (Bryan et al. 2016).
- Mitigating human impacts to improve population viability of threatened species: Modelling the impact and potential mitigation of cold water pollution on Murray cod populations downstream of Hume Dam, Australia (Sherman et al. 2007)
- A simulation platform to assess the impact of land use and management change scenarios (simulated in ArcGIS) on a suite of water quality, biodiversity and economic performance indicators (Bohnet et al. 2011). The tool combines biophysical, social and economic models in a single simulation environment, where the impacts of different land use change scenarios can be systematically evaluated. Geo-referenced input data can be used to identify priority areas where land-use changes will have greatest impacts, in terms of social, ecological and economic consequences.

The decision-making context in which Systems Models are most useful includes situations in which:

- The decision-maker does not have a ‘primary’ goal of protecting/maintaining elements of either the natural or human systems.
- There are strong or numerous interactions between the natural and human systems (e.g. one is grappling with a problem relating to the human use of natural resources, rather than focusing primarily on elements within one or other of those realms)
- It is sufficient to glean a fairly broad-scale understanding of interactions and likely trajectories of change under different scenarios (in largely qualitative, rather than quantitative terms) – in which case development of a fairly simple systems model using existing software platforms is possible – potentially implemented in a participatory/mediated approach
- OR
    - There are already quantitative models of various aspects of the system (e.g. an ecological model, an economic model), capable of being ‘coupled’ (capability will depend on variables used within the models, and on the spatial and temporal scale at which those variables are measured)
      OR
    - There is ample time (and money) to develop a comprehensive coupled model from the ‘ground up’

3 INSIGHTS FROM NORTHERN STAKEHOLDERS

3.1 Methods

We developed a questionnaire to learn more about the IDSTs that had been used or developed for use by people in Northern Australia. We compiled a list of people who had developed, used, or were likely to benefit from the use of IDSTs across Northern Australia (hereafter, northern stakeholders), and interviewed them to document applications of these modelling tools. More specific details are provided below.

3.1.1 Development of 'end-user' and 'builder' questionnaires

We used insights from the literature to characterise the 'model building' and 'model using' process (Figure 5) and used that characterization to inform the development of two questionnaires – one for 'users' and one for 'builders'.

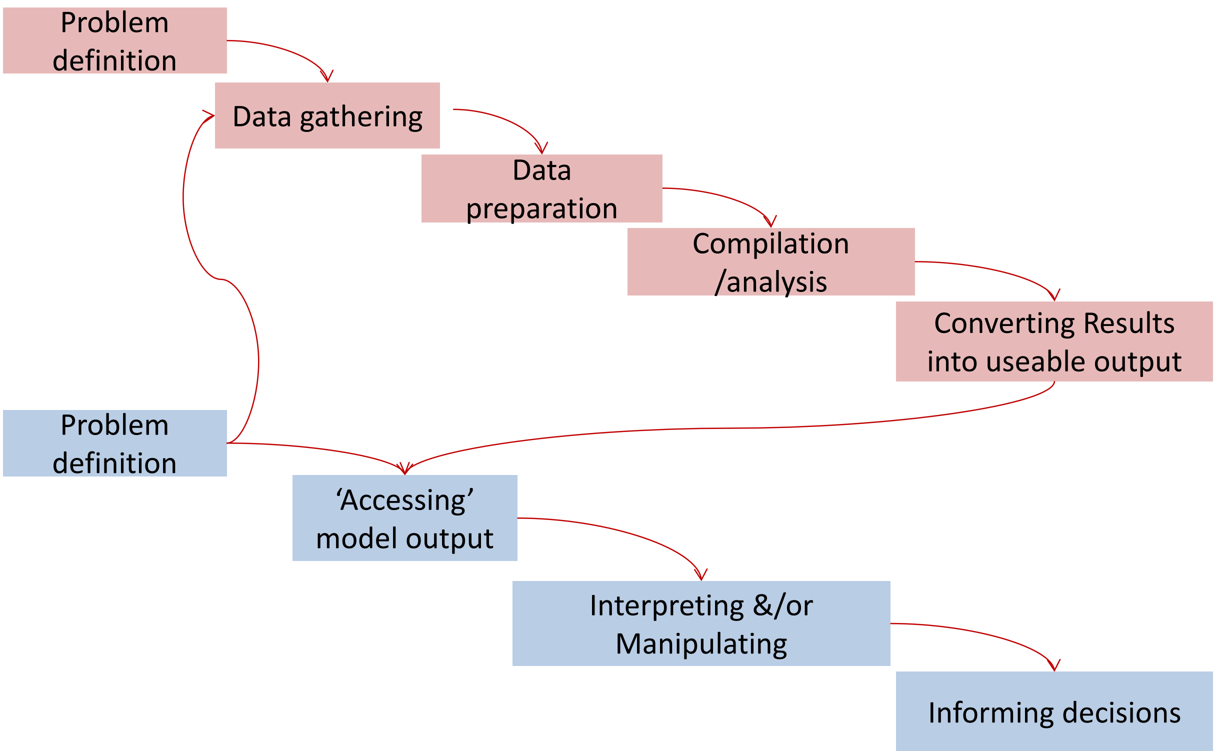

Figure 5: Conceptualisation of the steps taken to 'build' an IDST (red) and to 'use' it to inform decisions (blue)

Linkages between the 'build' and 'use' processes highlight that many 'builders' are also 'users' and that these links may help ensure that the tools which are 'built' are genuinely fit-for-purpose

The 'user' questionnaire was divided into sections, the first of which sought information that could help us to learn more about the decision-making context in which the respondent was operating, and also about the methods (which may, or may not, include the use of IDSTs) they employed when making decisions. Specifically, we started the interview by asking respondents to tell us about the types of decisions/plans/policies they were responsible for, their potential impacts, region/area and the types of people likely impacted. We then asked respondents to tell us about the strategies they employed to collect information when needing to make those types of decisions (e.g. having private consultations with key people; public meetings/discussions/workshops; online research; use of IDSTs, etc), and about how successful those approaches were.

If the respondent had never used an IDST, we stopped the interview at that point (offering to provide more information should they wish it); those who had used an IDST were asked for more information – in the first instance about the (decision-making) context in which they used the IDST. We also asked them to comment on the information generated by the IDST, specifically about the format (e.g. map, table, fully interactive computer program), the clarity of information and ease of interpretation, frequency of usage, and usefulness of outputs. We also asked for their perceptions of the overall usefulness of the model, its usefulness compared to other methods used to support decision-making, its ability to provide answers to key questions and to influence policy/plans, and about the likely transferability of insights to other contexts.

The ‘builder’ questionnaire was also divided into sections – the first collecting information about the purpose or intended use of the IDST (what question/problem was it intended to inform), the intended ‘user(s)’ of either the IDST or the information generated by it, and the extent to which ‘users’ were involved in the design or development of the model. We also asked about the length of time taken to build the model, the data, resources (financial, human, IT, etc) and skills required to do so.

3.1.2 Sampling / Data collection

Using a snowball sampling technique, we contacted a total of 80 ‘users’ and 25 ‘builders’. We did this by firstly using the networks of researchers involved in this project and of those associated with the Northern Australian Environmental Resources Hub of the NESP, to compile initial lists; specifically aiming for a stratified sample by both organization (e.g. state or federal government departments, NRM groups, Indigenous Organisations, Other NGOs) and jurisdiction (specifically, Western Australia, Northern Territory, Queensland and Australia). After having obtained ethics clearance,[41] we sent an email to these people, explaining what the project was about, providing a copy of the questionnaire, and alerting them to the fact that we would contact them via telephone in the next few days. When contacting potential ‘end users’ for the first time, we asked a ‘screening’ question (Chew et al. 2008:):to be eligible for inclusion in the study, end users needed to be actively involved in making decisions or devising plans and policies about issues that could have multiple impacts across multiple realms. If an ‘eligible’ respondent agreed to be interviewed, we arranged a suitable time to do so (over the telephone) and sought permission to record the interview (to speed the process and facilitate the flow of the interview). We asked all people (irrespective of eligibility) to provide us with the names of other key stakeholders who could/should be considered for interview – hence the ‘snowball’ sampling.

[41] James Cook University Human Ethics Clearance number: H6273

We used descriptive statistics to summarise (quantitative) responses from the ‘builder’ (Section 3.2.2) and ‘user’ (Section 3.2.1) interviews.

3.2 Results

3.2.1 The user survey

We interviewed 40 (potential) IDST ‘users’, although 10 of them had never used an IDST. For these non-’users’, we captured information about the other methods they used to make decisions and then terminated the interview. Although not all respondents were directly responsible for decision-making (such as those from research centers/universities or private consultancies), they did nonetheless have a key role in helping to provide the necessary information required by policy makers and environmental managers. Others (e.g., those associated with industry groups) see their primary role as one of providing an industry view for government policy and advocating for strategies that support their industries.

The 30 ‘user’ respondents we spoke to provided information about 30 different tools[42]. We attempted to categorise each of the tools/models described by our user respondents according to the system described in Section 2.3, however, we found that not all tools/models satisfied all the criterion we used to define an IDST. Some, for example, considered *only* the natural or the social realm; some only ‘described’ (or mapped) data but did not predict or decide. Nonetheless, all of the tools and models described by our ‘users’ and the categories to which we assigned them are listed in Table 4. Thus, Table 3 presents not only IDSTs described in the previous section, but also various non-IDSTs reported as used by stakeholders.

[42] Ten respondents had used, and agreed to provide information about, more than one IDST. So we conducted a total of 46 separate interviews about the IDSTs. As such, there is not a one-to-one mapping between users and IDSTs: for some IDSTs we have information from only one ‘user’, for other IDST’s we have information from multiple users

Table 4: Tools described by end-users

Model	Broadest Category	Sub-Category
1. Maxent	IDST - Biophysical	Species Distribution Modelling
2. Ecopath[43] (Marine SDM ** related model – EcoSIM is dynamic simulation)	IDST - Biophysical	Species Distribution
3. Conservation planning prioritisation	IDST - Biophysical	Conservation planning
4. Conservation prioritisation	IDST - Biophysical	Conservation planning
5. The Landscape Fragmentation Tool	IDST - Biophysical	Conservation planning
6. Marxan with zones	IDST - Biophysical	Conservation planning
7. Prioritisation tool	IDST - Biophysical	Conservation planning
8. Conservation Action Planning (CAP) Tool[44]	IDST - Biophysical	Conservation Planning
9. Aquabam	IDST - Biophysical	Conservation Planning
10. MIRADI[45]	IDST - Biophysical	Conservation Planning
11. Healthy country planning method[46]	IDST - Biophysical	Conservation Planning
12. eWater Source[47]	IDST - Biophysical	Hydrological
13. eWater Catchment[48]	IDST - Biophysical	Hydrological
14. IQQM[49]	IDST - Biophysical	Hydrological
15. MEDLI[50]	IDST – computing/mathematical	Dynamic simulation
16. MSE – Daly	IDST – computing/mathematical	Dynamic simulation
17. MSE – Fishery Tool[51]	IDST – computing/mathematical	Dynamic simulation
18. BWQIP.	IDST – Social	Bio-economic
19. Normalised Multiple Objective Analysis (NMOA)	IDST - Social	Asset/Project evaluation
20. Multicriteria analysis	IDST - Social	Asset/Project evaluation
21. JAVA, GIS, Oracle database	Non-IDST	Data presentation and storage
22. Google Earth, GIS	Non-IDST	Data presentation and storage
23. OPPIS[52]	Non-IDST	Data presentation and storage
24. NRM Spatial Hub	Non-IDST	Data presentation and storage
25. Planning framework	Non-IDST	Conceptual
26. Ready Recknoner	Non-IDST	Conceptual
27. Critical Path Analysis (Pyramid decision)[53]	Non-IDST	Project management tool
28. enQuire[54]	Non-IDST	Project management tool
29. Farm Economic Analysis Tool[55]	Non-IDST	Financial analysis
30. The Renewable Resource Model[56].	Non-IDST	Financial analysis

[43] http://ecopath.org/about/; http://celebrating200years.noaa.gov/breakthroughs/ecopath/welcome.html
[44] https://www.conservationgateway.org/ConservationPlanning/ActionPlanning/Pages/conservation-action-plann.aspx; https://www.wilderness.org.au/articles/conservation-action-planning-managing-future-great-western-woodlands; https://www.conservationgateway.org/Documents/Cap%20Handbook_June2007.pdf
[45] https://www.miradi.org/
[46] http://www.natureaustralia.org.au/our-impact/local-communities/healthy-country/; http://www.natureaustralia.org.au/2013/02/healthy-country/
[47] http://ewater.org.au/h2othinking/?q=2010/08/source-catchments-realising-whole-catchment-water-management; http://ewater.org.au/products/ewater-source/for-catchments/
[48] http://www.toolkit.net.au/Themes/Catchment
[49] http://www.toolkit.net.au/Tools/PublicationDetail.aspx?id=1000000&publicationID=1000049
[50] http://npsi.gov.au/products/er960336; http://www.simmondsbristow.com.au/medli-version-2-is-finally-here
[51] http://www.cmar.csiro.au/research/mse/
[52] http://www.nrmhub.com.au/mapping-2/
[53] http://www.tutor2u.net/business/reference/critical-path-analysis; https://www.mindtools.com/critpath.html
[54] http://enquire.net.au/; http://enquire.net.au/tour/grant-management/; http://enquire.net.au/tour/project-management/
[55] https://www.daf.qld.gov.au/plants/field-crops-and-pastures/sugar/farm-economic-analysis-tool
[56] https://www120.secure.griffith.edu.au/rch/items/5c89d98d-3fe6-10d5-eed0-19b2a1f64383/1/

Our sample was dominated by 'users' from various Queensland State Government departments (Figure 6).

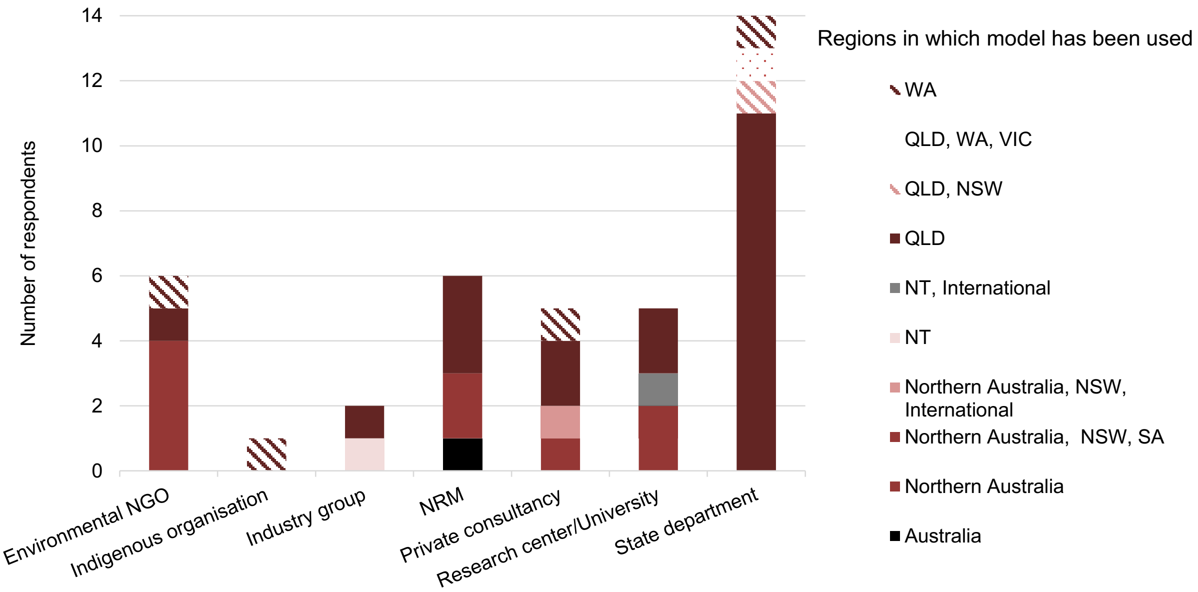

Figure 6: Respondent 'users' by type or organisation in which user works, and region in which model is 'used'

Excluding researchers and those associated with industry, examples of the sorts of decisions our respondents indicated they had to deal with include those relating to:

- Water management – e.g., potential impacts on water resources (quality, quantity and consumption); water treatment; productive use of water resources; water allocations; surface and groundwater planning;
- Park management – e.g., statutory planning for protected areas, ratings for park (tourism; scientific, etc.); resource allocation; values of parks;
- Wetland management – e.g., RAMSAR; conditions of land;
- Land use/agricultural planning – e.g., project management for cattle grazing;
- Cultural heritage – e.g., managing country (flora and fauna - land and sea management); native title;
- Environmental offsets framework or programs to improve practices;
- Coordination of NRM plans across different regions;
- Species conservation;
- Landscape management (e.g., fire management, weeds and pest management); and
- Urban planning.

Even amongst our respondents – who were deliberately selected because of the likelihood that they had used IDSTs – decision-makers employ a variety of different methods and collect information from a variety of different sources when required to "assess multiple (positive or negative) impacts across multiple realms – particularly when there are both positive and negative impacts (e.g. economic growth with environmental degradation)" (Figure 7).

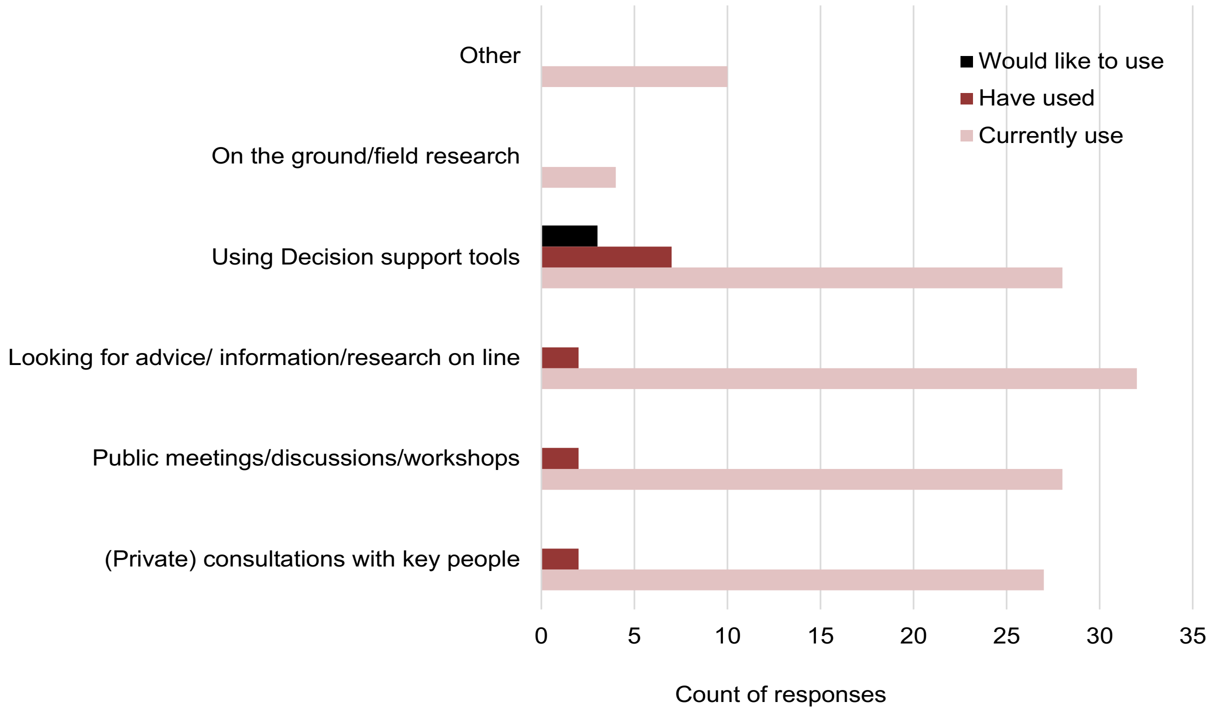

Figure 7: Frequency with which people use IDSTs compared to other methods

When asked to rate the overall usefulness of these different approaches (on a scale of 0, being *completely useless*, to 10, being *extremely useful*), IDSTs were generally given higher 'usefulness' scores than public meetings and internet surveys (Figure 8), but lower scores than private consultations and 'other' methods (which we have collectively termed *negotiation and consensus seeking approaches*). Most respondents thought that consultation with key people was the most effective approach (Figure 8): it was "*indispensable*" and "*multi-dimensional*", with some noting that "*there is no other way to have transparent and direct input*" from stakeholders. As fervently argued by one respondent, "*Bringing about change is difficult, and all sorts of approaches might be needed to make change happen. Getting in the ear of key people, so that they can help champion the cause, is important*". Moreover, the "*engagement process facilitates the prioritisation of issues, producing very clear messages compared to other methods*". This approach was noted as being particularly "*critical in Indigenous communities*". Although public meetings were highlighted as a legislative requirement by respondents belonging to state departments, and thus generally seen to be "*vital*", they were also seen as "*inflexible*" since "*it depends on the willingness of participants*" and can be quite "*difficult in remote areas*".

Decision support tools were deemed useful, primarily because their *"output is critical for decision-making*" – although it "*can be difficult and time consuming to learn*" how to best use these tools. Respondent generally struggled to identify a 'favourite' method. Most participants were adamant that "*it is not a choice*" – all of the approaches are required "*for accountability*" and "*to properly understand the system*". In fact, "*bringing about change is hard, so tackling a problem in multiple ways is needed*".

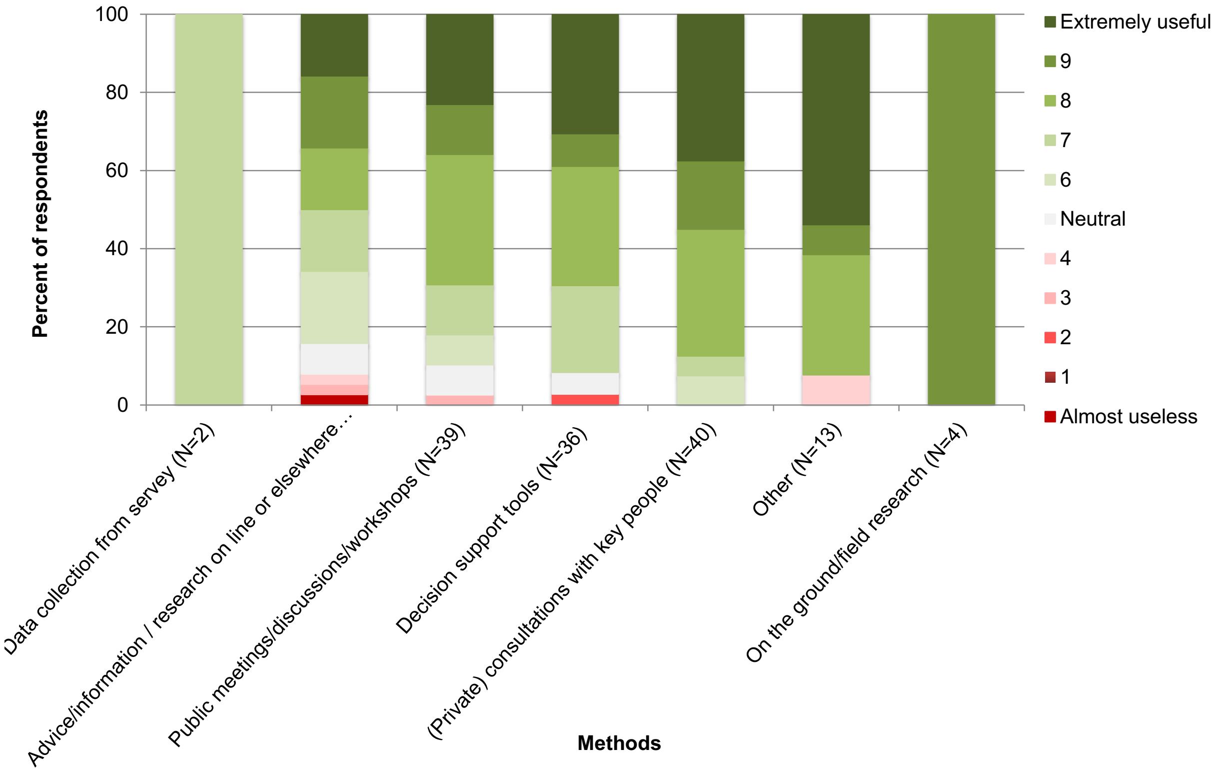

Figure 8: Respondent perceptions of the overall 'usefulness' of different methods employed when assessing multiple (positive and negative) impacts across multiple realms

Of those who indicated that they had used decision support tools (whether formally classified as an IDST, in this report, or not), the people with whom we spoke were most familiar with conservation planning tools (Figure 9) – and several had been quite intensively engaged in the development of both species distribution models and conservation planning tools (Figure 10).

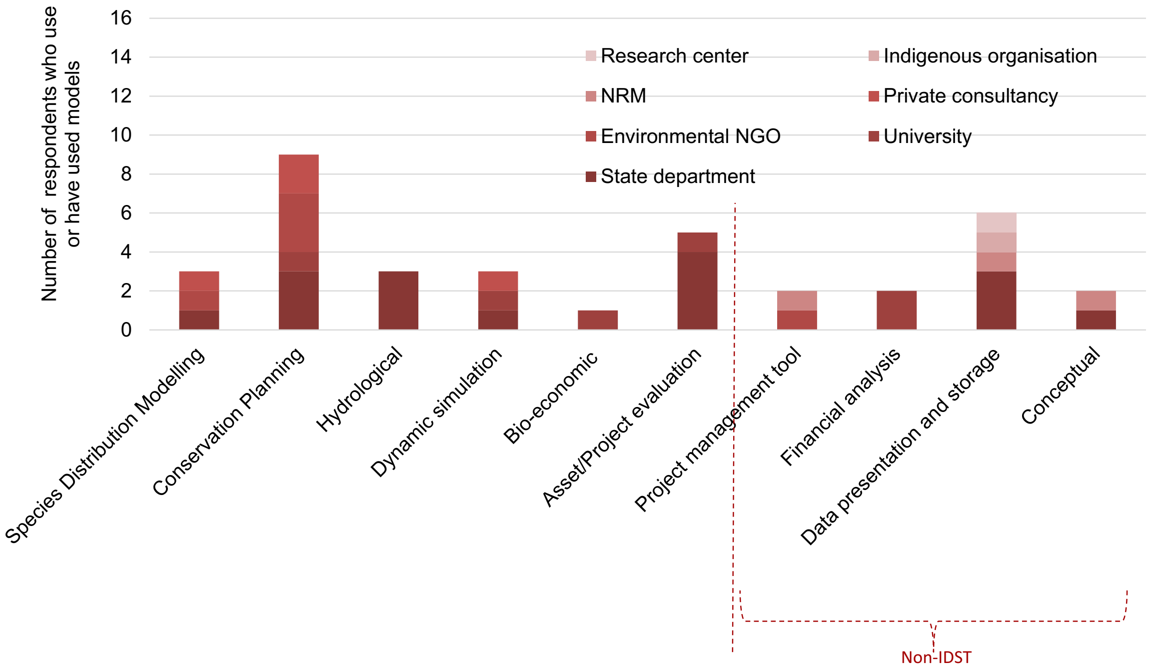

Figure 9: Respondent familiarity with different tools – number of times they have used different tools by (type of) organisational affiliation

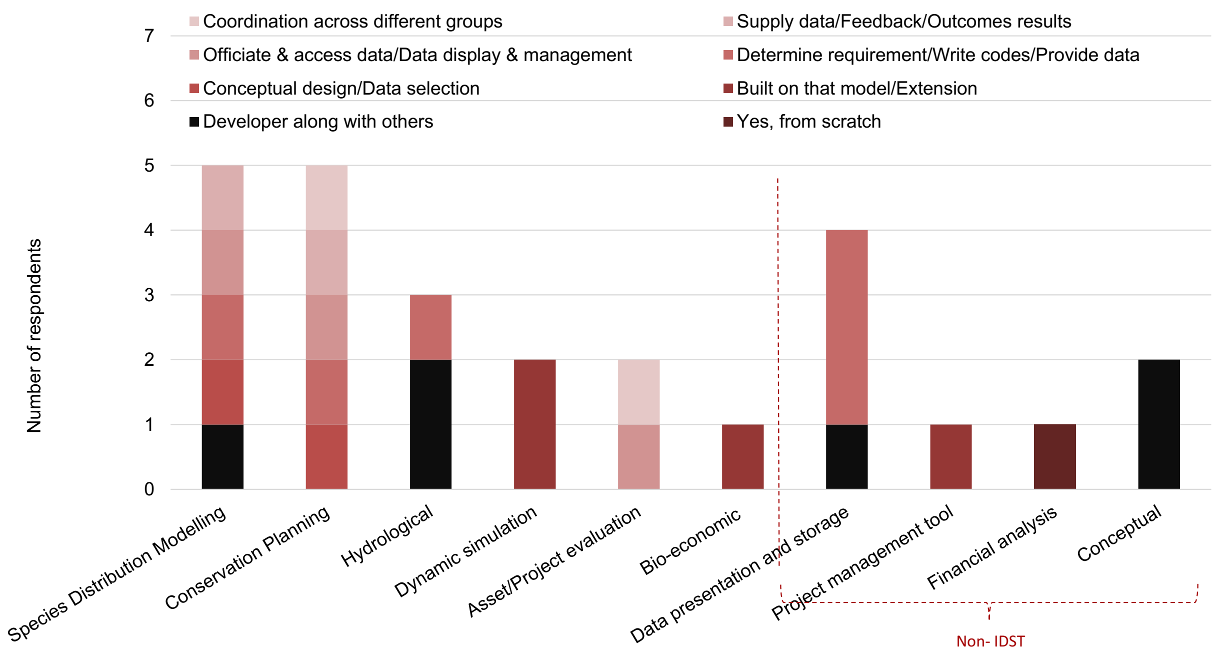

Figure 10: Respondent familiarity with different tools – engagement during development of different tools by (type of) engagement

Tools which we formally classify as IDSTs were not used as frequently as other models/tools – particularly those which facilitated the representation and storage of data/information and those helping with financial analysis (Figure 11). Species distribution and bio-economic models in particular, were used very infrequently. Frequency of use does not appear to be correlated with 'ease of understanding': species distribution models are used intermittently, but end users indicated that it was relatively easy to understand their outputs (Figure 11). We surmise that this may be because of the very 'visual' nature of outputs (including charts and maps) from the species distribution, conservation planning, and hydrological models (Figure 12).

Tools considered to be particularly difficult to understand were those focusing on economic and financial issues – although the end-user with whom we spoke gave these models very high scores with respect to their 'overall usefulness' and ability to influence policy (Figure 13 - we caution readers when interpreting this chart, since we spoke with only a small handful of 'users' about each type of model).

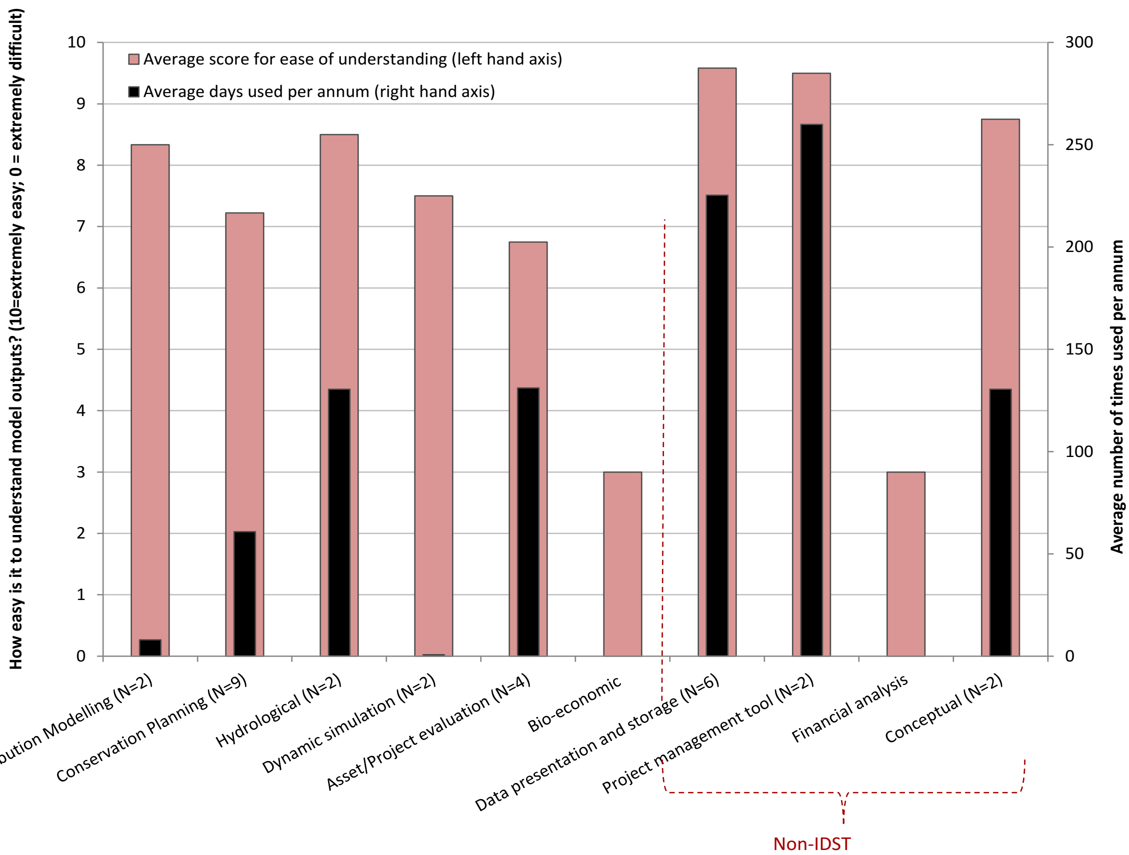

Figure 11: Respondent familiarity with different tools – frequency of use and perceptions of how 'easy' the outputs of tools are to understand

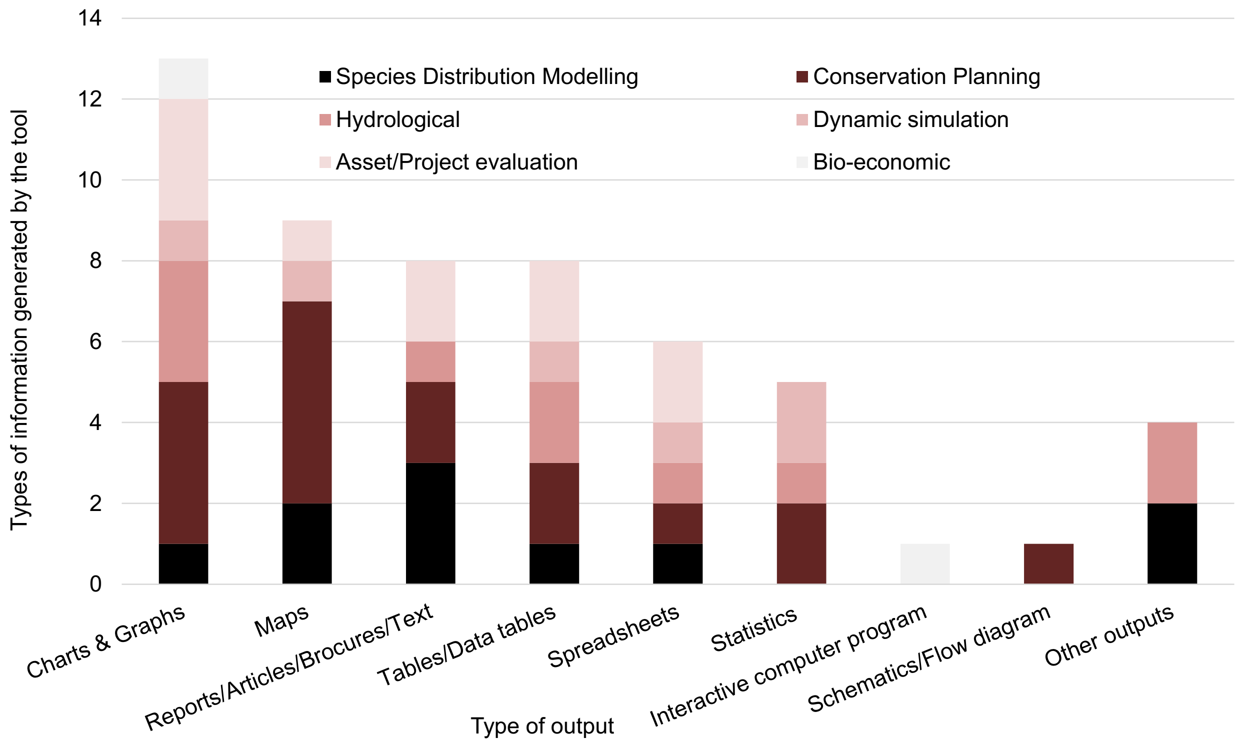

Figure 12: Types of outputs generated by different IDSTs

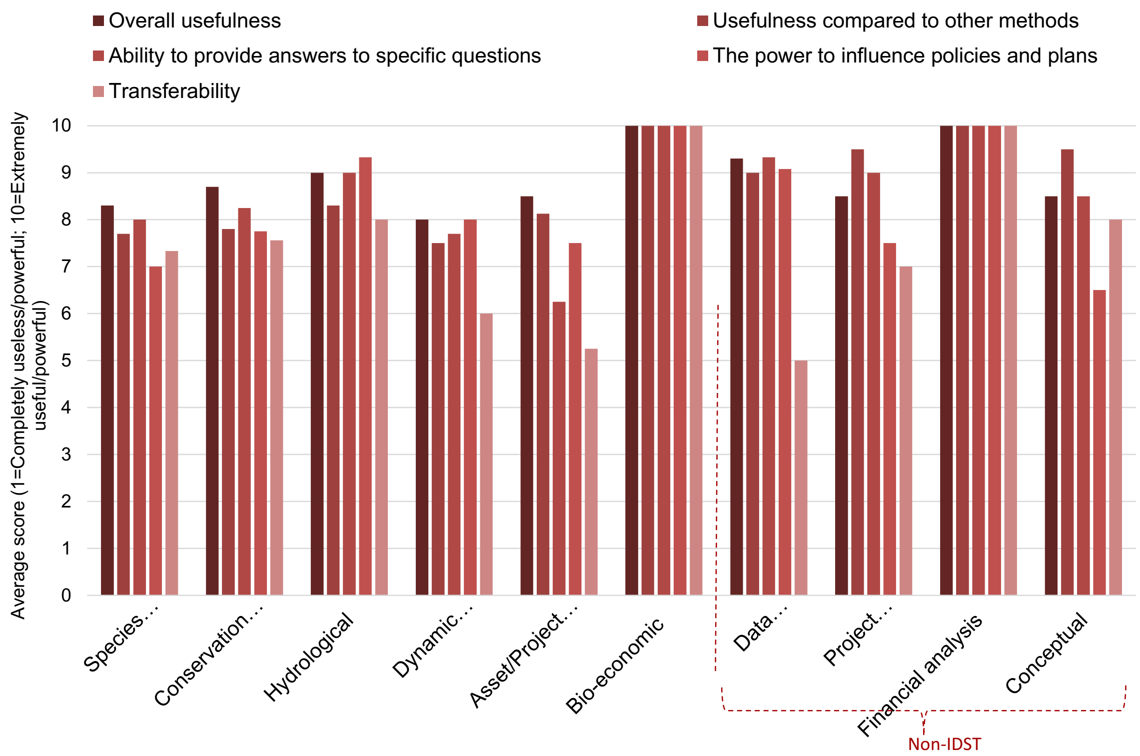

Figure 13: Respondent perceptions of the overall 'usefulness' of different tools, of the transferability of insights, and their power to influence policy

3.2.2 Builder survey

We interviewed 17 model 'builders' who provided us with information about 15 different models, which we categorised according to the system outlined in Section 2.3 (Table 5). As discussed in Section 2.3, although historically, distinctions between modelling approaches were readily apparent, many modern day IDSTs do not fall neatly into one category or another. Researchers involved in the development of CHIA, for example, used participatory approaches to capture information about socio-cultural values, and these values were considered in a broader conservation planning type approach. We have classified CHIA as an Asset/project evaluation model, but it could also have been classified as a (hybrid) conservation planning model.

Table 5: Tools described by model 'builders'

Model	Broadest Category	Sub-Category
1. Biodiversity Forecasting Tool	IDST - Biophysical	Species Distribution
2. Pest Priority Matrix[57]	IDST - Biophysical	Conservation planning
3. Priority Threat Management Tool	IDST - Biophysical	Conservation planning
4. C Plan	IDST - Biophysical	Conservation planning
5. Marxan	IDST - Biophysical	Conservation planning
6. Software developed to help prioritise conservation.	IDST - Biophysical	Conservation planning
7. Weed Management Scenario Model	IDST - Biophysical	Conservation planning
8. Fitzroy Basin Water Quality Improvement Plan (prioritisation of actions for water quality improvements, includes hydrological information)	IDST - Biophysical	Conservation planning / hydrological
9. Australian water balance model (AWBM) Rainfall-runoff hydrological model	IDST - Biophysical	Hydrological
10. Australian Hydrological Geospatial Fabric (GEOFABRIC)[58]	IDST - Biophysical	Hydrological
11. Atlantis[59]	IDST – computing/mathematical	Dynamic simulation
12. Land-Use Trade-off Model[60]	IDST - Biophysical	Dynamic simulation
13. Coastal Lake Assessment and Management (CLAM) Tool[61].	IDST – computing/mathematical	Network
14. Bayesian Belief Network model	IDST – computing/mathematical	Network
15. Collaborative Habitat Investment Atlas (CHIA)	IDST – Social	Asset/project valuation

Caveats aside, most of the model builders with whom we spoke were researchers working at universities (37.5%) or research centers (37.5%); 18.75% worked for (state) government and 6.35% were private consultants.

[57] http://www.fnqroc.qld.gov.au/files/media/original/003/d7a/a59/809/Framework.pdf
[58] http://www.bom.gov.au/water/geofabric/
[59] http://atlantis.cmar.csiro.au/
[60] http://www.sciencedirect.com/science/article/pii/S0959378016300231
[61] https://ebmtoolsdatabase.org/tool/clam-coastal-lake-assessment-and-management-tool

Model builders were asked about the time and resources involved in the development of IDSTs. As shown in Table 6 – it can take years (and thousands, sometimes even millions of dollars) to develop IDSTs 'from scratch', although some are available for download for free (or a nominal fee). Some 'began their life' as small models / projects and developed into larger IDSTs over time – as more data were added, and component parts of the tool were refined.

Table 6: Overview of the resources required to develop IDSTs

Name of tool	Development cost	Development time
Collaborative Habitat Investment Atlas (CHIA)	*> $600k (≈ 4 x 150k)***	4 years
Biodiversity Forecasting Tool	> $225k (≈ *1.5 x 150k*)**	1.5 years
Atlantis	~$4 million	~1 year
Bayesian Belief Network	~$300 000	~4 years
Priority Threat Management Tool	$100 000 to $300 000	2 years
C Plan	*> 300k (2 x 150k)***	~2 years
Marxan	*> 450k (3 x 150k)***	3 years
Weed Management Scenario Model	$40 000	2 years
Pest Priority Matrix	A wage salary by council ≈ $150k**	1 year
LUTO	~$5 million	3 years - still ongoing
Australian Hydrological Geospatial Fabric (GEOFABRIC)	$300 000 for software, $40 million for data	1 year
Fitzroy Basin Water Quality Improvement Plan	$160 000	1 year & 4 months
Australian water balance model (AWBM)	*>$3.75 m (25 x 150k)***	25 years
Method to use GIS and SD model	$50 000	2 years

** our 'best case' estimates from development time.

Different types of IDSTs require different skills to develop and are most time/labour intensive at different stages of model development. Species distribution models, for example, require much time to be spent collecting and collating data; whereas the largest proportion of time required for the development of hydrological models is associated with computer programming/software manipulation (Figure 14). There is not, however, a direct correspondence between the time required to complete different IDST-building tasks and the difficulty (thus skills required) to complete those tasks. In most cases, it seems that the computer programming and software development side of the problem poses the most challenges for model builders (Figure 15).

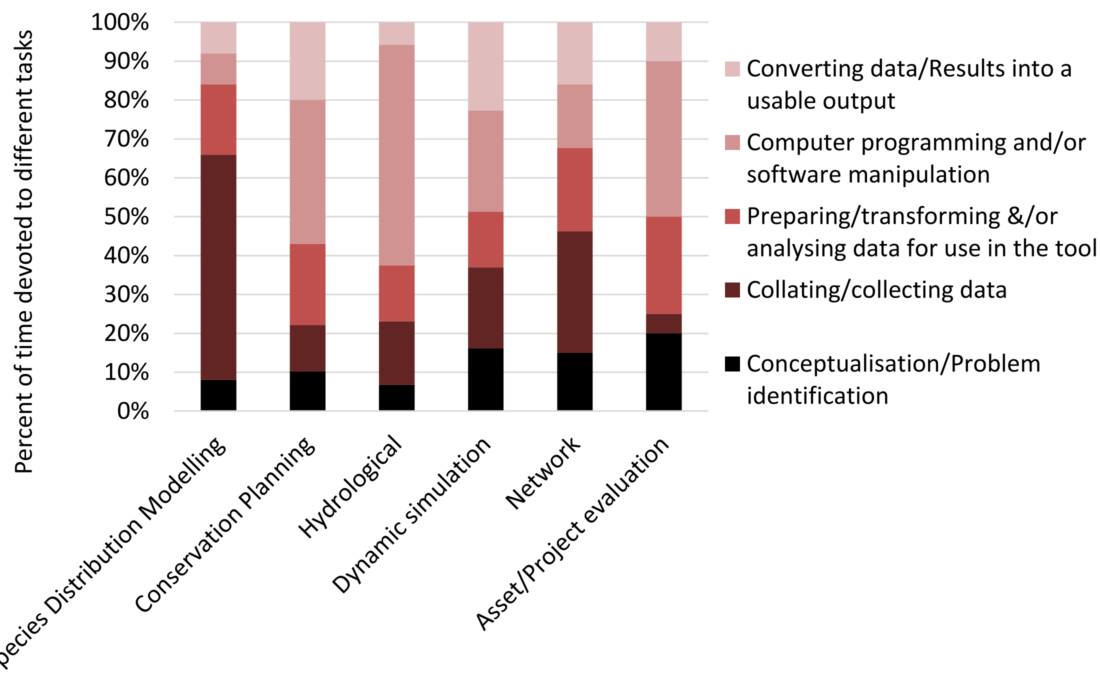

Figure 14: Time required to complete different tasks when 'building' an IDST

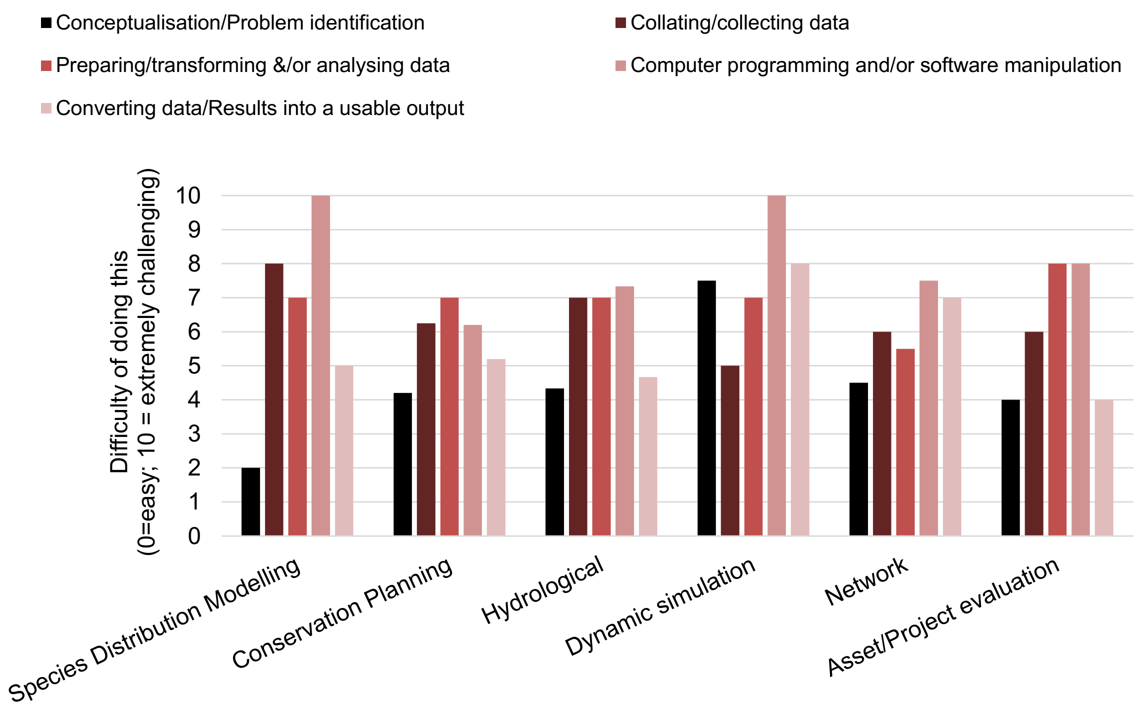

Figure 15: Difficulty of completing different tasks when 'building' an IDST

4 SUMMARY AND RECOMMENDATIONS

To support planning and development for decision-makers across northern Australia, this project aimed to create resources to help current and potential end-users (practitioners) of models to assess (a) the availability and suitability of particular models, and (b) the feasibility of using, developing, and maintaining different types of models.

In this report, we documented the different modelling tools that have been developed and trialled in northern Australia and elsewhere. We grouped these different modelling tools according to their key characteristics and identified their strengths and limitations. A summary and the key learnings about the various modelling tools available, from both literature and our own surveys, are presented in Section 4.1.

In Section 4.2, we go further and provide guidance about how to choose a modelling tool that best suits the objectives of decision-makers, and suggest ways in which modelling tools could be made more useful from the perspective of key northern Australian stakeholders.

4.1 Key learnings

The literature review in this report shows that there are innumerable different modelling tools which could be and are used by decision-makers. This variety can make it difficult to determine which model is most suited to a particular task.

We identified three main groups of modelling tools, summarised in Figure 17. The primary goal of one group of IDSTs, mainly developed by biophysical scientists, is to protect the environment at least cost to society. The primary goal of the group of IDSTs developed by the social and economic scientists was often to promote economic growth with minimal disruption to the natural realm. The third broad group, IDSTs mainly developed by the mathematical/ computing scientists, often focus on the modelling problem per-se and do not generally ‘focus’ or ‘favour’ either the natural or the human realm.

Our more detailed discussion of IDSTs (in Section 2.3) highlighted that within those three broad categories, innumerable sub-categories of models exist, differentiated in many ways, including but not limited to the realms considered, the spatial and temporal scale of data used, the outputs generated, the techniques used to analyse data, the ability to deal with uncertainty, and the handling of scenarios (Table 2). As such, each sub-category of IDSTs is most suited to different decision-making contexts (identified within Sections 2.3.2.1 to 2.3.4.3). We used these characteristics to identify nine sub-categories of IDSTs, the technical specifications for which are summarised in Appendix 1.

Figure 17 uses different coloured lines, drawn from each primary objective to specific types of research questions/problems to indicate which sub-categories of models are likely most able to generate information that can inform those questions. Below each model type, we also provide additional insights from the stakeholder interviews that highlight which categories are viewed by practitioners as being easiest to understand (Section 3.2.1) and which are more difficult (and expensive) to develop than others (Section 3.2.2), as well as examples from the case studies (Appendix 2).

Models lacking visual outputs were generally rated by our respondents as potentially difficult to understand. Interestingly, there appears to be no correlation between ease of understanding and frequency of use: for example, species distribution models were used intermittently, but practitioners indicated that it was relatively easy to understand their outputs. This suggests that those wishing to further encourage use of models to support decision-making could make models more user-friendly by carefully explaining the underlying conceptual models, variables and linkages (without excessive use of jargon) and having easily interpretable visual outputs.

As we saw in Table 6, models can be very expensive to build from scratch and can take years to become functional. Although numerous off-the-shelf models are ‘free’ of charge, it is not a costless exercise to contextualise them. One needs data to populate the models (which often needs to be ‘cleaned’/prepared for use), and one needs people/labour to run the models and to help interpret model outputs. The most efficient way to go about model development might be to first carefully assess instances where existing off-the-shelf products or approaches can be efficiently, cheaply and quickly modified and populated with existing relevant data. As we see from Figure 17, the ‘simple’ models can generate valuable insights in many instances. We note also the significant opportunities offered by modern-day advances in computing, and thus suggest that whenever possible (irrespective of whether one is developing a model from scratch or modifying off-the -shelf applications), models should be conceptualised as ‘modules’ – leaving open the possibility of later incorporating them into a larger (coupled) systems model that could lend true insights into intra and inter realm dynamics.

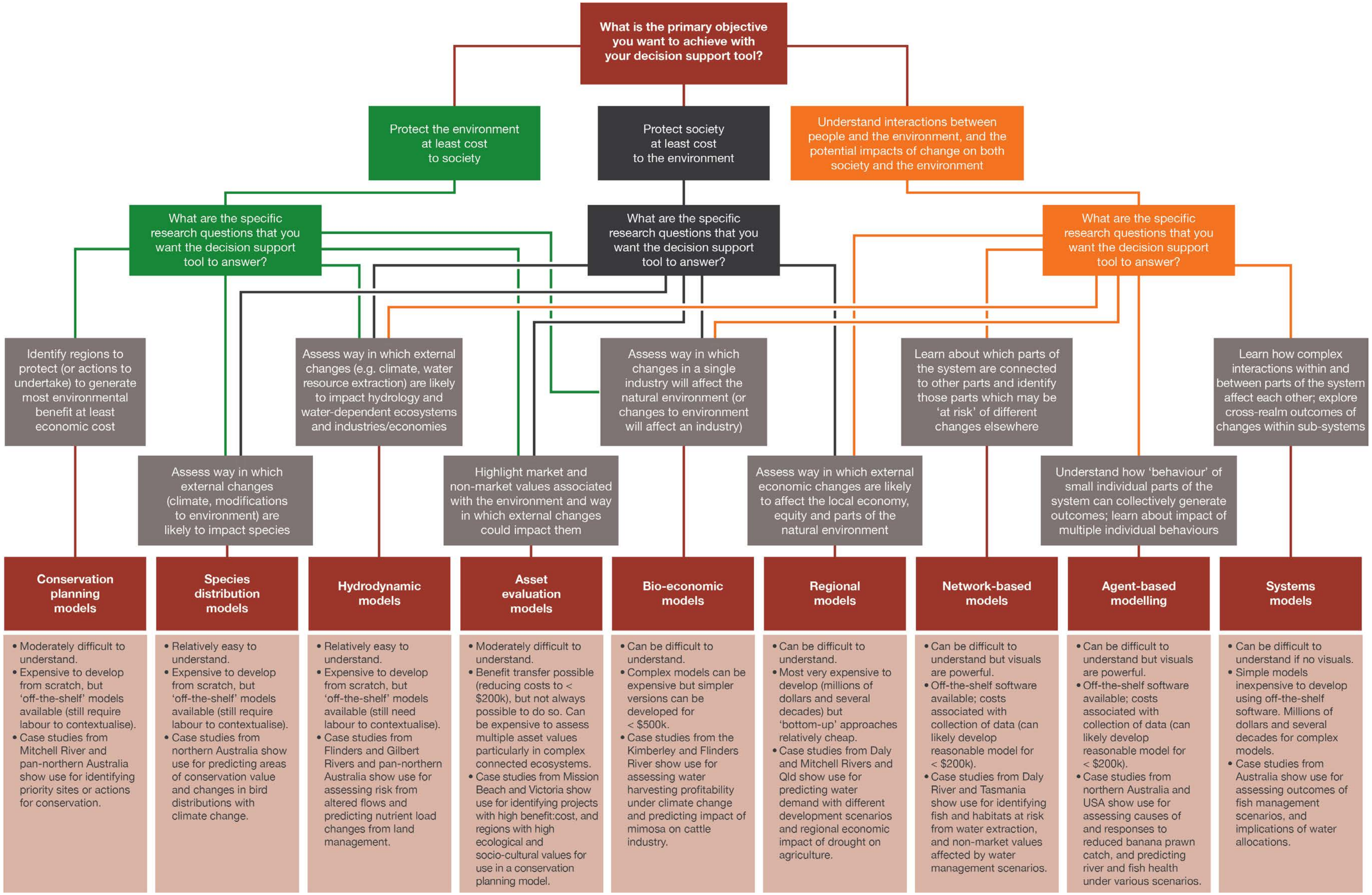

Figure 17: Selecting an IDST according to primary objective (of decision-maker) and typical problem being considered

4.2 How to choose a tool that best suits your objectives

The discussion of Section 2.3.1 highlights that a useful way to think about which type of model to use is to first consider one's primary objective and then use that objective as a first-round 'filter'. Practitioners who have a primary goal, or even a legislative requirement, to protect aspects of the natural realm (e.g. conservation of a species), may find that models which protect environment at least cost to society are most useful. In contrast, practitioners whose primary goal/concern is a socio-economic one may find that models which protect society at least cost to the environment are most appropriate. Finally, decision-makers who are not bound by legislation or role to favour either the natural or the human realm but instead are primarily interested in interactions between them, may find that integrated transdisciplinary models have most to offer.

We stress that the primary objective itself should drive the choice of model, rather than choosing a model just because it originated in the same field in which the researcher or practitioner operates. For example, hydrological and bioeconomic models often involve deep integration (as per Polhil et al. 2016), thus helping to foster understanding about the way in which different parts of the human system interact with the natural system. Similarly, although hydrological models focus primarily on the biophysical (hydrological) system, their objective is often largely anthropogenic – namely, to determine how much water is 'safe' to extract for use in an economic system. So, primary objectives that are linked to the environment (such as wanting to conserve a species) are not necessarily best met with models from the biophysical sciences. Likewise, objectives that are primarily linked to society are not necessarily best achieved by models from the social and economic sciences.

Figure 18 presents a generic flowchart that can be used to assist the model selection process. Although this particular flowchart was developed to assist people when selecting hydrological models, the guiding principles are relevant in a much broader context. Once the initial objective is clear and the initial broad idea about model choice is formed, the important question is: does a suitable off-the-shelf model exist that would suit my purpose? As we learned in our interviews (Chapter 3) building models from scratch is very time-consuming and extremely, sometimes prohibitively, expensive (Table 6), but there is 'off-the-shelf' software available for most models (Chapter 2).

The next, and potentially most important step to consider, is that of data availability. Although there is always a danger of developing models that are too complex and contain too much data, a model is really only as good as the data that populates it (Hunt et al. 2007). If insufficient region/catchment/landscape data exist and funds are limited, focusing on data collection might be the best option, with the view of data modelling in the future. This would be in lieu of developing a data-deficient model (Figure 18) – although we note that some types of models are able to provide extremely good insights with very small amounts of data (e.g. Dambacher et al. 2015). The need for and availability of other resources, such as time, money and expertise (not just in modelling, but also in the collation and interpretation of data/information, and in liaison with stakeholders – as discussed below), should also be assessed at this stage.

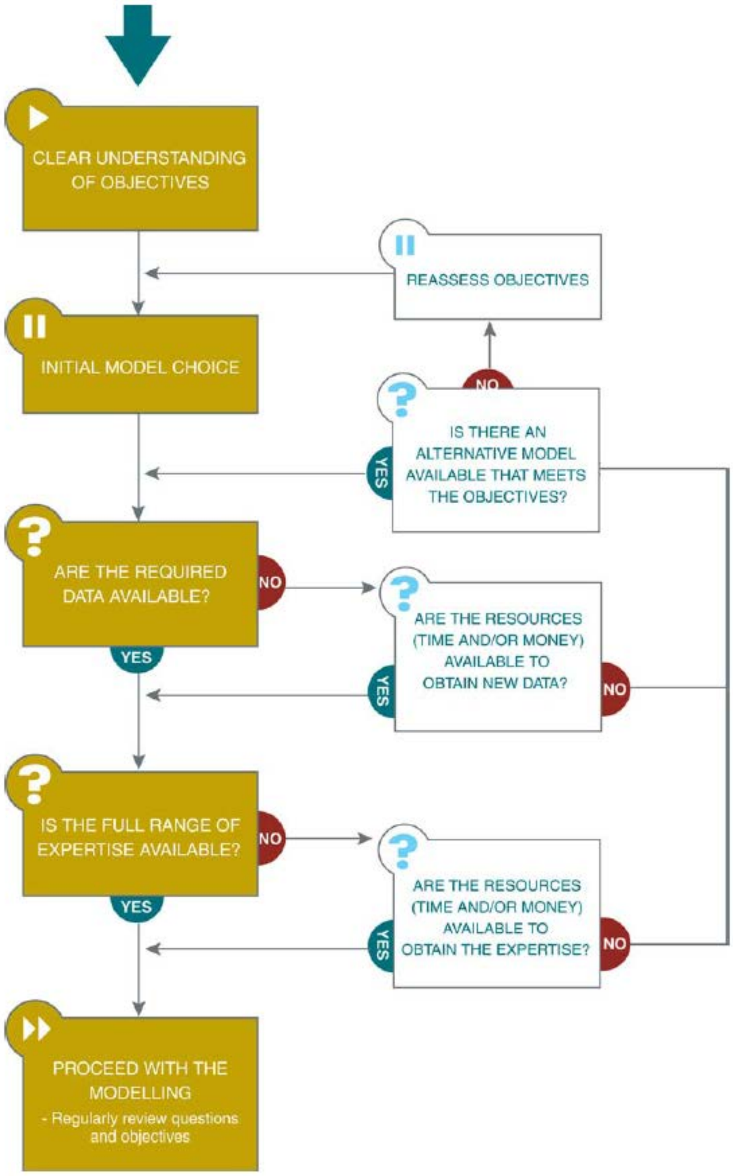

Figure 18. Choosing a tool that best suits your purposes

Source: eWater Toolkit, available at: http://www.toolkit.net.au/Tools/

Once and if the decision is made to proceed with data modelling or the use of a model, a second round of decisions on the actual model to use should be undertaken. As presented in Appendix 1 and discussed in Section 2.3, each sub-category of models, as well as the actual models within those sub-categories, have their specificities. To use the case of the socio-economic group of models as an example, models in the bioeconomic sub–category are generally highly context-specific by type of industry and by environment in which industry is operating, and therefore it is likely they will need to be built from scratch. In such cases, we suggest doing a literature search first, to see who has developed similar models for such industries and getting advice straight from them. However, in most instances where the objective is not an assessment of the entire industry, but rather of a particular development project (e.g. assessment of the mining industry in Queensland versus assessment of impacts of the proposed expansion of the Mine X), an asset valuation tool such as a CBA, SROI or Multi-criteria analysis might suffice. In all cases, it is important to consider 'social' (specifically non-dollar-denominated) values in addition to monetised values, and then choose methods, tools and models that can deal with issues such as complex social goods and income inequalities (e.g. group deliberative methods for social goods, and non-dollar-denominated or (inverse) income-weighted approaches for income inequalities).

To help practitioners choose the model best suited for their needs, our discussion of Section 2.3 provides references to numerous studies and also to detailed reviews of (sub)categories of IDSTs. We have also prepared a comprehensive collection of case studies – examples of real-life situations in which each sub-category of IDST was applied. These are presented in Appendix 2. Wherever possible, the case study is located in northern Australia. However, as we have seen in the user interviews, not many decision-makers are using modelling tools in the north. So, where we were unable to find examples from northern Australia, we used case studies from other locations, where the landscapes and the socio-economic systems were similar to those of the north. Each case study is organised as follows:

- What they set out to do – a brief overview of the main objectives of the undertaking
- What they tried
- What they got
- What they learnt
- What they may need to do next

In all cases, understanding and trust between the decision-maker and the modeller/model developer are very important. As we can see from our case studies, "what they set out to do" and "what they got" are not necessarily one and the same.

This highlights the importance of including key stakeholders in deliberations, including those relating to model choice. Evidently, the manner in which decisions are made, including the perceived fairness of the process, is just as important to their success as the tangible outcomes of decision-making (Syme et al. 1999). Indeed policies (particularly those relating to natural resource management) often fail when the knowledge and values of the local community and other stakeholders are discounted (Dryzek 1990). Not only does the process of including key stakeholders ensure that the decision-making process is transparent and/or defensible (Fuller 2014; Lockie and Rockloff 2005), but stakeholder involvement helps reduce the chances that people will become polarised over: problem definition (i.e. identifying root causes, stakeholder issues); requirements (i.e. the conditions that any acceptable solution to the problem must address); goals (i.e. intent and desirable values); and, criteria (i.e. objective measures to help discriminate among alternatives) (Fülöp 2005; Harris 2012; Lockie and Rockloff 2005). Such sentiments were strongly echoed by the northern Australian practitioners of IDSTs that we interviewed (Section 3.2.1).

Finally, we re-iterate a point made earlier: decision support tools help make the decision-making process transparent, documented, reproducible, robust, and also contribute a coherent framework to explore the options available (Sullivan 2002). But they are not, and should not, be a substitute for thinking about complex problems in other ways. They are, instead, complementary. There is evidence to suggest that better computers do not, by themselves, lead to better decisions (Cortés et al. 2000; Ascough et al. 2008) – the same is likely also true of IDSTs.

APPENDIX 1: TECHNICAL SPECIFICATIONS

In this appendix we provide more detailed technical information about each broad category of models considered in this review, as follows:

Appendix 1.1. Species Distribution Models

Appendix 1.2. Conservation Planning Models

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App. 1.1 Species Distribution Models – Technical specifications

Examples:	Correlative: Machine learning (ANN - Artificial Neural Networks, SOM - Self Organising Maps, GARP - Genetic Algorithm for Rule Set Production, CART - Classification and Regression Trees (Random Forests, Boosted regression Trees, Multivariate CARTs), Maxent - Maximum Entropy); Regression (GLM - Generalised Linear Model, GAM - Generalised Additive Model, MARS - Multiple Adaptive Regression Splines, BHM - Bayesian Hierarchical Models, LDA - Linear Discriminant Analysis, GDM - Generalised Dissimilarity Modelling); Profile BIOCLIM - bioclimatic envelope model, ENFA - Ecological Niche Factor Analysis, DOMAIN, SRE - Surface Range Envelope; Other (expert-based Geographic models, Filters & LED - Environmental filters and limiting environmental differences (LED), Mechanistic (deductive): MNM - Mechanistic niche modelling; s-MCM - semi-mechanistic community modelling; SDM-DLM&PM - Linked SDMs with dynamic landscape and population models
Purpose	Identify spatial distribution of species of interest.
Outputs	Simplistically, the model generates a 'map' which shows the distribution of species one would expect to see in different spatial regions ('planning units') in different situations (e.g. with different climatic futures).
Realms considered	
Terrestrial plants & animals	Yes - species distribution able to be estimated if "potential niche" is identifiable. Resolution generally at individual species level or assemblage types
Aquatic plants & animals	Yes - species distribution able to be estimated if "potential niche" is identifiable. Resolution generally at individual species level or assemblage types (
Hydrological	Sometimes - Considered only if it is correlated with species distribution. Resolution at partitioned region level.
Other biophysical	Yes – Considered if correlated with species distribution. Resolution at partitioned region level, but no 'processes' considered' (i.e. not modelling variables and interactions within this realm).
Social	Very rarely – only if considered to be correlated with species distribution and if data are available. Resolution at partitioned region level, but no 'processes' considered.
Economic	Sometimes – if considered to be correlated with species distribution and if data are available (in these cases, often a highly aggregated index – e.g. one representing extent to which landscape has been modified by human/economic activity). Resolution at partitioned region level, but no 'processes' considered.
Dominant Realm	Terrestrial, Aquatic
Interactions within realms?	Considers interaction between neighbouring species populations within the terrestrial/aquatic realm.
Interactions across realms?	The interaction across geophysical and terrestrial/aquatic realms is used to estimate species distribution. For example, BdMaxent uses geophysical realm temperature variables and a sample of grid based (temperature, species population) data to predict species population.
Length of time to run analysis	Typically short run times.
System requirements	Model dependent e.g. MaxEnt is platform independent requiring java enabled web browsers. Numerous modelling approaches are available in the free R statistical environment.
Cost to purchase	Many are freeware
Training requirements	Medium – e.g. Maxent has tutorials at http://www.cs.princeton.edu/~schapire/maxent
Popularity	SDMs are popular e.g. MaxEnt >1000 published applications
More background on capabilities	Typically, estimates the probability of observing a species of interest based on the 'niche' concept: • Suitable geophysical conditions for a species is called a niche; • Finding the niche increases the probability of finding the species of interest; • The Niche-species covariation is established via a range of different techniques e.g. Principal Component Analysis, MaxEnt, etc
Problem Solving Technique	Simplistically, the model estimates the covariation between the geophysical realm variables and the terrestrial/aquatic realm species population distribution and using easily obtained geophysical data, infers probable species distribution. NB: in integrated models, the geophysical realm is directly affected by anthropogenic variables e.g. Human driven climate change where (geophysical variables) temperature and sea level change as a result of social and economic dynamics. Identifying geophysical variables that are highly correlated with observing a species of interest underlies all SDM techniques; this is the niche concept. For example, in BdMaxEnt, because the species distribution is a probability then the entropy may be calculated. Maximising that entropy subject to constraints (being the observed temperature and species number samples) leads to a probability function that has the least number of assumptions (i.e. efficient use of sample data).
Spatial nature of data	These models work with 'spatial' data – mostly GIS data These models require niche level spatial data relating to: - Geophysical variables e.g. temperature, rainfall, etc

	- The covariation between geophysical variables and aquatic/terrestrial variables.
Temporal nature of data	These models generally work with data from one point in time, and produce maps for one point in time, and are unable to model dynamic feedbacks. It is, however, possible to create projected increase or decline in species populations by running models for each time step of geophysical change.
Ability to cope with stochastic data	The nature of data input is probability distributions of species across space and as such they are inherently stochastic models.
Data and resources required for input	GIS geophysical data with niche level grid sizes and an input array of geophysical variables and species observations is the minimum requirement.

App.1.2 Conservation Planning Models – Technical specifications

Examples:	Marxan, *Marxan with zones, Zonation, C-Plan, ConsNet, GREDOS, ResNet, WORLDMAP Turak et al. 2011; Stewart et al. 2003
Purpose	Identify 'optimal' spatial location of areas for a particular type of land use and/or management interventions, from strict reservation to off-reserve management. These models thus provide decision support for a range of conservation planning problems, including: designing new reserve systems (including conservation covenants), prioritizing management actions (e.g. fire and invasive species control), and/or developing multiple-use zoning plans that can achieve both conservation and socio-economic objectives.
Outputs	Simplistically, these models generate 'maps' (or sets of projects) which identify the sites or areas ('planning units') which should be managed (and how) to meet explicit (preferably quantitative) objectives (e.g. conserving 20% of the current distribution of threatened species occurring in a study region) in a cost-effective manner. CPMs with multiple objective functions can generate 'trade-off curves' – which demonstrate the trade-off (costs) of meeting one objective in terms of the other objective(s) that must be foregone.
Realms considered	
Terrestrial plants & animals	Yes - consider biodiversity patterns and threats; often an objective, but few (if any) process modelled
Aquatic plants & animals	Yes - consider biodiversity patterns and threats; often an objective, but few (if any) processes modelled
Hydrological	Rarely – more commonly used to represent the distribution of threats (e.g. reduced water quality or modified water flows) or in freshwater conservation prioritisation applications can be considered to represent up/downstream habitat links and longitudinal/lateral movements of aquatic biota to be protected in reserve systems
Geophysical (e.g. soil type)	Yes – commonly used to identify and map conservation features (e.g. habitat types) as surrogates of biodiversity, especially given limited or incomplete data on species distribution (which can be improved by using the SDMs described above)
Social	Rarely – although some consider social values as an objective; few (if any) processes modelled
Economic	Yes – but mostly in a relatively rudimentary way, as a cost or profit (e.g. opportunity costs) per planning unit. Typically incorporates a cost to be minimised; few (if any) economic processes modelled.
Dominant Realm	Terrestrial, Aquatic
Interactions within realms?	Able to explicitly consider connectivity across geophysical and hydrological realms - e.g. Marxan incorporates a boundary penalty to induce grouped planning unit solutions to maintain ecological connectivity and to create reserve systems that promote species/population persistence; grouping (i.e. concurrent selection of planning units) can be based on adjacency or long distance links between planning units, as well as on symmetric or asymmetric links (the second of particular interest in marine and freshwater systems).
Interactions across realms?	Uses both biodiversity and economic data, but does not typically (and explicitly) model 'interactions' between realm variables in the anthropogenic and naturogenic categories (e.g. biodiversity per hectare not connected within the model to cost per hectare, they are both assumed to be exogenously determined). However, the inclusion of socio-economic objectives or costs (e.g. Marxan, Zonation) or incorporating budgetary constraints to prioritise management actions implicitly include a link to the 'economic' sub-system within the human realm. Likewise, compatibility and contribution of different zones (e.g. Marxan with Zones) with conservation features implicitly assume relationships or interactions between the 'human' and 'natural' realms.
Length of time to run	Depends on the tool, but factors influencing running time include: number of objectives, extent of planning domain, number of planning units, number of scenarios explored, explicit links between units (e.g. to design connected reserve systems), among others. Individual scenario runs almost always take a few minutes and rarely more than a few hours, but modellers often consider many simulations and a number of alternatives (scenarios), plus sensitivity analysis and calibration of parameters, which can take a few days (after all data is compiled and prepared).
System requirements	Model dependent, but most models can be run in Windows and Mac, and some in Linux systems; some models (e.g. Marxan) can now be run directly in R or using web-based applications that allow uploading your own data, which significantly increases computation speed.
Cost to purchase	Most are free to download and in some cases (e.g. Marxan) open source; the costs associated with model development are in the data preparation, analysis and interpretation.
Training requirements	Medium: most require some basic to medium GIS skills and can be self-taught; Marxan has online tutorials at UQ website and there are regular live trainings; Marxan also has a very active and efficient users' list and PACMARA (http://pacmara.org) constantly improves manuals and training materials. User manuscript provided for most models. Most models are also well documented (and mathematical formulations explained) in papers and books.
Popularity	CPMs are very popular, particularly Zonation and Marxan, which is widely used across >100 countries

More background on capabilities	Typically, identifies areas that meet objectives (conservation or otherwise) at minimal cost; • The objective of Marxan, for example, is to minimise global cost whilst satisfying species global target population constraints. • Uses the principle of complementarity to select planning units which complement the larger network of units (recognising that the value of the whole is more than just the sum of its parts); • Can meet spatial requirements such as compactness/connectivity of a reserve system; • Can also include data on ecological processes, threats, and condition, in addition to 'actions' (see case-study in section 0); • Can be used to identify trade-offs between conservation and other objectives
Problem Solving Technique	Typically, CPMs attempts to determine if and which planning units will be included in or out of the final map/solution in a notional reserve system or will be associated with a given use/action. The two most typical conservation planning optimisation problems are: (a) minimum set problem, i.e. aim to capture a set amount of biodiversity for the least cost and (b) maximum coverage problem, i.e. to capture as much biodiversity as possible with a fixed budget. There are different approaches to solve these problems including integer linear programming (ILP), which aims to minimise or maximise an objective function subject to a number of constraints and conditional on the decision variables (the variables corresponding to the selection of actions to implement) being integers. Another, more commonly used approach is the use of heuristic methods such as simulated annealing (e.g. Marxan), which iteratively, stochastically explore the state-space of the decision variables. There are numerous other heuristics (e.g. ranking procedures, genetic algorithms, and mixtures of these approaches) that could also be used (Beyer et al. 2016).
Spatial nature of data	These models work with 'spatial' data (but can be populated using non-spatial information, e.g. related to conservation projects being assessed/compared) describing the distribution (and sometimes abundance) of conservation features (e.g. species, habitats), threats (e.g. invasive species), and human uses (e.g. land use, fishing intensity). These models can, in theory, work with data at almost any spatial scale, but the limiting factor is generally the availability, resolution and quality of relevant data (not all is available at fine spatial scale, but coarse scale data can be sufficient in some contexts). Specifically, these models require spatial data relating to: - the conservation feature(s): e.g. presence (or abundance) of species and habitats within each planning unit; the output of species distribution models are often used to generate these data - if within-system links are considered, some spatial representation of the links between planning units mediated by the movement of species across the land/seascape - the constraints, e.g. the cost of each planning unit (e.g. opportunity cost associated with the notional reservation of a given area) Note on budget/cost constraint: simplest CPMs can simply use uniform cost or area as a proxy for "cost" of conservation actions (especially if there is not enough or reliable socioeconomic information), but preferably CPMs should incorporate some measure that recognises cost heterogeneities (e.g. using productivity of the land, rather than just area). But there is growing recognition of the fact that costs are influenced by a range of other factors (including willingness of lad/water users to participate in management), thus the challenge is work out how best to measure/estimate them (perhaps gathering data, at property scale, from land managers), and then convert those estimates into a cost per hectare.
Temporal nature of data	These models are commonly designed to work with data from one point in time, and produce maps for one point in time, and are thus unable to model dynamic feedbacks. It is, however, possible to iteratively generate (using customised programming and the tools, such as Marxan) priority maps based on previous iterations and then simulate expected changes in landscape as a result of conservation interventions (e.g. changes in threats and species distribution and abundance associated with sequential notional reservation/management actions).
Ability to cope with stochastic data	These models are unable to easily integrate stochastic data - however it is possible to perform sensitivity analysis on the model e.g. producing several different 'maps', each generated with a different assumed set of underlying data relating to the objective function and constraints. Also, Zonation and a modified version of Marxan have the ability to use probabilistic maps of species and threat distributions.
Data and resources required for input	Species distribution maps and species distribution targets and associated costs are needed as input to the CPM models; these are described in more detail above.

App. 1.3 Hydrological Models – Technical specifications

Examples:	*eWater Source; eWater Catchment; IQQM, Australian Water balance model, Australian Hydrological Geospatial Fabric model
Purpose	Model the dynamics of water and how it affects or is affected by anthropogenic variables. For example, *eWater Source* is used to consider the way in which different farm management practices are likely to affect sediment and contaminant loads in river systems across space and time.
Outputs	Simplistically, the model estimates the change in hydrological variables - flow rates, sediment loads, etc. GIS are often used to create maps that to show predicted "constituent load numbers" in a river system in different situations/scenarios.,
Realms considered	
Terrestrial plants & animals	Not always but can be considered as a determinant of water flows & quality; can also be considered as an 'outcome'
Aquatic plants & animals	Not always but can be considered as a determinant of water flows & quality; can also be considered as an 'outcome'
Hydrological	Always
Other biophysical	Meteorological conditions were considered a determinant of water flows & quality; other biophysical variables (e.g. landscape condition, soil type, slope) also frequently included
Social	Social factors sometimes considered indirectly, e.g. as a driver of behaviours (e.g. land management practices) which influence water flows and quality
Economic	Economic factors often considered indirectly, e.g. as a driver of behaviours (such as water extraction) with impacts water flows and quality
Dominant Realm	Although biophysical factors dominate the model and modelling processes, the implicit intent of hydrological models is often anthropogenic (e.g. to determine how much water can be sustainably extracted from a system, or to make predictions about the way in which climatic changes will likely influence water storages)
Interactions within realms?	Considers interaction within realm e.g. eWater Source considers dynamics between river flow and load; models also often consider interactions between surface and ground water flows.
Interactions across realms?	Interacts across all other realms e.g. eWater Source considers dynamics between farm level management and contaminant load of river system; some models also consider way in which changes to the hydrological system will impact water-dependent assets/ecosystems
Length of time to run	Model dependent. Complex nonlinear feedback inherent in systems model.
System requirements	Model dependent
Cost to purchase	Model dependent e.g. eWater Source has a 'limited functionality' version that is freeware, or a downloadable full version with a first 12-month license fee waived
Training requirements	Model dependent e.g. eWater Source provides a 2-day course, support forums and documentation.
Popularity	Hundreds of documented applications throughout the world – with particularly rapid growth recently
More background on capabilities	Typically, model attempts to solve complex nonlinear water and sediment/flow equations: • Lumped systems models are typically applied but due to computer power increasing these are being replaced by distributed approaches e.g. eWater Source provides information on flow and load across space and time. • Key geophysical elements are captured by models within the hydrodynamic problem (e.g. eWater models account for evaporation, flow rates and sediment/pollutant loads)
Problem Solving Technique	Ranges from simplified statistical estimates to cellular automata. Ultimately, the parameterisation of the model using real world data is central to model validity. Simply put, the underlying problem solving technique is to use past time series data to forecast future time series data at a particular spatial region. That spatial region's hydrodynamics are then related to other realms via equations (complex or simple) e.g. eWater Source has evolved over a decade of previous versions into one that is considered ready for full rollout retiring other models.
Spatial nature of data	These can be modelled as lumped or distributed spatially e.g. eWater Source provides and incorporates spatially distributed information
Temporal nature of data	Models require temporal data (e.g. daily/hourly rainfall, Radiation, ET) – for some models, the temporal data is spatially specific (e.g. eWater Source is able to provide dynamics across time at any spatial point).
Ability to cope with stochastic data	Times series data for a spatial resolution is typically stochastic in nature. Sensitivity analysis is used in some models to calibrate and validate.
Data and resources required for input	Model dependent. Ordinarily time series data for each spatial cell is required. Also, equations relating to hydrological impact on other realms is incorporated

App. 1.4 Bio-economic Models – Technical specifications

Examples:	Petherman et al (2013); Cook et al. (2015); Pascoe et al. (2013)
Purpose	Assess way in which changes in a single industry will affect the natural environment, or to assess the way in which changes to the external environment (e.g. climate change, reductions in carrying capacity of fisheries, weed incursion) will affect an industry/ies
Outputs	Model dependent e.g. often, but not always presented in graphs and figures
Realms considered	
Terrestrial plants & animals	Yes – if focus of model (e.g. agricultural bio-economic models include complex sub-modules of the terrestrial environment)
Aquatic plants & animals	Yes – if focus of model (e.g. fisheries bio-economic models include complex sub-modules of the marine environment)
Hydrological	Yes – if focus of model (e.g. hydrological bio-economic models include complex sub-modules of hydrological processes)
Geophysical	Yes- if impacting the biological side of the model
Social	Not normally (unless one consider the influence of profits/costs on individual and social welfare)
Economic	Yes- in detail – and interacting with the natural environment
Dominant Realm	Economic
Interactions within realms?	Always includes at least two quite detailed sub-modules (one focusing on the economic realm, one focusing on an aspect of the natural realm), each of which models complex interactions within that realm
Interactions across realms?	Always include at least two quite detailed sub-modules (one focusing on the economic realm, one focusing on an aspect of the natural realm) – a core focus/intent of the model being to model interactions between those realms
Length of time to run	Model dependent, but typically less than a day. Factors influencing running time include: number of objectives, number, and complexity, of sub-modules, spatial and temporal resolution of input data, number and complexity of scenarios considered, and time-horizon of modelled scenarios. Individual scenario runs typically quite short (rarely more than a few hours), but modellers often consider many scenarios which can take a several days (weeks even, in complex analyses)
System requirements	Model dependent e.g. some models can run within excel
Cost to purchase	Model dependent
Training requirements	Model dependent
Popularity	Numerous examples of bioeconomic models world-wide, but relatively few applications across Northern Australia
More background on capabilities	These are generally partial equilibrium 'optimisation' models – seeking to, for example, maximse the profit (or minimise the costs) of an industry subject to various constraints, and assuming that changes within that industry are small enough to avoid generating larger changes (in the macroeconomy) which could potently feed-back. These models blend quite sophisticated sub-models from both the natural and human (economic) realms – often allowing for complex inter-reactions within and between modules. Relations are typically described in equations (often difference equations that embed dynamics within the models). Deep interaction between human and economic realms is embedded within these equations. Costs/profits are normally relatively complex functions of numerous variables, which include biophysical variables – and those biophysical variables are themselves relatively complex functions of numerous variables (largely biophysical, but also including economic variables).
Problem Solving Technique	Typically a profit maximisation problem with constraints e.g. BWQIP: maximises 'farm profits less monetised impact on water quality; almost always including temporal dynamics, some also include spatial dynamics
Spatial nature of data	Requires data to assist with initial model parameterisation; this can be done using either spatially differentiated or temporally differentiated data (or both). Some of the models also use spatially and temporally differentiated data (e.g. daily rainfall in different locations during previous 100 years) to mimic stochasticity in simulations. Some generate spatially differentiated predictions/outcomes.
Temporal nature of data	Requires data to assist with initial model parameterisation; this can be done using either spatially differentiated or temporally differentiated data (or both). Some of the models also use spatially and temporally differentiated data (e.g. daily rainfall in different locations during previous 100 years) to mimic stochasticity in simulations. Most generate temporally differentiated predictions/outcomes.
Ability to cope with stochastic data	Often built as a series of mathematical equations (often with difference equations), parameterised from empirical models. Some use, as input, Scenarios and sensitivity analysis used to highlight
Data and resources required for input	Model dependent e.g. BWQIP requires farm and NRM data; some models require daily meteorological data, some require detailed data on soil and vegetation, etc.

App. 1.5 Regional Models – Technical specifications

Examples:	The Enormous Regional Model (TERM); TERM-H2); Water-use Input-Output Models
Purpose	Assess way in which external economic changes are likely to affect the local economy, equity and parts of the natural environment
Outputs	Predictions about the way in which the size and structure of the economy, and environmental variables which are linked to the economy will change over time – most frequently shown using time-series graphs; spatial maps also possible.
Realms considered	
Terrestrial plants & animals	Rarely, need to be able to link economic impact, to terrestrial environment (e.g. tree loss, per unit of population growth)
Aquatic plants & animals	Rarely, need to be able to link economic impact, to aquatic environment (e.g. increased fish harvest, per unit of population growth)
Hydrological	Sometimes included as water-use per sector or as water-pollution per sector.
Geophysical	Often included as pollution (e.g. CO_2 emitted) per sector
Social	Social indicators included in some models e.g. SIA (Sustainability Impact Assessment); all models consider distributional issues – e.g. identifying which sectors of the economy and which types of households gain most/least from economic growth
Economic	Yes – stock and flow of money underpins these models
Dominant Realm	Human (economic)
Interactions within realms?	Provide detailed information about interactions within the economic realm (modelling financial flows between sectors). Limited to no information about interactions within natural realm
Interactions across realms?	No 'deep' integration of human and natural realms. The natural system is incorporated (or appended to the model of the economic system) using simple indicators (e.g. CO_2 emissions per dollar of production in each economic sector).
Length of time to run	Model dependent - the simplest models can be run almost instantaneously, but most modellers run numerous scenarios, so even with the simple models, a full analysis can take several days/weeks. The more complex models may involve several thousand equations, with dynamic feedbacks, requiring much more time (and more sophisticated resources) to run
System requirements	Model dependent - the simplest models can be run from within excel; more complex ones have their own platform
Cost to purchase	Model dependent – see above
Training requirements	Model dependent
Popularity	Innumerable applications of models that focus only on the economy; somewhat fewer incorporating environmental factors – those that do tend to focus on pollutants (these models are regularly used to assess impact of climate change policies).
More background on capabilities	The simplest IO models take, as input, data relating to the expenditure (and income) of businesses and households, and also their 'interaction' with the environment (e.g. average water use). The information is used to populate a simple matrix, describing how each spends money within other industries (and on households/wages). Matrix algebra is used to make predictions about the way in which an expansion of one sector, would affect the other sectors and the environment. Amongst other things, these simple models assume Leontief production technology, constant prices, and perfectly elastic supply. More sophisticated models use mathematical equations to instead represent production functions/technologies; taking into account potential for price changes (and other factors). These models generally comprise thousands of mathematical equations, parameterised from observations, and/or from 'expert opinion'.
Problem Solving Technique	Simple IO models use simple matrix algebra. More sophisticated models use deterministic equations – often with complex dynamic interactions between variables over time (thus allowing for an element of 'chaos' and non-equilibrium). They do not 'optimise'; instead they generate predictions of change over time.
Spatial nature of data	Requires data to assist with initial model parameterisation; this can be done using either spatially differentiated or temporally differentiated data (or both). Some models produce spatially differentiated data as output
Temporal nature of data	Requires data to assist with initial model parameterisation; this can be done using either spatially differentiated or temporally differentiated data (or both). All models produce temporally differentiated data (i.e. scenarios of the future) as output
Ability to cope with stochastic data	Probability distributions not typically incorporated into models; scenarios used regularly to display model uncertainties
Data and resources required for input	The equations used in these models need to be parameterised from observations, and/or from 'expert opinion'. The larger, and more complex the model, the more data required to populate.

App 1.6 Asset/Project Evaluation Models – Technical specifications

Examples:	CBA, SROI, INFFER; INVEST and the numerous non-market valuation approaches used to monetise values for use within these broader frameworks (including, but not limited to hedonic pricing, travel cost analysis, contingent valuation, choice modelling and benefit transfer). Also non-monetised evaluative systems such as the Participatory Modelling component of Collaborative Habitat Investment Atlas (CHIA), Multi-criteria analysis (e.g. Hajkowicz 2007), and Life-satisfaction/well-being approaches
Purpose	Assess the 'value' of environmental assets or projects that impact environmental assets
Outputs	Model dependent e.g. Inffer identifies 'best' projects; INVEST generates visual 'maps' of values; other approaches may estimate benefit cost ratios, or returns on investment/programs.
Realms considered	
Terrestrial plants & animals	Yes – possible using either monetised or non-monetised 'valuation' methods
Aquatic plants & animals	Yes – possible using either monetised or non-monetised 'valuation' methods
Hydrological	Yes – possible using either monetised or non-monetised 'valuation' methods
Geophysical	Yes – possible using either monetised or non-monetised 'valuation' methods
Social	Yes – possible using either monetised or non-monetised 'valuation' methods
Economic	Always –value' is considered to be related to the 'utility' (benefit) that is incurred on humans
Dominant Realm	Human realm – in that assets/projects are assessed with respect to their ability to benefit humans
Interactions within realms?	Some models have intrarealm interaction e.g. Inffer considers multiple projects which compete for funding to improve common realm; most non-market valuation methods are, however, *partial equilibrium* in nature, and thus assume that all 'values' are independent from each other. As such limited modelling of within-realm interactions.
Interactions across realms?	Superficial acknowledgement of interaction – noting, for example, that parts of the natural realm are 'valuable' to the human realm, but generally no deep integrative modelling of ways in which changes in one system impact another. Can mimic some of this using multiple scenarios, showing, for example, 'value' in different situations.
Length of time to run	Generally not particularly long to 'run' these models (some, almost instantaneous), but can take a long time to collect data underpinning 'valuations' and collaborative processes embedded within some mean that even if computations are quick, deliberations could take considerable time.
System requirements	Model dependent
Cost to purchase	Model dependent
Training requirements	Model dependent
Popularity	In some countries (e.g. USA), some government departments are required to use cost benefit analysis when evaluating programs. This ensures the widespread use of CBA and the numerous non-market valuation approaches required to monetise values for use in CBA. There is a vast literature and numerous models.
More background on capabilities	Monetised techniques are essentially weighted voting systems (with one dollar one vote), which can be problematic if comparing 'values' across stakeholder groups with divergent incomes. Most monetised techniques consider 'value' from individual perspectives (identifying what is best for most individuals), rather than from a social perspective (identifying what is best for society as a whole). Non-monetised systems available which circumvent some of these issues.
Problem Solving Technique	Aiming to identify priorities by determining what is of most 'value'. 'Value frequently, but not always, measured in monetary metrics (e.g. net benefit, benefit to cost ration, total benefit); but can be determined using non-monetary processes (rating, ranking, multi-criteria analysis)
Spatial nature of data	'Value' inextricably tied to the benefits that the environment generates for humans). Some data are spatially delineated (e.g. water purification abilities of particular ecosystems can be represented as an average value per hectare), but some values transcend geographic boundaries (particularly cultural values; likely also values associated with migratory species) and are thus not always amenable to spatial mapping. Many asset evaluation models are non-spatial
Temporal nature of data	Many of the non-market valuation approaches used to populate broader asset valuation models are non-temporal (assessing 'value' at just one point in time). But scenarios often used to demonstrate way in which those 'values' could change in different circumstances. CBA estimates costs and benefits into the future, but dynamics are not generally built into these models
Ability to cope with stochastic data	Many of the non-market valuation approaches used to populate broader asset valuation models use statistical techniques to generate value estimates. CBA normally includes sensitivity analysis.
Data and resources required for input	Model dependent e.g. Inffer requires multiple stakeholder input

App 1.7. Network Models – Technical specifications

Examples:	Chan et al's Daly River Bayesian network model, Coastal Lake Assessment and Management Tool (CLAM)
Purpose	To make predictions about the way in one part of an interconnected system will affect other parts of the system (e.g. eFlow Bayesian Belief Network BBN was applied to the Daly to determine the impact on agricultural expansion and the associated water extraction on two fish species given that 90% of rainfall occurs in the wet season causing dry season threats to fish).
Outputs	Model dependent: outputs node(s) may be interpreted as states of the world, probabilities, decisions.
Realms considered	
Terrestrial plants & animals	Yes - Constrained only by data (e.g. relations between aquatic species can be included by showing different 'nodes' in the network; key challenge is to parameterise/train these modules)
Aquatic plants & animals	Yes - Constrained only by data (as above)
Hydrological	Yes - Constrained only by data (as above)
Geophysical	Yes - Constrained only by data (as above)
Social	Yes - Constrained only by data (as above)
Economic	Yes - Constrained only by data (as above)
Dominant Realm	Model dependent
Interactions within realms?	Able to aggregate different variables of the same realm via a node; able to have several 'nodes' from within a realm, thus effectively considering within-realm interactions
Interactions across realms?	Constrained only by data / knowledge. Able to able to a 'nodes' from any 'realm' connected to any other node, thus effectively considering cross-realm interactions
Length of time to run	Model dependent
System requirements	Model dependent e.g. Netica can work on multiple OSs
Cost to purchase	Model dependent e.g. Netica demo version is free
Training requirements	Model dependent e.g. Netica has a tutorial on norsys.com site
Popularity	Numerous applications worldwide, with readily available platforms to facilitate access and development
More background on capabilities	Network models complement statistical models and methods. Networks typically us statistical and/or expert information to: - identify relevant 'nodes'; - determine which 'nodes' affect and are affected by other 'nodes' (some deliberately facilitate simple mapping from an influence diagram (a simple human friendly tool) to the more complex network configuration.); and - parameterise nodes (all models 'train' on this data/information to calculate the key node parameters). Cause and effect is typically modelled in a single direction (considering, for example, how a 'change' in one node affects other nodes further down the string of linked nodes). Feedback is possible but convergence to point solutions is not guaranteed if so doing.
Problem Solving Technique	Experts create network structure that best solves problem. Expert/statistical information parameterises nodes. Validity of the network is tested on known input/output data sets. Sensitivity is tested using parameter variations or mutual entropy measures (which take into account how much information is gained by the addition of a node).
Spatial nature of data	Able to deal with process spatial data.
Temporal nature of data	Able to deal with process temporal data.
Ability to cope with stochastic data	Uses stochastic data to train/parameterise network
Data and resources required for input	Parameter values can be difficult to estimate due to lack of empirical data e.g. eFlow applied to Daly River used experts to estimate parameters. Parameters therefore need to be validated via model runs on known input/output data.

App. 1.8 Agent Based Models – Technical specifications

Examples:	Dambacher et al. (2016); Gao and Hailu (2012); Gross et al. (2006); Eagles et al. (2012); Wang et al. (2015); Welch et al. (2014)
Purpose	To make predictions about the way in which the actions of different 'agents' (each with different objectives) will collectively impact parts of the system which are influenced by all 'agents'. These models are particularly well suited to the task of exploring the aggregate outcome of the choices/decisions of numerous individuals on a shared resource. 'Agents' are typically assumed to represent 'individuals' (e.g. a single person, a tree) (See section on Dynamic Systems Models for models which are conceptually similar, in that they can mimic the aggregate outcome of the simultaneous actions of different 'agents', but which work with 'agents' that are much more aggregated – e.g. representing an entire industry, or an entire hydrological system)
Outputs	Emergent pattern - typically used to facilitate prediction and decision-making
Realms considered	
Terrestrial plants & animals	Yes - Constrained only by data (e.g. relations between aquatic species can be included as an 'agent' or module; key challenge is to parameterise/define agent rules for these modules).
Aquatic plants & animals	Yes – as per above
Hydrological	Difficult to include as a highly disaggregated 'agent', but can be included as boundary conditions to model. At regional level of resolution.
Geophysical	Yes - Possible to model evolution of Geophysical features as agents.
Social	Yes – Possible to model at individual or group level of resolution
Economic	Yes - Possible to model at individual or group level of resolution
Dominant Realm	Model dependent – but possible to have no dominant realm
Interactions within realms?	Model dependent – but models often include multiple actors within a single realm, thus effectively considering within-realm interactions
Interactions across realms?	Model dependent – but models often include multiple actors from across different realms, thus effectively considering cross-realm interactions
Length of time to run	Model dependent –simple models may take just a few seconds/minutes to run; others (with numerous agents interacting (simulated) long periods of time may take several days
System requirements	Model dependent
Cost to purchase	Model dependent but some software platforms (e.g. Cormas) can be downloaded for free
Training requirements	Model dependent
Popularity	Agent based models are popular when modelling emergent complex phenomena. They are simple to relate to and a reasonability test of agent rules is possible. There are numerous international, national, and Northern Australian applications of these models in different environment/development contexts.
More background on capabilities	Agent based models can allow parallel processing whereby there are simultaneous multiagent computations taking place at the same time. These models are thus truly 'complex' models (in the scientific sense of the word) with true 'chaos' driving outcomes. As such there is no guarantee of equilibrium or convergence and the models will not generate unique and specific predictions. They do, however, allow one to compare likely outcomes (across space and /or time depending on model), under different scenarios. As such, they allow one to make general predictions about the future, and to test the sensitivity of predictions to underlying parameters. Stability can be an issue e.g. Dambacher's model (DM) performed a stability analysis (but does not seem to have used the Lyapunov exponent which is typically used in loop analysis).
Problem Solving Technique	Key agents are identified. Reasonable simple rules for each agent are determined. Multiple runs with varying initial conditions and sometimes agent rules are undertaken for both scenario and sensitivity analysis. E.g. Dambacher's model trades off realism for precision in 'sign only' agent relationships
Spatial nature of data	Model dependent. Some are 'a-spatial', some requires spatial data and generate spatially delineated outcomes
Temporal nature of data	Generally predicts 'outcomes' over a (model dependent) time-frame. Input-data (e.g. objectives and likely actions of agents) not necessarily generated using temporal data.
Ability to cope with stochastic data	Probability distributions typically incorporated into model
Data and resources required for input	Model dependent e.g. in DM the interaction between real world people (agents) and extracting scenarios and desirable outcomes can be a long process. Typically the data required is (1) identifying agents (2) identifying agent rules (3) identifying desirable outcomes/hypotheses (4) identifying possible initial conditions.

App 1.9 Systems Models – Technical specifications

Examples:	MSE Atlantis; MEDLI; MSE-Daly, Land Use Trade-Off Model (LUTO)
Purpose	Like agent based models, dynamic systems models aim to generate predictions about the way in which the actions of different 'agents' (each with different objectives) will collectively impact parts of the system which are influenced by all. In these models however, 'agents' are often complex models of sub-systems – e.g. representing an entire regional economy, a hydrological system, or an entire ecosystem)
Outputs	Scenarios each with multiple submodels outputs
Realms considered	
Terrestrial plants & animals	Yes – underpinning goal is to typically aggregate information from all relevant submodels including the models for this realm
Aquatic plants & animals	Yes – underpinning goal is to typically aggregate information from all relevant submodels including the models for this realm
Hydrological	Yes – underpinning goal is to typically aggregate information from all relevant submodels including the models for this realm
Geophysical	Yes – underpinning goal is to typically aggregate information from all relevant submodels including the models for this realm
Social	Yes – underpinning goal is to typically aggregate information from all relevant submodels including the models for this realm
Economic	Yes – underpinning goal is to typically aggregate information from all relevant submodels including the models for this realm
Dominant Realm	Model dependent
Interactions within realms?	Some models have intrarealm interaction e.g. Atlantis vertebrates and invertebrates interact
Interactions across realms?	A defining characteristic of these realms is that they focus on cross-realm interactions. Agents from different realms typically interact e.g. Atlantis aquatic and economic (exploiting aquatic realm) interaction.
Length of time to run	Model dependent e.g. the simplest models (like those using STELLA or other off-the-shelf modelling platforms) can be run almost simultaneously. More complex models can take much longer. Factors influencing running time include: number, and complexity, of sub-modules, spatial and temporal resolution of input data, number and complexity of scenarios considered, and time-horizon of modelled scenarios. Even if individual scenario runs are short, modellers often consider many scenarios which can take a several days (weeks even, in complex analyses).
System requirements	Model dependent - most off-the-shelf platforms for the (smaller) systems models will run on standard computers
Cost to purchase	Model dependent (off-the shelf platforms can be purchased very cheaply; some are free). The large coupled-systems models are often built by specialists over years/decades, requiring significant funds to develop.
Training requirements	Model dependent
Popularity	Systems models with feedback are centuries old and still popular. There are innumerable examples of these, using off-the-shelf modelling platforms.
More background on capabilities	These models blend (sometimes quite sophisticated) sub-models from both the natural and human (economic) realms – often allowing for complex inter-reactions within and between modules. Relations are typically described in equations (often difference equations that embed dynamics within the models). Deep interaction between human and economic realms is thus embedded within these equations. Dynamic feedback is the key focus of these models, which are truly 'complex' models (in the scientific sense of the word) with 'chaos' driving outcomes. As such there is no guarantee of equilibrium or convergence and the models will not generate unique and specific predictions.
Problem Solving Technique	Models use deterministic equations – often with complex dynamic interactions between variables over time (thus allowing for an element of 'chaos' and non-equilibrium). They do not 'optimise'; instead they generate predictions of change over time. Modellers often use this to great advantage, within an adaptive management approach. That is, information is considered by managers and scenarios are run in the model. This new information is then used for further runs of models for consideration by management ad infinitum.
Spatial nature of data	Requires data to assist with initial model parameterisation; this can be done using spatially differentiated data, temporally differentiated data, or (most common in the simpler models) expert opinion. Some models produce spatially differentiated data as output
Temporal nature of data	Requires data to assist with initial model parameterisation; this can be done using spatially differentiated data, temporally differentiated data, or (most common in the simpler models) expert opinion All models produce temporally differentiated data (i.e. scenarios of the future) as output
Ability to cope with stochastic data	Probability distributions sometimes incorporated into model; scenarios used regularly to display model uncertainties
Data and resources required for input	Requires data to assist with initial model parameterisation; this can be done using spatially differentiated data, temporally differentiated data, or (most common in the simpler models) expert opinion.

APPENDIX 2: CASE STUDIES

In this appendix we present several ‘case studies’: examples of situations where different categories of IDSTs have been used in Northern Australia. For several categories, we could find no document case of their use in Northern Australia, and have thus, instead, provided case-studies from elsewhere in the world.

Appendix 2.1. Species Distribution Models

2.1.1. Species Distribution Modelling to provide spatially consistent freshwater biodiversity data for conservation planning in Northern Australia

2.1.1. Species Distribution Modelling to provide spatially consistent freshwater biodiversity data for conservation planning in Northern Australia

Appendix 2.2. Conservation Planning Models

2.2.1. Integrating multi-directional connectivity requirements in systematic conservation planning for freshwater systems in Northern Australia

2.2.2. Spatially-explicit prioritisation of multiple conservation management actions to address threats to species, Mitchell River Catchment, Northern Australia

2.2.3. Development by Design – Conservation planning with mitigation hierarchy [Wyoming Basin, USA]

Appendix 2.3. Hydrological Models

2.3.1. DSITIA hydrological model using quantitative risk management for ecological assets associated with the Flinders and Gilbert rivers’ catchments

2.3.2. SedNet/ANNEX in Tully Murray Basin and land management scenarios to reduce impact of inorganic nitrogen on the Great Barrier Reef, Australia

Appendix 2.4. Bio-economic Models

2.4.1. Farm scale water harvest viability in the Flinders Catchment, Australia

2.4.2. Mimosa pest control – Bioeconomic Model applied to Western Australia

Appendix 2.5. Regional Models

2.5.1. Water Use Input Output (WIO) Model applied to Australian Daly River and Mitchell River

2.5.2. 2.5.2. The Enormous Regional Model (TERM) analysis of the 2002-2003 Australian drought

Appendix 2.6. Asset/ Evaluation Models

2.6.1. Investment Framework for Environmental Resources (INFFER) a Modified Cost Benefit Analysis (CBA) Project and Asset Valuation Model applied to North Central region of Victoria.

2.6.2. Collaborative Habitat Investment Atlas (CHIA), Mission Beach Australia

Appendix 2.7. Network Models

2.7.1. eFlow Bayesian Belief Network (BBN) Model applied to Australian Daly River water extraction impact on fish species

2.7.2. Network Models using Bayesian (Belief) Decision Network (BBN/BDN) called CLAM (coastal lake assessment & management) to assess the impacts of management decsions on Merimbula Lake, NSW, Australia.

Appendix 2.8. Agent-Based Models

2.8.1. Northern Prawn Fishery (NPF) Dambacher et.al, – Agent-based modelling, Australia

2.8.2. Envision / Evoland – Agent-based modelling in the Willamette Basin, USA

Appendix 2.9. Systems Models

2.9.1. LUTO (Land Use Trade Offs) Systems Model –applied to global change and Australian land use sustainability policy scenarios to 2050.

2.9.2. Atlantis Dynamic Systems Model, SE Australia

2.9.3. Coupled Hydrologic - Economic Model for Murray-Darling Basin Australia

Appendix 2.1. Species Distribution Models – Case Studies

2.1.1. Species Distribution Modelling to provide spatially consistent freshwater biodiversity data for conservation planning in Northern Australia

Case study based on Kennard et al., 2010

What they set out to do

Provide decision-makers with an 'accurate' species distribution map to properly inform potential conservation planning investments in northern Australia. Substantial (inaccurate) spatial biases exist in the availability of freshwater species distribution data across Northern Australia. The use of patchy and incomplete species distribution data can have major implications for accurate and objective identification and prioritization of high conservation value areas. The researchers aimed to minimise these spatial biases by developing species distribution models (for freshwater fish, turtles and waterbirds) that related species occurrences records to environmental characteristics at sampling locations and using the models to make predictions of species distributions in unsurveyed areas. These spatially consistent estimates of present-day species distributions were used as biodiversity surrogates in systematic conservation planning of freshwater systems in Northern Australia.

What they tried

- A comprehensive database of sampling records was assembled for 89 freshwater fish species 13 turtle species and 106 waterbird species occurring across Northern Australia. Sampling records were attributed to individual fine-grained subcatchment polygons for model development. This included 2,328 and 350 sucbcatchments for fish and turtles, respectively (average subcatchment area of 3.6 km^2), and 2,109 subcatchments for waterbirds (average subcatchment area of 72 km^2).
- A range of ecologically-relevant minimally redundant local and catchment scale environmental variables were selected from a larger number of candidate variables for use in the predictive models of species distributions. The candidate variables were obtained from the National Catchment Database (Stein et al. 2014) and described climate, terrain, substrate, vegetation (present day), hydrology, stream network characteristics, terrestrial primary productivity, and lake and wetland area and shape characteristics. As we aimed to predict present-day distributions, not re-construct historical distributions prior to human activities, we also included an indicator of human disturbance (River Disturbance Index; Stein et al. 2002) as a predictor variable.
- Species distribution models were developed using Multivariate Adaptive Regression Splines (MARS, Leathwick et al. 2005). MARS is a method of flexible non-parametric regression modelling (Elith and Leathwick 2007). It is useful for modelling complex non-linear relationships between response and explanatory variables and has been shown to perform well in comparative assessments (e.g. Elith et al. 2006: Ferrier and Guisan 2006). Models were fitted and externally validated using true presence-absence data for fish, whereas turtle and waterbird models were fitted and validated using presence-only data.
- Model performance was assessed using the area under the receiver operating characteristic (ROC) curve (AUC). The predicted probabilities of occurrence (ranging from 0 to 1) from the MARS models were converted to a presence/absence estimate with a threshold. For fish, a threshold was used in which the predicted prevalence equalled the observed prevalence (as recommended by Freeman and Moisen 2008). For turtles and waterbirds the threshold where the ROC curve makes closest approach to 0 or 1 was used.

What they got

- The predictive models developed performed with moderate to high predictive success. AUC values were 0.82, 0.87 and 0.78 for fish, turtles and waterbirds, respectively.
- A relatively small number of environmental variables were selected as predictors of species distributions, ranging from six variables for turtles to 12 variables for waterbirds. Fish distributions were best predicted variables describing stream size, slope and relative position in

the riverine landscape. Climate (solar radiation and temperature) was also important, probably due to its role in determining upper temperature lethal limits and in influencing the permanence of refugial habitats. Turtles were predicted using a generally similar combination of variables as used for fish. Waterbirds, the most vagile of the faunal groups examined, were predicted by a combination of terrain, climate and habitat variables related to the distribution, size, productivity and characteristics of lacustrine and palustrine waterbodies.

What they learnt

- The moderate to high predictive performance of the species distributions models supported the application of the models to derive predictions of present day species occurrences in unsampled areas based on their environmental characteristics.

What they may need to do next

- Model validation would be improved by using true presence/absence data for turtles and waterbirds – therefore a research priority could be to collect these data in the future
- The use of multiple statistical modeling methods and generation of consensus predictions would allow better quantification of uncertainty in predictive modelling of species distributions.
- Development of SDMs to forecast species distributions under future scenarios of environmental change would be a useful input to future spatial conservation planning exercises.

Additional references

- Kennard, 2010.
- Elith & Leathwick, 2007.
- Elith et al., 2006.
- Ferrier & Guisan, 2006.
- Freeman & Moisen, 2008.
- Leathwick et al., 2005.
- Stein et al., 2002.
- Stein et al., 2014.

2.1.2. Species Distribution Modelling using MaxEnt to incorporate precipitation effects into niche space velocity estimates – applied to Australian birds.

Case study based on VanDerWal et al., 2013

What they set out to do

Provide conservation planners and decision-makers with revised speed and direction information on Australian bird migration caused by climate change. They demonstrate that climatic change effects were underestimated when temperature data was used in modelling niche space velocity; instead of using combination "temperature and precipitation" data. The authors argue that the dominant theory emphasizing poleward niche space shifts does not take into account equatorial-ward shifts and as such although there is a net poleward niche shift velocity this is resulting from an equatorial-ward niche shift velocity and a larger poleward niche shift velocity.

What they tried

- Analysed 60 years (1950 to 2010) of past climate change data (specifically rainfall and temperature) and 464 Australian bird species (using actual species observation records from a range of sources).
- Collated this information into a database with space (5km x 5km cells) and time (732 month 'slices') records.

- Used MaxEnt for each monthly slice to determine the distribution of bird species across (niche) space.
- Calculated the centroid (measure of middle of distribution) of the niche space that included temperature, but also included precipitation (note: including the complex interaction between temperature and precipitation on niche space movement had not been done before. Authors suggest that this is because global warming is often thought of as more easily measured and understood using temperature).
- The velocity of the niche space centroid was calculated (using a grid neighborhood gradient method e.g. derivative/maximum slope of iso-therm-precipitation).

What they got

- Niche shift velocities were found to be larger than previously calculated in other studies. Importantly, there was equatorial-ward niche shifting identified; in part due to species responding to spatial movement in rainfall across the 60 years studied.
- Findings agreed with previous studies in so far as there was a net poleward movement of niche spaces.
- In general niche space movement is multidirectional (not just poleward) and results for the complex interaction between temperature and rainfall; the latter of which has not been previously considered in such studies.

What they learnt

- Spatial bias existed in the raw observational data due to species/space correlations. This bias was removed by aggregating all raw species data and sampling spatial data from this aggregate to be used as the input to MaxEnt.
- Resolution of observational data varied across time and risked 'coarse resolution causing over prediction errors' occurring. This was remedied by excluding data that caused a model AUC of less than 0.7. The final mean of the AUCs across all species models was 0.9 i.e. reliable models.

What they may need to do next

- Past climatic data analysis was performed in this study. The authors note that a model incorporating future climate scenarios can be undertaken building on this work. Refer Warren et al. (2013) in below references and their approach to this future scenario modelling.
- They may need to refine models to incorporate expanding and contracting distributions i.e. not just the movement of a centroid across time. The authors do note that expansion and contraction also influences velocities.
- Perform a sensitivity analysis to test stability of model conclusions; by multiple resampling at the 'bias removal' stage mentioned above.

Additional references

- Warren et al., 2013.
- Reside et al., 2010.

Appendix 2.2. Conservation Planning Models – Case Studies

2.2.1. Integrating multi-directional connectivity requirements in systematic conservation planning for freshwater systems in Northern Australia

Case study based on Hermoso et al., 2012

What they set out to do

Accounting for river connectivity when identifying priority sites for conservation aids maintaining natural ecological processes and minimising the propagation of threats. This is critical for the long-term persistence of freshwater biota. However, freshwater conservation planning has mainly focused on longitudinal connections along the river (longitudinal connectivity) and has overlooked lateral connections; for example, between the river channel and the adjacent floodplain wetlands. Some water-dependent biota are not restricted to water as the medium for movement and may move aerially (e.g. waterbirds and adult stages of aquatic insects) or overland (turtles and some crustaceans) to access nearby or distant freshwater areas (e.g. lakes and wetlands), so spatial proximity of aquatic habitats within and between river catchments (inter-subcatchment connectivity) may be important to sustain these species. In this study, the authors demonstrate how to integrate longitudinal and inter-subcatchment connectivity into conservation planning for freshwater systems.

What they tried

- Implemented different rules for accounting for longitudinal and inter-subcatchment connectivity, using the Marxan conservation planning software.
- The longitudinal connectivity rule accounts for all pairs of planning units longitudinally connected through the river network, while the inter-subcatchment connectivity rule accounts for all pairs of planning units not longitudinally connected along the river.
- Demonstrated how varying the importance of different connectivity rules affected spatial priorities for conserving freshwater fish and waterbirds in Northern Australia.

What they got

- The spatial configuration of priority sites required to conserve freshwater species depended on the connectivity rule considered.
- When achieving longitudinal connectivity was more important than achieving inter-subcatchment connectivity, priority sites were mainly located along the main river channel.
- When achieving inter-subcatchment connectivity was more important than achieving longitudinal connectivity, priority sites were located along the connections between rivers and lakes, or wetlands.
- When longitudinal and inter-subcatchment connectivity were both important in the selection process, priority areas contained whole lakes or wetlands, their closest neighbors, and the upstream/downstream reaches of rivers the flow into or from them.

What they learnt

- This new approach to defining and implementing different connectivity rules can enhance movements and long-term persistence of freshwater species, maintain the ecological integrity of freshwater ecosystems, and ultimately improve the adequacy of conservation recommendations.
- This approach can also aid integrated conservation planning across different realms (terrestrial and freshwater) by identifying critical areas that connect the river and the adjacent floodplain.

What they may need to do next

- The authors assumed that connections in different directions had the same ecological importance (i.e., symmetric connectivity). For example, for the longitudinal connectivity rule, they assumed that connections from upstream to downstream areas were as important as connections from downstream to upstream areas. Similarly, for the inter-subcatchment connectivity rule, they assumed that connections from the river channel to the floodplain were

as important as connections from the floodplain to the river channel. However, different connectivity directions might have different importance depending on the ecological requirements of different species. Whenever adequate ecological information is available, this should be used in future studies to weight differently (longitudinal and inter-subcatchment) connectivity in different directions.
- Moreover, the authors considered designation of a nature reserve as the only conservation management to implement at a site. However, the range of different threats affecting biodiversity requires multiple different remediating actions. Future work should investigate the potential for prioritizing multiple actions with the same site.

2.2.2. Spatially-explicit prioritisation of multiple conservation management actions to address threats to species, Mitchell River Catchment, Northern Australia

Case study based on Cattarino et al., 2015

What they set out to do

Provide to conservation planners and decision-makers a way to minimise the cost of conserving a species of interest. In short, they reduced the budget by finding the minimum set of actions (and saved money by removing redundant actions) on a site by site basis while still achieving the conservation goals. Current systematic conservation planning tools (e.g., Marxan, Zonation, Marxan with Zones) assume that all threats occurring in priority sites need to be abated to conserve species. As a consequence, these tools prioritise multiple actions within the same site as a fixed set, and have limited capacity to evaluate individually the benefits and costs of implementing alternative actions within the same site. This study developed a new approach for prioritizing alternative individual actions within the same site. It also accounts for spatial connectivity between priority sites where actions are prescribed. This new approach leads to more efficient (i.e., conservation objective met at lower cost) conservation management investments.

What they tried

- Developed an optimization algorithm that finds the minimum set of actions and sites to abate threats to species, at the lowest cost.
- The algorithm uses simulated annealing to find the solution by minimizing the value of an objective function.
- The importance of selecting actions in sites that are connected through the river network can also be weighted in the algorithm.
- Tested the algorithm using a case study from northern Australia, where they prioritised actions to address four threats (water buffalo, cane toad, river flow alteration and grazing land use) to 44 freshwater fish species.
- Compared how the efficiency of 1) prioritizing actions independently within the same site (independent prioritization approach) and 2) prioritizing actions as a fixed set (fixed prioritization approach) varied as the importance of connectivity increased.

What they got

- They found that the efficiency of the solutions generated using the independent prioritization approach was twice as high as the efficiency of the solutions generated using the fixed prioritization approach.
- The improvement in efficiency was more pronounced as the importance of connectivity increased.

What they learnt

- Prioritizing individual actions to address threats to species is more cost-effective than prioritizing all actions as a fixed set to abate all the threats occurring in a site.
- Their approach can aid cost-efficient habitat restoration and land-use planning.
- It is also particularly suited to solving resource allocation problems, where consideration of spatial design is important, such as prioritizing conservation efforts for highly mobile species,

species facing climate change-driven range shifts, or minimizing the risk of threats spreading across different realms (terrestrial, marine and freshwater).

What they may need to do next

- The model assumes a "binary" species response to actions. This means that (1) when an action is not implemented the threat is not abated and the species is lost from a site; (2) when an action is implemented the threat is abated and the species persists.
- A new version of the prioritization approach is currently being developed where species responses to actions are represented by continuous curves, where any level of effort can be allocated to an action, in an area, with continuous outcomes in terms of probability of species persistence.
- This new approach will allow improving precision of allocation of conservation management effort, thus further increasing cost-efficiency of conservation decisions. It will also aid to enhance ecological realism of prioritization of conservation actions, which yield a continuous range of ecological benefits (not necessarily binary).

2.2.3. Development by Design – Conservation planning with mitigation hierarchy [Wyoming Basin, USA]

Case study based on Kiesecker et al., 2009

What they set out to do

Provide policy makers with a map to solve the "economic development versus conservation" tradeoff. In short, the map identified conservation areas, development areas, and development areas with offsets (where offsets simply incentivise developers to make conservation investments). Specifically, they attempted to blend the mitigation hierarchy framework (i.e. seek to minimise infrastructure development impacts by: avoid, minimise restore, offset) with conservation planning goals by ensuring biodiversity offsets (project by project planning in development to ensure net neutral environmental impact) were available in locations that offered the best chance of sustainable development.

What they tried

- What-if review of the Wyoming Basin tradeoff between development and conservation – an ecoregion of high biodiversity importance and also rich in oil and gas deposits. Specifically, applied mitigation hierarchy to balance conservation objective with future oil and gas development.

What they got

- 27 Conservation sites identified as intersecting targeted development sites.
- 22 of these sited identified as offsets to mitigate whole of region development impacts.
- Of these 22 there were 9 sites that could have their conservation goals achieved elsewhere.
- Some development sites did not affect conservation goals. However, irreplaceability scores in some sites flagged them for further consideration.

What they learnt

- Had this holistic mitigation strategy been applied to the region both development and conservation goals could have been achieved.
- Mitigation incorporated into development planning is an opportunity to inject large financial resources for conservation into a region (far in excess of what was currently available to the Wyoming region prior to development – the estimate was in the order of 6 times the current conservation funds apportioned to the region).
- Offsets financially incentivise developers to be proactive participants in conservation planning.

What they may need to do next

- A key challenge to address is identifying funding to underwrite offsets associated with conservation areas targeted for development.

Appendix 2.3. Hydrological Models – Case Studies

2.3.1. DSITIA hydrological model using quantitative risk management for ecological assets associated with the Flinders and Gilbert rivers' catchments

Case study based on DSITIA, 2014

What they set out to do

Determine the risks and possible risk mitigation strategies associated with "water flow dependent ecosystems (ecological assets) in the Flinders and Gilbert rivers' catchment" under different agricultural water extraction scenarios.

What they tried

- Utilised an ecohydraulic modelling approach which determines a Threshold of Concern (ToC) water flow that would threaten an ecological asset (species, ecosystem function) and uses spatio-temporal data of water flow to quantify the probability of ecological asset exposure to ToC levels.
- Considered various water extraction scenarios (for agricultural purposes) and their effect on probability of ecological asset exposure to ToC levels.
- Considered numerous risk mitigation strategies under different flow scenarios.

What they got

- 15 ecological assets for the Flinders and Gilbert river catchments were identified to quantitatively model risk.
- The large water development options (even with mitigation strategies) were found to risk ecological assets.
- Subsequently other water extraction scenarios were considered (266 GL in the Flinders and 489 GL in the Gilbert) with risk mitigation strategies:
    - 6 ecological assets were identified: Migratory fish guild, Freshwater turtles, Floodplain vegetation, Wetlands, Fluvial geomorphology and river forming processes, Floodplain energy subsidy.
    - Risk mitigation included: "providing seasonal overbank connection between the active channel and adjacent floodplain wetlands for turtles and vegetation" and "dam water flow rules to ensure natural ecosystem water flow cues are maintained") to reduce the probability of ecological asset exposure to ToC levels.
    - Overall these led to improvement in risk.

What they learnt

- Knowledge of flow dependent ecological assets for Gilbert and Flinders catchments was low
- Application of knowledge obtained from other northern regions applied to the Gilbert and Flinders catchments was considered reasonable.
- Further information is required to properly manage the tradeoff between ecological asset management and agricultural opportunities

What they may need to do next

- Authors suggested undertaking knowledge improvement activities including: studies on persistence of refugial water holes, fish and turtle lifecycles and habitats, and sediment load levels under different flows.
- Introduction of stream gauges to inform management of wetlands (which are very important for e.g. migratory birds)
- Study dependency of Marine and Estuaries on catchment flow management.

Additional references

- McGregor et al., 2016.
- Department of Natural Resources and Mines, 2016.

2.3.2. SedNet/ANNEX in Tully Murray Basin and land management scenarios to reduce impact of inorganic nitrogen on the Great Barrier Reef, Australia

Case study based on Armour et al., 2009

What they set out to do

Use SedNet/ANNEX to model various Sugar Cane and Banana land management scenarios to reduce loads of inorganic Nitrogen (N) in water ways feeding Chlorophyll (which is impacting the Great Barrier Reef (GBR)).

What they tried

- Used SedNet/ANNEX (a sediment load model) in conjunction with recent data and revised soil erodibility factors (via the Revised Universal Soil Loss Equation (RUSLE)) to estimate the N load runoff from Sugar Cane and Banana farms in the Tully region.
- Compared the N load estimates against monitor derived data.
- Used the model to run various land management scenarios that reduced N loads in water e.g. trash blanket on sugar can soil surface to prevent erosion feeding N loads and grassed inter-rows for banana land.

What they got

- The SedNet/ANNEX model correctly predicted monitor derived data; so could be used to model scenarios given it was correctly parameterised.
- Verified that N loads were primarily driven by sugar cane and banana land erosion into waterways.
- Best case scenarios reducing N sediment load in water ways was approximately only a quarter of the required N reduction targets for the GBR.

What they learnt

- The SedNet/ANNEX/RUSLE methodology used here resulted in good alignment of predictions with actuals.
- Current planned land management improvements fall significantly short of meeting GBR targets.
- Daily calibration of RUSLE may be required for accurate predictions in contexts involving "steep wet forested areas".

What they may need to do next

- Improved management of Phosphorous (P) emitted from fertilised land needs P management techniques given it also adversely impacts the GBR.
- SedNet/ANNEX is an average annual model. A daily time step model (e.g. waterCAST) would possibly improve N load management; refining the details of the model enough to identify the exact location of erosion derived N for maintenance.
- Over-bank flows are currently not measured by gauging stations and therefore the N load to the GBR is understated. A way to estimate the contribution of this to N loads needs to be developed.

Additional references

- Hateley et al., 2007.
- Kinsey-Henderson et al., 2005.
- Dougall et al., 2005.
- University of Canberra,1998.

Appendix 2.4. Bio-economic Models – Case Studies

2.4.1. Farm scale water harvest viability in the Flinders Catchment, Australia

Case study based on Petheram et al., 2016

What they set out to do

Evaluate the economics of dispersed on-farm water storages and determine the sensitivity of economic returns to scale of water extraction, factors affecting the reliability of water extraction and other factors that influence returns such as crop choice and irrigation type.

What they tried

- Constructed a farm Net Present Value model (7% discount rate justified by comparable investments, and 15 years of cashflows) and that depended on water extraction amounts (three crop types of variable growing seasons and three irrigation types).
- Reliability of extraction was incorporated as a 20% chance that water extraction was not possible and therefore crop failure occurs (in years 1-5). Average NPV was calculated across 1000 stochastically generated sequences of 15 years each.
- Constructed a hydrological model that determined the influence of water extraction at one spatial location on other locations; and vice versa (for 5 incrementally larger new catchment entitlements assuming full use of existing entitlements).
- The Agricultural Production Systems Simulator (APSIM) was used to simulate crop yield and water use data for the Flinders catchment.
- The new catchment water entitlements were modelled over 10 hypothetical irrigators such that upstream irrigators could not extract water in a way that threatens the downstream entitlements (on the river reach).
- Simulations assumed high evaporative losses meant that stored water was not carried over to next season's crops.
- Sensitivity analysis was performed across all assumed parameters (by halving the value of each).

What they got

- Short season length crops (e.g. Mungbeans) are most viable under land holder designed surface irrigation.
- Medium season length crops (e.g. Cotton) are most viable under best practice surface irrigation.
- For year-round cropping (e.g. Cotton-sorghum rotation) spray irrigation had the lowest annualised cost but taking into account gross margins best practice irrigation is likely to be slightly more viable.
- NPV was most sensitive to changes in the discount rate and investment period (halving discount rate or doubling investment period is roughly equivalent increasing water reliability from 80% to 100%).
- Ultimately, researchers found that irrigated agriculture supported via water harvesting was unlikely to be profitable, and short to medium season crops provide the best return, although still negative; this is because short to medium season crops return no income for at least half the year while permanent cropping requires prohibitively expensive water storage infrastructure.
- If an additional 240 GL entitlement were added to the existing 105 GL catchment entitlement most new irrigators could extract entitlements ~70-80% of years; these reliabilities would require high prices to be sustained over the 15-year investment period.

What they learnt

- Early year cashflows had significant effects on the NPV, thus late crop failures (in year 5) provide a higher possibility of viability compared to early crop failures (year 1-4).
- Cotton was identified as the only profitable crop (but cotton was only viable when assuming high sale prices were maintained for the whole 15 years and a reliable supply of water was ensured). In short, no crops were considered viable.

- Profitability was most sensitive to crop price changes, reliability of water supply, discount rate, cost of water storage, and timing of crop failure.
- Maintaining a high reliability of water use is one of the best strategies landholders can employ for improving the profitability of their enterprise.

What they may need to do next

- APSIM was not validated with local data for many plant modules. APSIM model should be locally validated using site specific climate, soil data and local cultivars.
- NPV analysis does not reflect farm owner (managerial options) and as such a real options framework may reveal additional economic value. See Hertzler (2007) in below listed references.
- The constraint that no excess water storage is carried from one season to the next may need to be relaxed given the advantage (and economic value) of water harvesting is arguably diminished by such a constraint.

Additional references

- Bell et al., 2008.
- Hertzler, 2007.

2.4.2. Mimosa pest control – Bioeconomic Model applied to Western Australia

<u>Case study based on Cook et al., 2015</u>

What they set out to do

Develop a bioeconomic model to facilitate policymaker weed control investment decisions; as they relate to the Mimosa week. The ceiling of investment funds was calculated to determine up to what level of investment government should spend.

What they tried

- Constructed a stochastic bioeconomic model
- 20-year timeframe was considered using the model
- 2 scenarios were compared; do nothing versus weed eradication
- Performed a breakeven analysis to establish up to what level of funding was economically viable for weed control.
- Used experts' input tempered by beta distribution to arrive at model parameters e.g. probability of eradication success with time.
- Considered probability of arrival (Poisson distribution like) of weed across time as a Markov process (transition matrix).
- Used the Fisher diffusion model to model dispersion (similar to random walk model approach)
- Considered satellite reinfestation as a Logistic model.
- Performed a sensitivity analysis using Monte Carlo technique.

What they got

- The model suggested a maximum investment of weed control of up to $2.95 million per year.
- Credibly formulated transparent model that can be used to inform future investments.
- High uncertainty in investment number (due to parametric sensitivity of model) means risk profile of policy maker may influence investment decision.

What they learnt

- They needed to focus on easy to quantify costs including livestock replacement and reduced grazing capacity as quantifiable model inputs.
- Simplified the problem by considering partial budget i.e. their actions do not affect other industries, and also assumed single planning body executed the infestation control task (DAFWA)

- Model was very sensitive to 3 parameters; cost of herbicide application, reinfestation probability, and probability of re-entry of Mimosa.

What they may need to do next

- Require further information to improve estimates of most sensitive parameters;
- May need to reconsider elasticity as it relates to cattle sale reduction due to weed control and model assumption being partial equilibrium type.
- Surveillance investment may be warranted for a well-informed model; in addition this would test the model of Mimosa distribution over time.

Additional references

- Cook et al., 2007.

2.4.3 Designing and testing weed management strategies– Integrating multiple models (Bioeconomic models, Conservation Planning Models).

Case study based on Adams et al., 2015

What they set out to do

Evaluate the costs of managing an invasive plant, gamba grass, and design and test management scenarios of management taking into account both the costs and benefits of action.

What they tried

- Constructed a spatially explicit spread model of gamba grass to estimate the future possible extent of invasion.
- Constructed a cost model for two management actions, eradication and containment, that takes into account size and density of infestation, accessibility and year of treatment.
- Mapped benefits of management including: conservation features of interest and economic features of interest (namely estimated profit values associated undertaking savanna burning carbon offset activities that would be threatened by gamba grass).
- Designed and tested weed management strategies for the Litchfield/Coomalie region in the Northern Territory using the dynamic spread model interfaced with a dynamic management model.
- Also designed optimal dynamic management strategies by interfacing the dynamic spread model with Conservation Planning tool Marxan.
- Scenario performance was assessed with indicators including avoided infestations and area of conservation features infested.

What they got

- By 2020, they estimated 63.5% of the study region will be infested with gamba grass (increased from 33.9% in 2010 to 63.5% in 2020 if not managed)
- If management budgets are limited, the more cost effective management option is containment (over eradication).
- Conversely, if management budgets are unlimited, eradication is more cost effective than containment.
- Considering the spatial distribution of benefits shifts the optimal allocation of management actions to protect these assets from future invasion.
- Refined testing of these strategies in Litchfield National Park indicates that under baseline scenario (no additional management budget), 32% of the park will be infested by 2020. However, under the preferred management strategy, a budget of ~$8million over 10 years will reduce the infestation to 15% of the park by 2020 and protect key conservation features.

What they learnt

- Optimization results shift spatial allocation of management budgets from typical priorities (such as satellite infestations) to areas of high priority based on presence of conservation features (i.e. benefits).
- If budget is limited, prioritise containment.
- If budget is unlimited, prioritise eradication.
- Larger budgets result in more cost-effective management of infestations by allowing eradication efforts to be undertaken and significantly reducing future invasion level.

What they may need to do next

- Consider further benefits of action (e.g. cultural values at risk from invasion, economic costs of inaction)
- Include interactions between multiple weed species (model is currently only for gamba grass).
- Incorporate spatial dynamics of multiple management agencies. Managing invasion will require participation of many stakeholders and the dynamics between these are an important consideration for estimating the success of different strategies.

Additional references

- Adams & Setterfield, 2014.
- Adams & Setterfield, 2015.
- Adams & Setterfield, 2016.

Appendix 2.5. Regional Models – Case Studies

2.5.1. Water Use Input Output (WIO) Model applied to Australian Daly River and Mitchell River

Case study based on Stoeckl et al., 2013

What they set out to do

Attempted to predict (1 to 20 year forecasts) the impact of economic growth scenarios on water demand and on the differences between Indigenous and Non-indigenous income and employment in two regions with prospects for economic development.

What they tried

- Used a modified version of Miyazawa Leontief's input output matrix to model, water demand, income and employment at the sectoral and household levels.
- Constructed their transactions tables using a 'bottom up' (Stoeckl 2012) approach, rather than building the base IO model from the 'top down' (e.g. using data collected at the state level and drawing inferences about the structure of the economy at regional levels)
- Expenditure data for the model were collected from businesses and from households in surveys. Household water use data was collected from households (estimated from questions about washing machine use and shower habits); Industry water use, and income data were collated from Australian Bureau of Statistics (ABS) data.
- Scenarios of economic growth across various sectors (including mining, tourism, and agriculture) were considered using WIO and the implications on water demand and differences between indigenous and non-indigenous employment and income were considered.

What they got

- Certain economic growth scenarios outperformed others e.g. a 1.5%pa economic growth across all industries led to the best employment and unemployment predictions.
- The gap between indigenous and non-indigenous employment and income widened in all scenarios.
- Water demand increased with economic growth towards and exceeding the dry season perennial river capabilities.
- A major constraint to economic growth is water capacity. Given the long dry season in Northern Australia economic development is particularly hindered by this and efficient water use technologies become important.
- Tourism growth provided the least and Mining growth the most aggregate income and employment benefits.
- Agricultural growth demanded the most water; however mining water consumption data is uncertain.

What they learnt

- Important household level data for many economic models are not readily available e.g. water usage per household – requiring one to collect that data, or to 'infer' it from other regions. Interestingly, authors noted that mining water consumption data is not readily available.
- At that time, no General Equilibrium (GE) models existed for relatively small remote regions in Australia (although models were available for larger, statistical divisions, in some states).
- WIO model findings should be qualified since ABS data on Indigenous household is likely being biased.
- Predictions are best communicated by comparing one scenario with another (rather than by focusing on point estimates)
- IO modelling suffers from lack of supply curve information and the assumptions of constant price and technology, however the authors note that valid long term predictions are still possible if certain conditions hold (even over the long term).

What they could do next

- The model could be extended to consider the impact of economic development on water quality (in addition to water quantity); It could potentially also be extended to include other environmental or social impacts.
- The model could also, notionally, be extended to include price/wage effects (perhaps important in regional areas were supply-side constraints can make prices particularly sensitive to increases in demand)
- The model was embedded within a systems models (Pantus et al. 2011); it could be used within that broader systems model to explore various other scenarios.

Additional references

- Stoeckl, 2012.
- Lenzen, 2001.
- Miyazawa, 1966.
- Miyazawa, 1960.
- Pantus et al., 2011.

2.5.2. The Enormous Regional Model (TERM) analysis of the 2002-2003 Australian drought

Case study based on Horridge et al., 2005

What they set out to do

Attempted to determine the impact of the Australian drought at a regional level given only aggregated national input data. This was undertaken to create a tool to facilitate policy makers who; are becoming more targeted (at small regional, rather than national level) in their response to economic shocks.

What they tried

- Using aggregate Australian (national level) data, a new regional dataset (expressing regional output, demand and productivity) was constructed for each of the 45 regions and 38 sectors defined in the model; using a mixture of economic reasoning and Australian Bureau of Statistics (ABS) data. For example, aggregately reported electricity generation was apportioned to regions according to fuel used (whereby fuel used was considered to be well correlated with amounts reported and variable at the regional level).
- A Computable General Equilibrium (CGE) model was constructed for each region, and CGE models were linked via trade flow matrices. This allowed for quick computation.
- Regional productivity was inferred by adjusting regional productivity factors so that TERM at an aggregate level agreed with readily available aggregate data from the Australian Bureau of Agricultural and Resource Economics (ABARE).
- Over the drought period regional productivity losses were assumed to vary with regional rainfall deficit.

What they got

- TERM provided estimates of Gross Regional Product and regional unemployment (arguably, useful metrics informing targeted national policies).
- Agriculture was seen to create a -1.6% Australian GDP movement; with 1% of this being economic losses in the agricultural sector and 0.6% being due to multiplier effects; TERM provides a means to view the possible underlying (regional level) dynamics of aggregate level data i.e. That agriculture was a driver for GDP decline but that there was also a multiplier effect on other sectors.
- 18 of the 45 regions suffered a GRP decline of over 5% with worst affected regions being in rural settings.

- A combination of a region's reliance on agriculture and severity of drought in the region were the drivers of large GRP declines.

What they learnt

- Data at the regional level is scarce or absent and must be inferred from aggregate statistics of ABS, ABARE, etc.
- Whilst the trade flow matrices linking CGE allows for quick computation time, it suffers from the Leontief structure of "intermediate inputs used per unit of output are at a given technology constant and independent of price". This implies demands are inelastic, contrary to the real-world experience in the drought shock setting.
- Construction of the new data set required many techniques and assumptions; from a gravity formulation of inter-regional state trade to measures at regional levels serving as proxies for the aggregate statistic to be disaggregated to a regional level.

What they may need to do next

- Find a way to relax the inelasticity constraint in TERM.
- Perform a sensitivity analysis on regional productivity and other parametric estimates of TERM.
- Australian Water and TERM: SinoTERM (a 2006 implementation of TERM in China constructed to identify measures to reduce inequality between provinces [referenced below]) identifies that both China and Australia may benefit from utilizing the TERM approach given the "water scarcity" issue in both countries.
- Evaluate regional predictions of TERM against actual (and credible) regional level data. SinoTERM had access to provincial level data, but there was concern that quality of data was low and thus the National Bureau of Statistics (NBS) data was disaggregated in a similar manner that TERM applied in the Australian drought 2002-2003 setting.

Additional references

- Horridge et al., 2008.
- Ding et al., 2011.

Appendix 2.6. Asset/Project Evaluation Models – Case Studies

2.6.1. Investment Framework for Environmental Resources (INFFER) a Modified Cost Benefit Analysis (CBA) – Project and Asset valuation model applied to North Central region of Victoria.

Case study based on Pannell et al., 2012

What they set out to do

To use a modification of Cost-Benefit Analysis (CBA) to prioritise 3 land-use change projects in the North Central region of Victoria.

What they tried

- Identified a workable CBA methodology via discussions with all stakeholders including Project management organization, policy makers and project funders.
- Identified 287 environmental assets via stakeholder discussions.
- A simple filter consisted of a Committee of stakeholders (Government, technical experts, Non-Government Organizations, Conservation and Other Community groups) to reduce the 287 environmental assets (which was considered too high to all be analysed in detail) to 32 environmental assets.
- Analysed 32 project investment (one for each environmental asset) in terms of: the benefits, costs, risks, and importantly the timing of these; the timing had not previously been considered.
- A detailed filter (assessment stage) involved small teams of staff collecting and analyzing information to ultimately present to the board for decision-making; staff were trained over a 2-day period.
- 10 Community workshops (300 participants) were held to collect preference information.
- Used a scoring system instead of non-market-valuation because of the discomfort for the latter expressed by some stakeholders.
- The scoring system was converted to dollars whereby each unit of score corresponded to $20M.
- Used net present valuation techniques on dollarised benefits and costs to discount environmental project benefits and costs distributed across time i.e. used a discount rate to account for time.
- A Benefit-Cost ratio (BCR) was constructed to prioritise the 32 projects.
- The organization selected 11 of the 32 to progress; considering the remainder as being mis-aligned with funding programs.

What they got

- BCRs underpinned by detailed analysis prioritizing 32 projects.
- BCRs providing a basis to negotiate project funding with State and Commonwealth Governments for 11 environmental projects.
- Quality of prioritization methodology was considered superior to the previous methodology.

What they learnt

- Time constraints meant that all 100 projects could not be analysed so an initial simple analysis was used to filter out projects with the remainder analysed in greater detail.
- Involving board members and staff provided the traction for change suggested by this CBA work.
- The more detailed analysis was criticised as being too complex by some participants.
- There is a trade-off between simplicity of the scoring and comprehensive detail of it.

What they may need to do next

- The initial simple projects filter although pragmatic risks eliminating potentially valuable projects (an insight the author also shares). Therefore the researchers may need to focus attention on improving the initial filtration step to assess the extent of this risk and attempt to minimise it.
- The researchers have proposed for future work that consistency across projects be checked to ensure project alignment with organizational goals and public policy.
- The researchers have noted a variation across project analysis in terms of quality of data and logic used. Quality control ensuring consistent analysis may need to be addressed.

Additional references

- Pannell et al., 2013a.
- Pannell et al., 2013b.
- Pannell & Gibson, 2016.
- Pannell, 2013.
- Greengraphics, 2016.

2.6.2. Collaborative Habitat Investment Atlas (CHIA), Mission Beach Australia

Case study based on Pert et al., 2013

What they set out to do

They saw a need to develop a real-time interactive participatory tool. That is, they wanted to aggregate the preferences of multiple decision-makers to aid in conservation planning decision-making. Specifically, incorporating public "social values" input involving social and political considerations in conjunction with the usual biodiversity evaluations.

What they tried

- CHIA allowed stakeholders to, in real time, vary weights relating to biodiversity importance, threat level, and current level of protection, and also vary formula based attributes. This was done at the cadastre level and "suitability maps" feeding into the conservation planning process was the CHIA output that suggested priority conservation regions.
- Community Viz allowed Interactivity between CHIA user and the ArcGIS platform. Scenario360 allowed input of user preferences and Scenario 3D / Google earth allowed real-time visual output.

What they got

- The CHIA prototype was implemented at Mission Beach Queensland within the Wet Tropics bioregion. Mission Beach was identified previous to CHIA as a priority biodiversity conservation area. The 'sea change' movement threatens rainforests and therefore the endangered 'southern cassowary' population. Mission Beach suffered disparate stakeholder views, un-coordinated fragmented institutional decision-making, and competing priorities.
- CHIA was considered useful in assisting a non-government body, Terrain NRM Ltd, to prioritise the set of possible land purchases marked for clearing and of biodiversity importance. Other key organisations involved were the Mission Beach Habitat Network Action Committee and government decision-makers at local, regional and national levels.
- An experts' panel was leveraged to fill gaps and identify 15 attributes of biodiversity importance. Experts were also utilised to use sliders to weight attributes on a scale of 0 to 10 (in a consensus format) for each polygon of land. Nonlinear standardisation was then applied to score the polygon between zero and one to arrive at a composite map of polygons. For each polygon there was a score for biodiversity importance model, level of protection model and threat model.

What they learnt

- The expert workshop at the start of CHIA identified gaps in biodiversity data and a preference to have a single map output and was crucial to the CHIA design.
- A key aspect was the ability of the expert panel to iteratively use CHIA to change inputs and see the impact on a map immediately. They then discussed this map and then reiterated until a consensus was attained.
- Three different models were aggregated into one score (0-100), however there was an issue of consistency across land parcels. This was accommodated for by using “the inverse of level of protection” in the weighted average function.
- CHIA output needed to be combined with other Council data of land value and owner data to arrive at planning decisions.
- CHIA caused wildlife corridors removed in the original local plan to be reinstated, and land marked for urban use to be transformed to rural use.

What they may need to do next

- An organization with the capacity to purchase land “marked for development that is also CHIA identified as important”, needs to be formed.
- The expert panel suggested modification of CHIA for application to other problems in the area.

Appendix 2.7. Network Models – Case Studies

2.7.1. eFlow Bayesian Belief Network (BBN) Model applied to Australian Daly River - water extraction impact on fish species

Case study based on Chan et al., 2012

What they set out to do

A Bayesian Belief Network BBN model was developed and applied to assist with environmental flow decision-making in the Daly River, Northern Territory. The Daly River is largely unregulated, with only a small volume of water extracted annually for agriculture. However, there is considerable pressure for further agricultural development in the catchment, particularly with demand for extra water extraction during the dry season. Because of their ecological, economic and cultural significance, and potential sensitivity to dry season flow regime changes, two freshwater fish species (black bream and barramundi) were used as a basis to predict the ecological risks of alternative water use scenarios and inform water allocation planning in the catchment. Modelled changes in dry season flow regimes under various water extraction scenarios, combined with outputs from two-dimensional habitat simulation models of fish species' hydraulic habitat requirements, and other scientific data, expert opinion and Indigenous ecological knowledge were used to develop, validate and apply the BBN.

What they tried

- BBN models were developed to predict the likelihood of changes in the abundances of the two fish species, barramundi and sooty grunter in response to modelled flow regime changes associated with dry season water extraction at five focal sites along the main stem of the Daly River.
- Quantitative field sampling of fish and habitat at 50 sites throughout the Daly River catchment was used to generate data on the distribution, abundance and habitat preferences of black bream and barramundi. Fish and habitat data was also collected biannually (early and late dry seasons) over a 3-year study period at the five focal study sites and was used for BBN validation.
- Simulated daily discharge data modelled for a 109-year period for four water extraction scenarios for each focal site was obtained from a finite-element FEFLOW model for subsurface flow and transport, including ground water–surface water interactions. The four water extraction scenarios provided were: 'natural' (i.e. no extraction), 'historic' (i.e. estimated actual levels of water extraction), 'current entitlements (fully utilised)' and 'possible future entitlements',
- Two-dimensional, depth averaged finite element hydrodynamic models (RMA-10) were used to estimated changes in hydraulic habitat availability at each focal site under each flow scenario.
- The structures of the BBNs were informed by expert-derived conceptual models relating fish abundance to flow and other physical and biological factors (e.g. habitat and food availability, connectivity, reproduction and recruitment, biotic interactions, etc).
- BBN nodes and links were defined i.e. node states were specified and link conditional probabilities (parameters) tables (CPT) using expert workshop elicitation.
- Sensitivity analysis was performed on the BBNs to identify which model nodes have the greatest influence on the prediction of the endpoints (abundance classes for each fish species)
- BBNs were externally validated by predicting fish abundances at the five focal sites sampled bi-annually over three years and comparing with fish abundances actually collected

What they got

- External model validation revealed that the BBNs performed well, with prediction errors of only 20–30%.
- Application of the BBNs to predict changes in fish abundance under the four water extraction scenarios revealed that historic levels of water extraction are unlikely to have affected natural variation in the abundances of sooty grunter and barramundi at all five focal study sites

- However, if current water entitlements were fully utilised, consequent changes to the dry season flow regime and associated physical and ecological changes to the riverine environment would increase the probability of low and extremely low abundances of both species. This impact was expected to be greatest in upstream reaches where water extraction is expected to be highest but is lessened further downstream where hydrologic impacts of water extraction are lower.

What they learnt

- Based on their findings, the researchers suggest that current and possible future water use entitlements in the Daly River catchment should be revised
- The researchers concluded that the BBN provided an ideal way to combine quantitative data with expert knowledge (where such data are lacking) to inform environmental flow management and planning particularly in areas such as Northern Australia where quantitative knowledge is limited
- New empirical data for most sensitive nodes would improve the model.

What they may need to do next

- Further research to reduce uncertainty of parameters with high reduction of Shannon Entropy (i.e. those nodes most sensitive to create errors in output nodes).
- The researchers note that further validation is required given the sparseness of data.
- Stronger and more sustained engagement with managers is required to improve uptake of the BBN models and scenario outputs

Additional references

- Shenton et al., 2011.
- Pollino et al., 2007.

2.7.2. Network Models using Bayesian (Belief) Decision Network (BBN/BDN) called CLAM (coastal lake assessment & management) to assess the impacts of management decsions on Merimbula Lake, NSW, Australia.

Case study based on Ticehurst et al., 2008

What they set out to do

Provide a decision support tool for catchment managers, stakeholders and other decision-makers of Merimbula Lake that assists in negotiating the tradeoffs between “flora and fauna and water quality” versus “urban sprawl, agricultural intensification, and tourism”.

What they tried

- Developed a conceptual influence map for the BBN and validated it with stakeholders (e.g. local council and Merimbula Airport Corporation) and experts.
- Built CLAM as a BBN in the Integrated Component Modelling System (ICMS).
- Used local data to calibrate network and expert input where data was lacking.
- Trained and distributed CLAM to relevant users (Catchment Decision-makers).
- Encouraged users to test various scenario outcomes versus current state of the world to test for reasonableness.

What they got

- A decision support tool to compare the impact of various policies trading off tourism, urban encroachment, and the environment.
- 279,936 scenarios were run to test the impact of different management choices.
- Controlled urban development with conservation goals leads to maintaining current water quality, economy and social values.

What they learnt

- The participatory approach resulted in “Boating activity” remaining in the model; whereas it would ordinarily be removed as a node so as to improve overall model certainty. However, it was of interest to stakeholders and as such remains. In short, there is a tradeoff between variables of interest and model performance.
- Updating CLAM with new information was considered easy.
- The detail of the causal relationships and discretization of states in the network may not be required by decision-makers.

What they may need to do next

- Authors identified the need for more information to better calibrate the model
- The model needs to be tested against data that still needs to be collected.
- Authors consider a key question is “how much certainty in CLAM is required for a management decision to be made?”

Additional references

- Ticehurst, 2008.

Appendix 2.8. Agent Based Models – Case Studies

2.8.1. Northern Prawn Fishery (NPF) agent-based modelling, Australia

Case study based on Dambacher et al., 2015

What they set out to do

Attempted to understand the reason for decline in Banana prawn catches near Weipa (in Queensland, Australia) region. Specifically, they applied loop analysis (which is one of the techniques used in what has been called Qualitative Mathematics) and considered the stability of 5 hypotheses that may explain the decline.

What they tried

- Discipline specific workshops (biologists, managers of fishing industry, statisticians, and ecosystem modelers) were held to consider each discipline's models from 2004 to 2005.
- Loop analysis was then applied to aggregate the information collected across all workshops by creating a digraph (graph with arrows) indicating positive, negative, or no feedback between agents in the Banana prawn setting.
- The Full (17 variable) model was reduced to the Core (6 variable) model by decomposing into subsystems and only keeping those variables which likely increased instability.
- Tested the stability of the Full and Core models under various perturbations/changes/ scenarios.

What they got

- The Full and Core model were considered by workshop participants as a useful way to visualise and communicate the interactions between agents across the various realms.
- The Core model was used to determine that Banana prawn catch reduces due to the repeating positive feedback loop: low catch season causes withdrawal of fishing effort in the following season which causes low catch in that season.

What they learnt

- The Core model represented the key feedback structure as the Full model of the NPF setting and was used because the Full model needed parameterization in order to describe some "signs" (but this parameterization would then introduce bias into the Full model). In short, the Core model preserved the key features of variable feedback in the NPF setting in the most concise way.
- In a complex environment of interconnected agents with negative and positive feedbacks (as in this NPF case study), simple "signed" (positive, negative, 0) feedback representation avoids the likely intractable task of parameterizing and then solving a large system of differential equations. Instead, the idea that "sign stability (probability of sign determinancy)" whereby perturbations do not affect the feedback signs, evidences a robust 'realistic (albeit trading off precise quantitative information)' model.

What they may need to do next

- Qualitative Mathematical analysis of this type (originating in Levin (1966)) provides an initial framework that is further refined as more information becomes available. They suggested an experiment that was rejected by NORMAC due to concerns of the impact on the potentially exploited Banana prawn resource. Further acceptable information collecting experiments are possibly required.
- Turbidity of water is identified as a barrier to aerial reconnaissance (of 'boils' indicating prawn numbers) affecting the NPF commercial industry productivity. There is possibly a need to further expand the sonar reconnaissance to manage a sustainable NPF industry in and around Weipa.

Additional references

- Weisberg, 2006.
- Orzack & Sober, 1993.
- Justus, 2005.
- Levins, 1966.

2.8.2. Envision / Evoland – Agent-based modelling in the Willamette Basin, USA

Case study based on Bolte et al., 2006

What they set out to do

Develop an "alternative future analysis" model that outputs a map (of the region in 50 years' time) for decision-makers to consider the impact of alternative policies. Attempted to model the bio complexity (complex interactions between humans and ecosystems) of Willamette Basin under two scenarios (each run for 50 years). Specifically, they considered conservation versus urbanisaton scenarios. The GIS landscape was divided into polygons (with attributes), and agents (which they refer to as actors) including home owners, farmers and forest owners each with an interest in the fish population of nearby rivers. All actors had policies (which updated over time; affected by the location and the cultural group characteristic). Various features were monitored including fish population and biodiversity, and urban and rural economic health. After 50 years these features converged onto a solution (state space in chaos terms). Sensitivity analysis was considered in terms of chaos theory concepts. That is, there were multiple possible solutions that the model could converge to (called attractors in chaos theory). Stability was considered in terms of how much perturbation on the system meant a shift from one solution/attractor to another.

What they tried

- Considered the impact of two different policy scenarios that tradeoff riparian forest (where water meets land) corridors used for conservation versus urban and rural development using a GIS agent based model. The two different policy scenarios were forest conservation versus economic development.
- Evoland (Evolving Landscape) polygon based GIS properties were defined and also decision policies of actors and their modifying effect on the polygons associated with Willamette Basin were specified. Evolution of landscape evaluators (features) were monitored as they evolved as the model self-organised via nonlinear feedback.
- An important novel idea was the use of genetic algorithms to change an actor's decision set and behavior over time as a result of the group the actor/agent belonged to and their location (which also affected the agent's decisions).
- They used a 50-year future prediction period and decision policies currently in place (and policies also being considered as future options).

What they got

- The initial percentage of land distribution of urban, rural, forest, water and roads was compared to 15 years and 50 years model predicted land distributions.
- They found after 15 year that habitat for fish improved, forest lands tripled in value, but rural land loses 75% of its initial value.

What they learnt

- By changing emphasis from a rural to forest products the economic health and fish health increase.
- Ecological effects take 15 years to mature.
- Evoland does not reflect reality but is useful to explore consequences of decisions.

What they may need to do next

- Identify when simple linear models offer as good as predictions (e.g. limited data and uncertain mechanisms potentially makes nonlinear models unreliable.)
- Need to verify the model predictions (but this is difficult given the long timeframe). That is, it is arguably difficult to validate a model that outputs 15 and 50 year predictions without waiting that long to compare the prediction with actual observation.

Additional references

- Envision Case Studies, 2016.
- Nelson & Daily, 2010.
- Bone et al., 2014.

Appendix 2.9. Systems Models – Case Studies

2.9.1. LUTO (Land Use Trade Offs) Systems Model – applied to global change and Australian land use sustainability policy scenarios to 2050.

Case study based on Bryan et al., 2016

What they set out to do

Create a high resolution long run systems model to consider scenarios assisting strategic decision-making about Australian land use policy in a global context. Specifically, to inform the tradeoff between land use for economic returns versus using it for ecosystem services.

What they tried

- Used LUTO (Land Use Trade Offs – partial equilibrium linear programming maximizing sum of consumer and producer land use surplus) model to create a high spatial resolution (1.1km grids) and 'per year' temporal resolution.
- Only clear agricultural land was considered (85.3Mha).
- This LUTO model was used to investigate various Australian domestic land use policies in a global context.
- Created bottom up (high resolution) LUTO systems model under 4 (CSIRO informed) global scenario and their implications from 2013 to 2050 on land use drivers (Using GIAM [global integrated assessment model] and ESM [energy sector model] to quantify climate, price and demand for carbon, oil, electricity, crops, and livestock) and measurable sustainability implications (economic returns to land, food production, greenhouse gas emissions, water, biodiversity and energy services).
- Relative profitability and a hurdle constraint determined whether a land grid changed from agriculture to environmental use. Value of non-agricultural land was measured via carbon prices per the amount abated.
- 2 domestic policy drivers were considered. First a land use payment policy (carbon incentives expanded to include biodiversity objectives) and second a biofuels/energy policy.
- Performed a sensitivity analysis.

What they got

- Strong domestic and global governance and global emission abatement incentives with domestic shift to biodiversity will lead to increased and diversified domestic economic returns.
- Quantitative scenario analysis emphasis in LUTO model implementation; to decide between sustainable land use policy options.
- 26GB (high spatial resolution) data pack that they have shared freely with other researchers to extend this work.

What they learnt

- Available top-down systems models did not have fine enough resolution, whereas bottom-up systems models fail to quantitatively link to quantitative global change.
- The model was highly sensitive to scenario parameter assumptions (productivity growth, adoption behavior, climate change, and capacity constraints).
- Global outlooks strongly affected the transition of land use in the modelling.
- There was a trade-off between carbon emission abatement and water resource use.

What they may need to do next

- May need to validate the 10% above inflation rate used in high risk investments and the 100 years annuity payments.
- Extend the analysis beyond the agricultural domain

- Quantify the stability (sensitivity) of the model results; refer reference 3 below where the researchers consider “deep uncertainty i.e. no credible associated probability distributions” and apply eFAST (a fourier transform technique that assists in determining the response characteristics in the frequency domain of various inputs, and to be used as a measure of parameter sensitivity for the decision-maker to consider)
- Possibly consider the likelihood of scenarios (authors note that they did not do this).

Additional references

- Connor et al., 2015.
- Gao et al., 2016.

2.9.2. Atlantis - Systems Model, SE Australia

Case study based on Fulton et al., (2011)

What they set out to do

Build Atlantis as a coupled dynamic systems model to ‘road test’ management scenarios in a ‘whole of ecosystem’ based approach to fisheries management.

What they tried

- Attempted to inform the strategic restructuring of SE Australian fisheries’ regulation via a whole of ecosystems adaptive management framework whereby models were used to ‘road test’ 3 possible fishery regulatory changes.
- Coupled the existing Atlantis Biophysical Submodel (coarse, spatial differential equations that model nitrogen and silica at 6,12,24 hr time steps) to newly defined fishing vessel and marine life submodels

What they got

- Policy makers were able to trial different regulatory changes and see the modelled effects on commercial fishery and ecosystem dynamics.
- A mix of gear, quota and spatial management provided a better solution than any one single regulation e.g. a quota based system alone was not considered better than the mix.

What they learnt

- Atlantis works well as a strategic tool considering the estimated impact on the whole-of-system level. The developers suggest that tools such as Marxan are more tactical in nature being aptly applied at the part-of-system level.
- Spatial resolution does matter. Too coarse a spatial resolution loses important dynamics (albeit simplifying the equations) and too fine a spatial resolution creates unstable nonlinear dynamics (meaning that the model is sensitive to initial conditions and small perturbations lead to very different outcomes).
- Atlantis should be considered part of a tool-kit of models and modified on a case by case basis e.g. the participatory fisheries management in Australia contrasts with that of the USA and as such different submodel equations are required.
- Simple sub model ‘quasi-agent-based-rules’ (e.g. Catch Per Unit Effort for fishing vessel) may result in better models than complex equations.
- The assumption of rational behaving Atlantis humans does not always mirror the real world.
- The indicators used to monitor in the Atlantis model need careful selection (as they may not be aligned to what is ultimately trying to be measured).

What they may need to do next

- The Authors suggest that Atlantis can be hard to implement and suggest that the 'patchy' documentation issue be resolved.
- The Authors suggest that large data demands, long run times, and long calibration times reduces the 'ease of use'.
- The Authors suggest that new methods to account for uncertainty of information needs to be developed given that scenario analysis (typically used to address uncertainty) in the whole-of-system Atlantis level require combinatorial large runs.

Additional references

- Smith et al., 2007.
- CSIRO Marine and Atmospheric Research | Atlantis Ecosystem Model Home Page, 2016.

2.9.3. Coupled Hydrologic - Economic Model, Murray-Darling Basin Australia

Case study based on Mainuddin et al., 2007

What they set out to do

Solve an optimisation problem using a spreadsheet model: maximise profit subject to policy determined hydrologic and economic constraints. Specifically, the model considers rainfall run-off and loss due to transpiration, irrigation demand, cost of water, regulated restrictions to trade and reallocation to the environment. The central motivation is the allocation of water to areas of environmental significance.

What they tried

- Used an excel spreadsheet to iteratively solve a nonlinear optimisation problem. That is, hydrological part solved followed by the economic part solved, followed by the hydrologic part etc. Iteration stops when target volume for environmental (ecological assets) allocation is reached.
- An equilibrium point for water supply (rainfall runoff annual volumes model) and water demand (irrigated agriculture annual volumes model) was identified subject to policy constraints (fixed allocations to specific place near river).

What they got

- Scenarios were analysed. Specifically, the location and volume of water removal was either fixed at a particular estimate or free to vary in the model. Water trade restriction were not incorporated into the model given the aim was to ascertain what was possible.
- Model identified "how and where water might be acquired for environmental use" (Mainuddin et.al. 2007).
- Model does not evaluate the benefits derived from water allocation to ecological assets.
- Model does not contain sufficient detail to assist with day to day river management.

What they learnt

- Lumped water loss factors in the model appear to exaggerate the water loss.
- The location of extraction has significant influence on the optimal solution.
- Whilst the economic part of the integrated model is able to be solved in a linear manner, the hydrological component requires nonlinear optimisation techniques.

What they may need to do next

- Model at the individual level: The current model does not consider individual farmer level responses; rather a regionally aggregated response is used in the equation which may lead to a different optimization solution.
- The model as it stands, considers short run effects only, thus the next version of the model may consider incorporating long run effects.
- Include omitted variables e.g. groundwater and temporal variability for a more comprehensive analysis.

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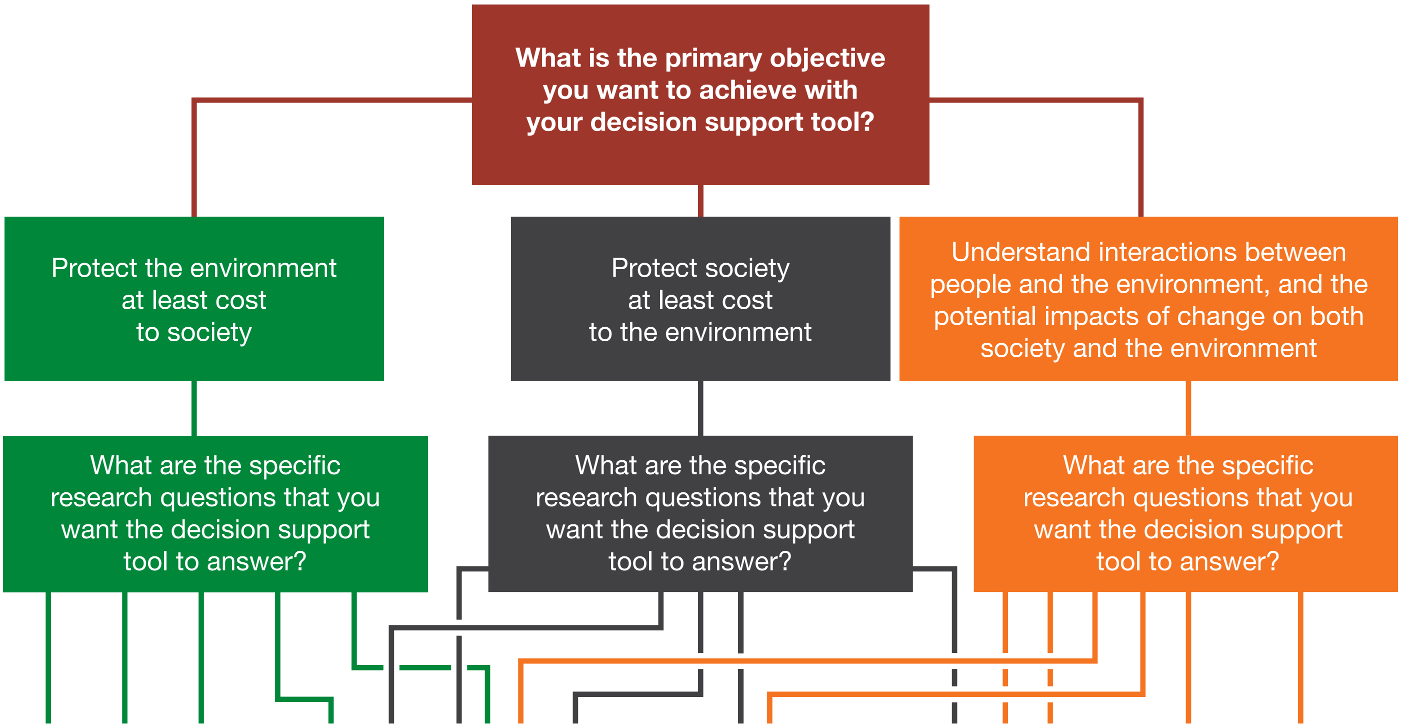

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