MODELLERS' ROLES IN STRUCTURING INTEGRATIVE RESEARCH PROJECTS

Marit E. Kragt[a,b], Barbara J. Robson[c], Christopher J.A. Macleod[d]

[a] Centre for Environmental Economics & Policy, School of Agricultural & Resource Economics, The University of Western Australia, Crawley, WA 6009, Australia

[b] CSIRO Ecosystem Sciences, Floreat, WA 6014, Australia

[c] CSIRO Land and Water, Black Mountain, ACT 2601, Australia

[d] The James Hutton Institute, Craigiebuckler, Aberdeen AB15 8QH, UK

Abstract:

Effective management of environmental systems involves assessment of multiple (physical, ecological, and socio-economic) issues, and often requires new research that spans multiple disciplines. Such integrative research across knowledge domains faces numerous theoretical and practical challenges. In this paper, we discuss how environmental modelling can overcome many of these challenges, and how models can provide a framework for successful integrative research. Integrative environmental modellers adopt various roles in integrative projects such as: technical specialist, knowledge broker, and facilitator. A model can act as a shared project goal, while the model development process provides a coordinated framework to integrate multi-disciplinary inputs. Modellers often have a broad generalist understanding of environmental systems. Their overarching perspective means that modellers are well-placed to facilitate integrative research processes. We discuss the challenges of interdisciplinary academic research, and provide a framework through which environmental modellers can play a role in guiding more successful integrative research programmes. A key feature of this approach is that environmental modellers are actively engaged in the research programme from the beginning—modelling is not simply an exercise in drawing together existing disciplinary knowledge, but acts as a guiding structure for new (cross-disciplinary) knowledge creation.

Keywords: Conceptual modelling; Integrated framework; Integrative studies; Interdisciplinary research; Knowledge management; Transdisciplinarity

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1. Introduction

Integrated assessment (IA) of the complex questions associated with environmental problems requires an interdisciplinary and participatory process of combining, interpreting, and communicating knowledge from different sources (Rotmans and Van Asselt 1996). The organisation, facilitation, communication, and technical development of integrated methodologies pose significant challenges to IA projects. In the IA literature, modelling has repeatedly been proposed as an approach to overcoming many of these challenges (Harris 2002; Wainwright and Mulligan 2004). Environmental modelling can have multiple purposes including: (a) education and exploration of systems; (b) operational forecasting; or (c) scenario evaluation and decision support (Jakeman and Letcher 2003; McIntosh et al. 2007). In this paper, we focus specifically on modelling for (d) knowledge integration and (e) generation of new knowledge in the context of interdisciplinary research. We discuss the role of the modeller or modelling team in this process.

Various terms are used in the literature to define 'knowledge integration'. *Multidisciplinary* research is characterised by the application of several distinct discipline-based methodologies, where disciplinary autonomy is retained rather than integrated (Wickson et al. 2006). *Interdisciplinarity* is typically defined as a process that involves a range of academic disciplines in a way that forces them to cross subject boundaries to create new knowledge and achieve a common research goal (Tress et al. 2007). *Transdisciplinarity* combines interdisciplinarity with a participatory approach, and involves both academic researchers and non-academic stakeholders—such as policy makers or members of the general public (Tress et al. 2007). We use the overarching term '*integrative research'* to indicate research that bridges multiple knowledge cultures, with the aim of creating new knowledge that cannot be assigned to a particular discipline, but is a joint product of interdisciplinary and/or transdisciplinary efforts (Tress et al. 2006; Winder 2003).

Much of the current research on environmental modelling as a tool to integrate knowledge, focuses on the role of participatory modelling with community stakeholders to enhance IA and environmental management (e.g. Bousquet and Voinov 2010; de Kraker 2011). However, research that spans a range of natural and social science domains is generally required to enable

IA. Such research has as its goal not only integration of existing knowledge, but also generation of new cross-disciplinary, knowledge. Integrative academic research faces additional challenges (technical-, knowledge-, and team-based) that have not yet been sufficiently addressed in the environmental modelling literature.

In this paper, we argue that environmental modellers (individuals or modelling teams) are well-placed to assume a key role in integrative research. Our focus is on interdisciplinary research and the integration challenges within academia. In particular, we describe the roles of modellers in integrative research projects, and the ways in which model development can contribute to breaking down the disciplinary silos that are often present when conducting integrative research. Building on our experiences and drawing information from various subject areas, we present a guiding framework that shows how the modelling process can formalise existing knowledge and generate a shared conceptual understanding of a system. In addition, models provide a concrete goal as an end-point for research and integration. A greater awareness of the roles of models / modellers in different phases of an integrative project, will facilitate the process of knowledge integration across diverse disciplines.

The challenges to integrative research and environmental modelling are briefly reviewed in the next section. We summarise how different subject areas have approached integrative modelling in Section 3, and provide a framework suggesting how modelling can contribute to better knowledge integration in Section 4. Sections 5 and 6 provide some words of caution and concluding thoughts for future research.

2. Challenges to integrative research and modelling of environmental systems

The term 'model integration' is widely used, but can cover different types of integration: linking multiple computer models, assessing various issues across different scales, and/or stakeholder participation in model development (Parker et al. 2002; Risbey et al. 1996). The interconnectedness and variety of natural and socio-economic systems affected by environmental management calls for interdisciplinary research that involves scientists from a range of fields (Argent 2004). However, integration is not automatically achieved when two or more academic disciplines are brought together in one project (Tress et al. 2006). Integrative modellers must interact with a variety of data, knowledge bases, and epistemologies. Although the focus of the present paper is on challenges to integrative *research*, we note that successful

IA and management may be confronted with further barriers related to (for example) changing stakeholder values or model users.

2.1 Technical issues: data and models

A common integrated modelling approach is to couple (existing) single-disciplinary models. Here, integration is achieved by using output from one model as an input into other model components (e.g. Bilaletdin et al. 2008). Such coupled models link knowledge from various disciplines, but individual modules are usually not designed for integration purposes (Voinov and Cerco 2010). Differences in data semantics can lead to problems at the integration stage. Such differences may include varying definitions of variables; different time- and spatial scales of application; different data types or level of aggregation; and software incompatibility (Harris 2002; Jakeman and Letcher 2003).

IA of environmental systems requires integration of issues across spatial and temporal scales (Parker et al. 2002). However, different disciplines often study processes and structures at different scales. For example, hydrological modellers may frame research questions about river flow processes around a time-step measured in hours, ecologists may consider ecosystem responses over a period of days or weeks, while socio-economic researchers may analyse system changes over monthly or yearly time-periods. An integrative project needs to define research questions in ways that can connect such disparate scales of analysis.

2.2 Knowledge issues: ontologies and epistemologies

Knowledge is organised and framed differently across academic disciplines. This can influence the methods used; the type of data collected; and the weighting and valuation of different types of knowledge and data by researchers. Next to specialist disciplinary knowledge, other forms of knowledge (e.g. tacit, historical, and common) may be pertinent to improve IA. While other types of knowledge are important, the focus of the current paper is on managing academic experts' knowledge, as a first step towards more integrated environmental assessment and management.

Despite its importance, little attention has been paid to how different ontologies (definitions of objects, classes, relationships and functions—Gruber 1993) and epistemologies (beliefs about the nature of knowledge itself) influence knowledge integration in interdisciplinary research

(Raymond et al. 2010).[a] Interdisciplinary integrative modelling needs to use processes that can accommodate varying types of knowledge and manage the ways in which such knowledge is categorised.

2.3 Team issues: values and language

Integrative research involves working as part of an interdisciplinary team, which poses challenges of its own. Successful team-work requires the development of team norms and values in addition to those of the individual researchers (Janssen and Goldsworthy 1996). Some specific team-based challenges include (Naiman 1999; Tress et al. 2007; Wickson et al. 2006): (1) Difficulties in communication because of the specialised language used by experts and/or considerable time demands to develop a common terminology; (2) Diverging project objectives and/or lack of clarity regarding the goals of the project—team members may recognise integration as desirable without having a clear understanding of what such integration would look like; (3) Variable levels of interest, engagement, or ability amongst team members to participate in interdisciplinary research; (4) Lack of ownership and potential for disagreement about ideas and data, particularly in the project's integration phase—each participant may be interested in cooperation, but see it as someone else's job to coordinate the integration process and make knowledge integration happen; (5) Long production times for publications involving multiple authors due to different styles and views on what is important. Frequent communication, and working towards a common goal can help to prevent internal group issues (Kragt et al. 2011), and it is our experience that the development of an integrative modelling tool can provide a framework for communication as well as a concrete common goal (Section 4).

3. Lessons from previous integrative modelling studies

Modelling across disciplinary boundaries can be found in the management, ecology, geography, integrated assessment, and computing science literatures. In this section we

[a] Ironically, much previous work on modelling as an integrative tool may have been lost to a more general modelling audience because of the specialised language used by experts. To avoid making that same mistake here, the interested reader is directed to, for example, McIntosh et al. (2007) and Villa et al. (2009) for more information on epistemology and ontologies in environmental modelling.

summarise some of the lessons learned from previous integrative studies in those domains (Table 1).

3.1 Technology integration

Our ability to carry out integrative modelling can be limited by variability in data and models used by different disciplines (Goodchild et al. 1996). These issues have stimulated the development of approaches that make greater use of object-orientated structures that allow components to be developed independently (e.g. Guariso et al. 1996; Reed et al. 1999; Sydelko et al. 1999). A key benefit of taking such a component-based approach is the ability to add or remove components to suit different questions. The overall model's continued existence is also independent of the usefulness of individual components (such as a short-lived user interface in the agricultural production systems simulator APSIM—Holzworth et al. 2010). In 'tight' coupled-component modelling, models are ported into a single modelling application. This has advantages of providing control over process representation and data structures, and allows the use of efficient numerical algorithms (Goodall et al. 2011). However, limitations of tightly-coupled modelling strategies are that fixed semantics and data structures can limit integration of new components (Holzworth et al. 2010).

In the computer sciences, one approach to overcoming technical model integration issues is the development and deployment of distributed internet-based services (Rizzoli et al. 2001), including the use of Markup languages (e.g. XML: Kokkonen et al. 2003). Foster (2005) used the term "service-orientated science" to describe research that is made possible through distributed networks of interoperating services. Service-orientated computing software is comprised of loosely coupled independent services or components that are able to exchange data over a computer network (Curbera et al. 2002). Component-based and service-orientated modelling thus share many common aspects. A service-oriented computing paradigm has the potential to enable construction of integrative modelling systems that allow interoperability between existing and new models. Disadvantages of deploying a service-oriented approach include: reduced performance that can be caused by large data transfers; reduced reliability due to availability of remote servers; and security issues related to unauthorised use and overuse of the services (Goodall et al. 2011).

Geographic information systems (GIS) and related spatial technologies have in many ways helped integration across disciplines. For example, assessing human-environment interactions at a landscape scale typically requires processing of large amounts of spatial data. Such spatial data can exist in many formats; from grid-cell based land use data to landscape based soil typologies. A structured GIS database provides a formalised approach to store, combine, manipulate and interrogate data to address complex spatial problems in a transparent way. Spatial data infrastructures (SDIs) provide the frameworks of policies, institutional arrangements, technologies, data, and people that make it possible to share and (re-)use geographic information (Craglia et al. 2002). In an SDI, spatial data, including the metadata describing the dataset, are stored; interoperability between data services is followed; and a framework is established covering the copyright, organisational and financial issues (Nebert 2001). The growth in SDIs has been driven by the need to make using and querying data more efficient. Experiences with GIS data and SDIs stress the value of providing clear and transparent metadata about the dataset and models used.

Argent (2004) predicted that as technological integration issues are resolved through the use of web-based techniques and compartment-based modelling that enable substitution, the focus will turn to (more challenging) issues of enabling compatible modelling practices and harmonising understanding within and across research disciplines. These issues will be discussed in the next sections. However, there remain significant technical issues limiting modelling for effective knowledge integration.

Table 1 Lessons from previous integrative studies

Challenge	Example ways forward
Technical issues	• Component-based models that can be extended or restricted to relevant modules • Service-orientated science using distributed networks • Data infrastructures and clear metadata
Knowledge issues	• Use iterative, participatory approaches • Set up institutional structures that enable collaboration • Document creation of new, cross-disciplinary knowledge
Team issues	• Use practical methods to articulate various belief systems • Create environment of mutual trust and respect

3.2 Knowledge integration

Knowledge is more than simply information inferred from data; knowledge is the 'know-how' to transform information into instructions (Rowley 2007). Integrating the breadth and depth of knowledge spanned by multiple research disciplines is essential for effective integrative research, but can be hampered by the different (disciplinary) theories of knowledge. Differences in research methods, work styles, and epistemologies must be bridged in order to achieve mutual understanding of a problem and to arrive at a common solution (Klein 2004).

The literature on modelling with community or policy stakeholders can provide lessons to improve integration across disciplinary knowledge bases. In the SEAMLESS project, for example, IA was seen as a cyclical and participatory process involving scientific, societal and policy stakeholders (Ewert et al. 2009). The role of scientists was to set out the range of possibilities based on state of art scientific knowledge. Scientists then worked with stakeholder input on what was desirable from a societal perspective, resulting in a participatory approach that fed into iterative problem definition processes. In addition to participation of societal and policy stakeholder, its cyclical, iterative approach also contributes to better integrate knowledge between *academic* stakeholders.

Another literature from which lessons can be drawn for integrated environmental research is 'post-normal science' (Funtowicz and Ravetz 1994; Ravetz 2006). Post-normal science considers the diversity in epistemology between disciplines, and the institutional challenges associated with cross-disciplinary research. Post-normal science has found that differences in socio-institutional structures of academia can pose significant barriers to integrative research planning. Indeed, experts who are "ensconced in their protective institution" (Ravetz 2006) may be less able to appreciate the complexities associated with integrated assessment and research. Institutional reform may be required to enable better knowledge exchange between researchers (Frame and Brown 2008).

An important barrier to effective knowledge integration lies in the absence of a unifying framework for integrative research (Rotmans and van Asselt 1996; Tress et al. 2007). Researchers (be they engaged in IA, systems dynamics, SDIs, or other interdisciplinary exercises) can become overly focused on technical information and scientific innovations, which may lead them to ignore the creation of experiential knowledge that crosses subject boundaries. It is important that integrative studies advance scientific technologies, but also manage the process of knowledge integration across disciplinary domains (e.g. Villa et al

2009). In Section 4, we argue that (environmental) modelling can address the issues set out above, by providing a transparent approach to unify disciplinary languages and combine different sources of knowledge and research methods.

3.3 Team integration

Integrative research involves bringing together a range of participants, to produce insights that cannot be gained from a single disciplinary approach. Such research is necessarily a team process, with all its associated challenges. Communication problems at the team level have been found to pose major obstacles in many collaborative projects (Bruce et al. 2004). For example, Moxey and White (1998) state that "entrenched academic territories, derived from disciplinary and data differences, make managing an interdisciplinary team of researchers a non-trivial task". In a more recent integrated modelling example, Kragt et al. (2011) encountered considerable challenges due to different terminology being used between natural scientists and economist, and sometimes limited understanding of other disciplines.

Barriers to integrative research projects may arise when scientists are reluctant to engage with colleagues in other domains. Scientists from differing background may prefer to operate within their own specialised fields, where the same values and models of analysis are used (Lélé and Norgaard 2005). It is important to find ways to overcome defensive routines of researchers (Moxey and White 1998; Sterman 1994). Effective interdisciplinary integration therefore needs to accommodate team-based activities that create an atmosphere of mutual trust and respect (Tress et al 2007). In the next section, we explain how environmental modelling can become a focus of team activity and how environmental modellers can facilitate this.

4. Modelling for effective knowledge integration

Despite widespread recognition of the need for integrative research, the development of practical methods to integration has been limited (Tress et al. 2006, McIntosh et al. 2008). Environmental modellers are well placed to participate in integrative research, as they are experienced in trying to simplify complex, interrelated systems. Modellers are more than software developers (Voinov and Cerco 2010): they often facilitate the integration process and contribute to broader project design.

In this section, we suggest how modelling with interdisciplinary teams can provide valuable tools and processes to advance integrative research. Table 2 outlines a suggested approach to integrative research, facilitated by the development of an integrated environmental model. In this approach, the modeller (or modelling team) is actively engaged in the research programme, and this role changes as the project evolves. The suggested approach may be best suited to a medium-sized project, involving researchers from a few different fields. Large projects, and particularly projects that are aimed at developing decision support tools, will often require more complex organisation and involvement of specialist facilitators and communicators. But even in large projects, modellers must play an active role to ensure that an integrated model is a viable output and adequately captures the knowledge generated.

Table 2 Suggested steps in an integrative research project

Step	Multiple roles of modellers
1. Identifying project objectives and defining research questions	Facilitator
2. Setting up enabling (institutional) procedures and structures for collaborative work	
3. Developing a preliminary conceptual model	Lead
4. Identifying knowledge gaps	Facilitator
5. Disciplinary studies, and studies at the interstices between disciplines, to address specific knowledge gaps	Knowledge broker
6. Refining the conceptual model (iterative throughout the project)	Lead, facilitator
7. Quantification of system components	Knowledge broker
8. Developing a (final) systems model	Technical specialist
9. Application and interpretation of the model	Technical specialist
10. Communication with academic and stakeholder audiences	Facilitator

4.1 Identifying project objectives and research questions

The planning period and the early phases of a project are crucial to the success or failure of integrative research. Project participants need to gain a shared understanding of the problem and the issues involved, in order to formulate the appropriate (scientific and policy) questions that will be addressed. In competitively funded projects, this first stage enables development of a (more detailed) project proposal, in which the intended integrative research scope is defined. Of course, if the modelling activity is to develop a decision support tool, the engagement of decision makers is crucial to clarify the relevant policy issues and decision makers' needs.

A challenge to developing integrative research programmes lies in the infinite complexity of environmental issues. This can 'trick' project teams into considering too wide a range of system components, leading to research outputs that are difficult to relate to an overall integrative research question. If the team is able to agree on a common research question or objective at the start of the project, they will be able to refer back to this objective to distinguish necessary process studies from distractions.

Scientists, including modellers, work within their own specific framework of beliefs and values, with potentially different understandings (perceptual models) of the system under study, and of the questions that should be addressed. Superficial agreement about a common research question (e.g. "How will climate change affect this system?") may hide disagreement about what this question means. For example, a question about 'climate change responses' could be interpreted as referring to the effects of changes in any of a wide range of meteorological, climatic, hydrological or socio-economic indicators; over short or long time-scales; at various levels of detail (e.g. ranging from individual biochemical processes, through effects on organisms, populations, and ecosystems, to social and economic systems). Participants will need to discuss and agree on very precise research objectives and desired outcomes of the project, such as the specific indicators that are to be monitored or predicted, and the time-scales of interest.

The goal of developing a systems model can help to highlight differences in interpretation of the questions being asked, and to clarify objectives. The model becomes a concrete, shared team goal, and the modeller (who has primary responsibility for developing this model) can use this shared goal as the focus for discussion. The modeller thus takes on the role of facilitator as the question for discussion becomes: "what do we want to represent, and what do we need to know in order to achieve that goal?" Specific research questions arise in response to this question, and potential research avenues that do not contribute to the modelling goal can be identified.

It is important to keep the goals of the project in mind, and involve disciplinary experts based on these goals rather than for the sake of interdisciplinarity (Tress et al. 2007). It is often the case that not all of those involved in the initial discussion of the proposal need to be involved in the final project. Clearly defined research questions and outcomes determine the scope of the project in terms of the processes to be modelled and the data that needs to be collected to analyse the problem (Liu et al. 2008).

4.2 Set up collaborative procedures and structures

Once the research scope has been determined, the project team should set up procedures and work structures that facilitate collaboration. Examples of (institutional) constraints that may limit collaboration include the internal distribution of project funds, physical distance between participants, and differing requirements of collaborating organisations.

There are currently not many institutional arrangements that actively enable collaboration. Integrative research projects will need to set-up new processes and structures that enable participation of multiple disciplines. Work packages can be developed to address specific interdisciplinary objectives. (Sub-)Project budgets and timelines should factor in time for sharing of information and knowledge, as well as specify milestones to ensure that this happens. Scientific leadership that creates an atmosphere of interdisciplinary cooperation, based on the science required and the expectations of the team, is vital.

In addition to good project management, collaborative information systems such as wikis (Kane and Fichman 2009) can facilitate ongoing communication. The communication system chosen should be one that all participants are comfortable using, and some training may be required to achieve this.

The role of the modeller in this step is similar to that of any other project participant. As modellers will play a key role in integration, they will have a particularly strong investment in ensuring that good communication strategies are adopted and used.

4.3 Development of a preliminary conceptual model

When agreement about the key questions and model objectives is achieved, a conceptual model is developed that captures the essential system variables, linkages and their dynamics (Galitz 2007; Liu et al. 2008). Developing a shared conceptual model is an effective way to reveal differences in views or values between participants. Conceptual models provide a practical tool to communicate a shared understanding of a system, and can help to visualise sub-domain ontologies, align narratives across project participants, and identify gaps in knowledge. Conceptual modelling is, in essence, the process of communicating and drawing together the individual mental models of the system held by the participants, which will differ according to their values, academic backgrounds, and knowledge systems (Haase 2011).

At this stage of the integrative modelling process, the appropriate spatial and temporal resolutions of the model should also be specified (Jakeman et al. 2006), along with the appropriate degree of model complexity. To achieve a sufficiently parsimonious model, team members will have to be willing to balance breadth and depth of their individual, disciplinary research components. Having to form a concise conceptual view of a process or system will generate knowledge in its own right. Indeed, the understanding gained in this step is one of the most important benefits of developing a model (Cross and Moscardini 1985).

In some disciplines, the system may be well understood on a conceptual level at the outset. Disciplinary sub-projects then typically aim to quantify various system components of the model. The conceptual model can then help team members see how their disciplinary sub-projects will fit into the integrated whole.

In most environmental system studies, however, the initial conceptual model will be largely tentative, both in terms of the disciplinary sub-components, and the relationships between components. In such cases, the conceptual model will need to be revisited several times over the course of the project as knowledge is developed. An iterative modelling process, in which conceptual models are regularly redefined and progressively refined, ensures that new understanding about the system is shared across disciplinary boundaries. It also clarifies what has been learned since the initial conceptualisation of the system (which may otherwise not be clear, as the initial state of ignorance is often forgotten).

The development of a conceptual model is typically led by modellers, who have experience in this as the first step in much of their own work. Conceptual modelling may be conducted through (for example) structured interviews, open discussions, and/or workshops during which stakeholders' understandings of the system (i.e. the emerging conceptual models) are drawn diagrammatically on a whiteboard, using 'sticky notes', or using more formal conceptual mapping techniques. Authors from various disciplines have noted the value of Bayesian Networks as a facilitating tool to visualise conceptual system models (e.g. Stewart-Koster et al. 2010). Mental models may also provide a useful approach to synthesising knowledge across disciplines (Jones et al. 2011). For example, Stone-Jovicich et al. (2011) explored how a formal method for elicitation of mental models can be used to assess the degree of consensus (and identify points of difference) in understanding a catchment system.

4.4 Identification of knowledge gaps

Significant disagreement or uncertainty about the form of the conceptual model, the components that need to be included, or the relationships between components, could directly indicate the presence of important knowledge gaps. If researchers agree over the broad conceptual model (or a component of it), knowledge gaps can be identified by further detailing components of the conceptual model. For example, it may be generally agreed that high phosphorus loads combined with low flow rates can cause algal blooms in a particularly estuary. Further inquiry of this model component may reveal that it is not yet clear how low flow plays a role in this process (is it simply a matter of residence time, or does flow control vertical mixing, light and water chemistry?)..

In a multidisciplinary integrative research project there is an opportunity to fill some knowledge gaps directly, by designing targeted disciplinary studies (see the next two steps). In the course of this third step, project participants may also discover knowledge gaps that exist between, rather than within, disciplines. Such gaps need to be addressed through collaborative, interdisciplinary research efforts.

The interdisciplinary interactions may even lead to discovery of critical new research questions for specific disciplines. Revealing such new science questions during the model development process can stimulate researchers' interest, which may help to encourage contributions needed from disciplinary researchers, and can thus strengthen participation in the integrative project.

4.5 (Cross-)Disciplinary studies to address specific knowledge gaps

Disciplinary and cross-disciplinary studies that address the knowledge gaps identified in the previous stage should be designed to provide information in a form that can be fed back into the developing model. Although disciplinary experts may discover many interesting scientific questions, for the purposes of integration it is important to focus research and data collection efforts on filling the gaps that contribute to the shared modelling goal, and the objectives of the project.

The role of the modeller at this step is to ensure that these shared objectives are understood and remembered. The modeller (or modelling team) needs to have an idea of the model's anticipated input requirements, to ensure that the data generated by disciplinary experts is compatible with the overarching goal.

Since integrative projects, by definition, try to integrate knowledge across disciplinary fields, project teams are faced with significant epistemological challenges (Tress et al. 2006). Modellers need to be aware that different disciplines perceive and understand the world in different ways. Scientists typically use varying standards of evidence – such as field data vs. lab experiments; or precise physical measurements vs. indirect ecological measurements vs. fuzzy socio-economic measurements. An important role for the model developer(s) is to combine such different approaches and act as knowledge broker(s) between the disciplines involved. This requires modellers to have a basic understanding of the sub-disciplinary knowledge cultures, ontologies (how is knowledge organised?), and terminologies (how do sub-domains communicate their knowledge?). Developing a shared model can force participants to agree on a common definition of the system components. Integrative modelling can thus facilitate the development of an overarching epistemology.

4.6 Refinement of the conceptual model

Disciplinary research and the required data collection may take some time. During this time, understanding about system components, and how they fit together, will evolve as new knowledge is developed. Modellers will continue to revise and refine the conceptual model, with the purpose of developing preliminary system models. It is important that participants are involved in the iterative model refinement: to see what has changed (or has been confirmed) as a consequence of the disciplinary studies conducted in stage 5, and what knowledge gaps remain (or what new gaps have been uncovered). This participation is important to capture new system understanding and also to prevent team members from losing a sense of model 'ownership', which could result in project participants dropping out or proceeding with research that may not fit the project's overall objectives.

4.7 Quantifying system components

The results of disciplinary studies and prior knowledge can now be translated into the terms required by the model. For example, if the integrative modelling framework is constructed as a Bayesian belief network, output of single-disciplinary studies will need to be defined as probabilities. For a fuzzy model, components may need to be categorised (e.g. "high", "medium", "low"). For a process-based stocks and flows model, quantification of the system will mean: a) defining initial conditions in terms of the intended modelling measurement units, and b) defining process rates in units that are relevant to the model's parameter values.

This step will require close cooperation between the modeller and disciplinary experts, who may be better placed to explain what types of transformations are possible and theoretically sound. The modeller's role here is to act as an inquisitor and knowledge broker, with the aim to translate findings into the intended modelling units. For example, phytoplankton concentrations can be defined in terms of Chlorophyll-*a* concentrations, or as carbon stores. The modeller will need to question what C:Chlorophyll-*a* ratio can be used (in a particular study case) to convert measured chlorophyll *a* concentrations. It is clear that the modeller will need a generalist system understanding in order to act as a knowledge broker in this stage.

Often, it will be useful to map the disciplinary research results against the element(s) of the conceptual model. Such mapping will help clarify how the information from each research component is being used in the model, and where knowledge gaps will be filled by other methods (such as assumption, inverse modelling, or model calibration).

4.8 Developing the (final) system model

It is at this stage that modellers themselves take on the role of technical expert. The modeller's task is to amalgamate and integrate the information collected by project participants in a final systems model. For best practise, development of models should follow the ten steps discussed by Jakeman et al. (2006). The modeller will by now have a head-start on some of the recommended steps (defining the model purpose, specifying the scope and context, and conceptualising the system), and will have already considered the selection of model features, structure, and parameters as part of the integrative research process. The development of the final model involves an iterative process of identifying model structure and parameter values; verification and diagnostic testing; quantification of uncertainty; and model evaluation (Jakeman et al. 2006). These steps must be conducted with no less rigour than would be required for any single-discipline research component.

4.9 Application and interpretation of the model

The process does not end when the model has been verified, evaluated and judged acceptable. Once satisfied that the model is performing well and is suited to the objectives of the study, it can be used to interrogate the system.

The manners in which the model is applied and the results interpreted are of critical importance to the overall success of the project. Development of scenarios to which the model will be applied will usually require further cooperation between the modelling team, disciplinary experts, but also other stakeholders (e.g. Kok and van Delden 2009). Mahmoud *et al.* (2009) discuss the questions that need to be considered when constructing environmental management scenarios. The authors provide a guiding framework to improve scenario development and assessment.

The model results need to be interpreted in terms of their implications for the various systems under review. This reiterates the importance that the output parameters are relevant and understandable to the multiple disciplinary ontologies. In many cases, the integrative model is an output in itself, as a tool to support research or decision making. The modeller will have a technical expert role in developing (where appropriate) a user interface that allows end-users to apply the model according to their needs.

4.10 Evaluation and communication

The final integrated product (consisting of the model, supporting research outputs from disciplinary studies, scenario results and interpretation) will need to be evaluated in light of the study's objectives. The modelling outcomes should be discussed with the wide, multidisciplinary, group of project participants. Such a 'participatory' approach to project evaluation can ensure whether the model is truly an output of an integrative research effort that project participants can identify with.

Beyond application, the project team has a clear role to communicate the project findings with reference to the original research problem. This requires an active understanding of the capabilities of the model as well as considerable communication skills, which will be discussed in the next Section.

Finally, the integrative knowledge development, and the team learning that has taken place based on dialogues between the project participants is often an important outcome to be communicated to academic audiences.

5 Discussion

In this paper, we argue that environmental modelling can contribute to better coordination and integration of knowledge in integrative research. We describe the various roles and contributions of modellers in helping to design research programmes and bridging gaps between academic disciplines. The framework is most appropriate for mid-sized projects in which specialist knowledge brokers, facilitators, project managers etc. may not be available. While no one person can be an expert in all these professions, 'integrative environmental modellers' are often in a suitably generalist position to take on many of these roles within the specialised context of integrative research projects. A career path for specialist 'integrative modellers'—i.e. modellers who have the necessary facilitation and communication skills to coordinate integrative research programmes—may offer an effective way to strengthen the integrative research that is necessary to tackle complex environmental problems (also Bammer 2006).[b]

Environmental modellers are well placed to develop functional skills across a broad range of areas. This will require modellers to gain training in the communication, leadership, project management, elicitation and facilitation skills required to bring together academic colleagues from various disciplines. Recognising the value of such skills, acquiring relevant training, and gaining an understanding of multi-disciplinary knowledge bases are possibly the greatest challenges for integrative modellers.

[b] We gratefully acknowledge two anonymous reviewers, who provided suggestions along these lines.

5.1 Communication and trust

An integrative modelling research project brings together academics from different backgrounds, such as natural sciences, economics, and social research. Each of the team members may have different ways to express their knowledge (Section 2.2). The use of different languages and methodologies across disciplines can frustrate knowledge integration. Aligning the terminologies between all project participants requires continuing communication and documentation during the model development process. Previous studies have used, for example, controlled vocabularies and common ontologies to document and organise participants' disparate languages (Villa et al 2009). The process of agreeing on a model structure and definition of components can actively support effective communication between team members.

An interdisciplinary modelling project needs integrity, trust, and mutual respect between team members to achieve successful integration and communication (Parker et al. 2002, McIntosh et al. 2008). Project participants should recognise the importance of shared ownership and on-going recognition of team achievements. Barreteau et al. (2010) highlight the importance of transparency in building trust in the process and acceptance of the research outcomes. The project leader (who may, or may not, be the model developer) needs to stimulate on-going sharing of information in the team. Issues of data ownership could arise if disciplinary specialists distrust the ways in which their knowledge and insights are used in the wider integrative process. If the process is poorly handled, team members may feel that their work is being appropriated unfairly. Clear documentation of data sources and the creation of metadata files are valuable in this respect. An environment of trust and active sharing of integrative achievements will build shared ownership of the process and outputs. This will help researchers to see the benefits of the integrative project for their own work. The team will also need to recognise the intellectual contribution of the modeller as a contributor and facilitator in the integrative process.

5.2 Modelling for decision support

Thus far, we have addressed the challenges related to integrative research projects. Our discussion shows how models, and the role of modelling teams, can provide practical tools to overcome barriers to research integration across academic disciplines. However, integrated assessment and modelling research typically addresses real world policy issues (e.g. natural resource management). It is important to emphasise that models that are meant to support improved decision making should not be developed within the 'ivory tower' of academia.[d] Any research project that aims to develop credible and useful decision support tools needs to establish a sound democratic representation in participation with a wide range of stakeholders (e.g. decision makers, community members, land managers). While we attributed development and use of environmental models with a central role in the *research* process, the process will be different when that research feeds directly into integrated assessment and decision-making. Projects may then attribute a less central role to the model *per se*, and put larger emphasis on communication and participation of end-users.

The issues discussed in this paper can help modellers to improve methodological learning about knowledge integration within academic teams. Our paper provides guidelines to overcome integrative modelling challenges within the academic context. Additional layers of complexity, and further demands on integrative team efforts, will need to be overcome before integrative models can grow to be meaningful decision support tools.

6. Conclusion

Integrative research can achieve a better understanding of the complex phenomena affected by natural resource management. Models, and modellers, can facilitate integrative research projects, through definition of a shared goal and concrete project outcomes. They can be useful to visualise (uncertainty in) knowledge, concerns and values of multiple disciplines; provide a scoping framework for project participants; can provide a common goal to focus research efforts; facilitate knowledge brokering across domains and development of a common epistemology; and bring together multiple scientific disciplines by communicating and aligning terminologies across disciplines. Modelling thus provides a communicative tool and a valuable methodology to merge the many structures and processes that are involved in interdisciplinary research projects. Although a model can provide an effective, practical tool to frame and articulate disciplinary knowledge into one framework, integrative modelling poses considerable challenges to team members. Project participants should be aware of the larger time commitments and flexibility required in integrative research. There is a need for commitment from team members to share knowledge and to collaboratively develop the integrated model. Furthermore, team members need to acknowledge that each discipline can have its own set of tools, epistemological basis, methods, procedures, concepts and theories.

Mutual respect and trust between disciplines are instrumental to the success of integrative research projects. Particular challenges are placed on the model developer. In mid-sized projects, there is a central role for the model developer(s) to act as knowledge brokers between disciplinary approaches. This requires modellers to have a generalist understanding about the processes and structures that are included in the model. We do not claim that environmental modellers should be super-humans whose knowledge transcends a multitude of disciplines. However, we argue that modellers are well placed to provide a facilitating bridge between disciplinary knowledge domains[c]. There is a task, and indeed responsibility, for the modelling community to bring together academic colleagues in integrative research teams.

Working across disciplines to create one integrative model involves the development of new tools and processes that are worthy of academic merit and acknowledgement. We encourage modellers to not only report the final projects, but describe the creation of new knowledge and theory during the integrative modelling process. Communicating positive and negative experiences with integrated model development to the wider scientific community will enable others to learn from past experiences and avoid mistakes. Once the scientific community has learned to better overcome barriers to integration within research projects, the modelling process will be better equipped to handle integration challenges outside academia for development of more effective decision support tools.[d]

References

Argent R.M. 2004. An overview of model integration for environmental applications--components, frameworks and semantics. Environ Model Softw 19 (3) 219-234.

Bammer G. 2006. Integration and Implementation Sciences: Building a New Specialisation. In: Perez P., Batten D.F. (Eds.), Complex science for a complex world: exploring human ecosystems with agents. ANU E Press: Canberra.

Barreteau, O., Bots, P.W.G, Daniell, K.A. 2010. A framework for clarifying “participation” in participatory research to prevent its rejection for the wrong reasons. J Ecology and Society 15(2): 1. [online] URL: http://www.ecologyandsociety.org/vol15/iss2/art1/

Bilaletdin Ä., Kaipainen H., Frisk T. 2008. Dynamic nutrient modelling of a large river basin in Finland, in: Prats-Rico D., Brebbia C.A., Villacampa-Esteve Y. (Eds.), Water Pollution IX 111Alicante, Spain.

Bousquet F., Voinov A. 2010. Thematic Issue - Modelling with Stakeholders. Environ Modell Softw 25(11), 1267-1488.

Bruce A., Lyall C., Tait J., Williams R. 2004. Interdisciplinary integration in Europe: the case of the Fifth Framework programme. Futures 36(4), 457-470.

Craglia, M., Annoni, A., Smith, R.S., Smits, P., (eds) 2002. Spatial Data Infrastructures: country reports 2002. Report 5.3.2(b) of the GINIE-project. Publication EUR 20428 EN of the European Commission. Joint Research Centre, p. 68.

Cross M., Moscardini A.O. 1985. Learning the art of mathematical modelling. E. Horwood: Chichester, UK.

[c] Interestingly, Haenn and Casagrande (2007) proposed a similar role for anthropologists as knowledge-brokers and intermediaries in environmental policy-making.

Curbera, F., Duftler, M., Khalaf, R., Nagy, W., Mukhi, N., Weerawarana, S. 2002. Unraveling the Web services Web - An introduction to SOAP, WSDL, and UDDI. IIEE Internet Comput 6(2), 86-93.

de Kraker, J., Kroeze, C., Kirschner, P. 2011. Computer models as social learning tools in participatory integrated assessment. Int J Agr Sustainability 9(2), 297-309.

Ewert F., van Ittersum M.K., Bezlepkina I., Therond O., Andersen E., Belhouchette H., Bockstaller C., Brouwer F., Heckelei T., Janssen S., Knapen R., Kuiper M., Louhichi K., Olsson J.A., Turpin N., Wery J., Wien J.E., Wolf J. 2009. A methodology for enhanced flexibility of integrated assessment in agriculture. Environ Sci Policy 12 (5), 546-561.

Foster, I. 2005. Service-oriented science. Science 308(5723), 814-817.

Frame B., Brown J., 2008. Developing post-normal technologies for sustainability. Ecol Econ 65 (2), 225-241.

Funtowicz, S., Ravetz, J. 1993. Emergent complex systems. Futures 26, 568–582.

Galitz, W.O. 2007. Guidelines for designing conceptual models. In: The Essential Guide to User Interface Design: An Introduction to GUI Design Principles and Techniques, 3rd Ed, Wiley Publishing, Indianapolis.

Goodall, J.L., Robinson, B.F., Castronova, A.M. 2011. Modeling water resource systems using a service-oriented computing paradigm. Environ Modell Softw 26(5), 573-582.

Goodchild, M.F., Steyaert, L.T., Parks, B.O., Johnston, C., Maidment, D., Crane, M., Glendinning, S.E. 1996. GIS and environmental modeling: progress and research issues. GIS World Books, Fort Collins.

Gruber T.R. 1993. A translation approach to portable ontology specifications. Knowl Acquis 5(2) 199-220

Guariso, G., Hitz, M., Werthner, H. 1996. An integrated simulation and optimization modelling environment for decision support. Decis Support Syst 16, 103-117.

Haase, D. 2011. Participatory modelling of vulnerability and adaptive capacity in flood risk management. Nat Hazards, in press, DOI: 10.1007/s11069-010-9704-5.

Haenn, N., Casagrande, D.G. 2007. Citizens, experts and anthropologists: Finding paths in environmental policy. Human Organ 66(2), 99-102.

Harris G. 2002. Integrated assessment and modelling: an essential way of doing science. Environ Modell Softw 17 (3) 201-207.

Holzworth, D.P., Huth, N.I., de Voil, P.G. 2010. Simplifying environmental model reuse. Environ Modell Softw 25(2), 269-275.

Jakeman A.J., Letcher R.A. 2003. Integrated assessment and modelling: features, principles and examples for catchment management. Environ Modell Softw 18 (6), 491-501.

Jakeman A.J., Letcher R.A., Norton J.P. 2006. Ten iterative steps in development and evaluation of environmental models. Environ Modell Softw 21(5), 602-614.

Janssen, W., Goldworthy, P. 1996. Multidisciplinary research for natural resource management: conceptual and practical implications. Agr Syst 51, 259–279.

Jones, N. A., Ross, H., Lynam, T., Perez, P., Leitch, A., 2011. Mental models: an interdisciplinary synthesis of theory and methods. J Ecology and Society 16(1): 46. [online] URL: http://www.ecologyandsociety.org/vol16/iss1/art46/

Kane, G.C., Fichman, R.G., 2009. The Shoemaker's Children: Using Wikis for Information Systems Teaching, Research, and Publication. Mis Quarterly 33(1), 1-17.

Klein J.T. 2004. Prospects for transdisciplinarity. Futures 36 (4), 512-526.

Kok, K., van Delden, H. 2009. Combining two approaches of integrated scenario development to combat desertification in the Guadalentin watershed, Spain. Environ Planning B – Planning Design 36(1), 49-66.

Kokkonen T., Jolma A., Koivusalo H. 2003. Interfacing environmental simulation models and databases using XML. Environ Model Softw 18 (5) 463-471.

Kragt M.E., Newham L.T.H., Bennett J., Jakeman A.J. 2011. An integrated approach to linking economic valuation and catchment modelling. Environ Modell Softw 26 (1), 92-102.

Lélé S., Norgaard R.B. 2005. Practicing Interdisciplinarity. Bioscience 55(11), 967-975.

Liu Y., Gupta H., Springer E., Wagener T. 2008. Linking science with environmental decision making: Experiences from an integrated modeling approach to supporting sustainable water resources management. Environ Modell Softw 23 (7), 846-858.

Mahmoud, M. Liu, Y., Hartmann, H., Stewart, S., Wagener, T. , Semmens, D., Stwart, S. Gupta, H., Dominguez, D., Dominguez, F., Hulse, D., Letcher, R., Rashleigh, B., Smith, C., Street, R., Ticehurst, J., Twery, M., van Delden, H., Waldick, R., White, D. and WInter, L. 2009. A formal framework for scenario development in support of environmental decision-making. Environ Modell Softw 24(7), 798-808.

McIntosh B.S., Giupponi C., Voinov A.A., Smith C., Matthews K.B., Monticino M., Kolkman M.J., Crossman N., van Ittersum M., Haase D., Haase A., Mysiak J., Groot J.C.J., Sieber S., Verweij P., Quinn N., Waeger P., Gaber N., Hepting D., Scholten H., Sulis A., van Delden H., Gaddis E., Assaf H. 2008. Bridging the Gaps Between Design and Use: Developing Tools to Support Environmental Management and Policy. In: Jakeman A.J., Voinov A.A., Rizzoli A.E., Chen S.H. (Eds.), Environmental Modelling, Software and Decision Support. State of the art and new perspectives. Elsevier

McIntosh B.S., Seaton R.A.F., Jeffrey P. 2007. Tools to think with? Towards understanding the use of computer-based support tools in policy relevant research. Environ Modell Softw 22(5) 640-648.

Moxey A., White B. 1998. NELUP: Some Reflections on Undertaking and Reporting Interdisciplinary River Catchment Modelling. J Environ Planning Manage 41, 397-402.

Naiman,R.J. 1999. A perspective on interdisciplinary science. Ecosystems. 2, 292-295.

Nebert, D.D. 2001. Developing Spatial Data Infrastructures: The SDI Cookbook, version 1.1.

Parker P., Letcher R., Jakeman A., Beck M.B., Harris G., Argent R.M., Hare M., Pahl-Wostl C., Voinov A., Janssen M., Sullivan P., Scoccimarro M., Friend A., Sonnenshein M., Barker D., Matejicek L., Odulaja D., Deadman P., Lim K., Larocque G., Tarikhi P., Fletcher C., Put A., Maxwell T., Charles A., Breeze H., Nakatani N., Mudgal S., Naito W., Osidele O., Eriksson I., Kautsky U., Kautsky E., Naeslund B., Kumblad L., Park R., Maltagliati S., Girardin P., Rizzoli A., Mauriello D., Hoch R., Pelletier D., Reilly J., Olafsdottir R., Bin S. 2002. Progress in integrated assessment and modelling. Environ Modell Softw 17(3) 209-217.

Ravetz, J.R. 2006. Post-Normal Science and the complexity of transitions towards sustainability. Ecol. Complexity 3: 275-284.

Raymond C.M., Fazey I., Reed M.S., Stringer L.C., Robinson G.M., Evely A.C. 2010. Integrating local and scientific knowledge for environmental management. J Environ Manag 91(8), 1766-1777.

Reed, M., Cuddy, S.M. Rizzoli A.E. 1999. A framework for modelling multiple resource management issues - an open modelling approach. Environ Model Softw 14 503-509.

Risbey J., Kandlikar M., Patwardhan A. 1996. Assessing integrated assessments. Climatic Change 34, 369-395.

Rizzoli, A.E., Argent, R.M., Manglaviti, M., Mutti, M. 2001. Encapsulating environmental models and data using Java and XML, In: Ghassemi, F., White, D., Cuddy, S., Nakanishi, T. (Eds.), MODSIM 2001, vol. 4. The Modelling and Simulation Society of Australia and New Zealand, Canberra, Australia (2001), pp. 1649–1654.

Rotmans J., van Asselt M. 1996. Integrated assessment: A growing child on its way to maturity. Climatic Change 34(3), 327-336.

Rowley, J. 2007. The wisdom hierarchy: representations of the DIKW hierarchy. J Information Science 33(2), 163-180.

Sterman, J.D. 1994. Learning in and about complex systems. Syst Dynamics Rev 10(2-3), 291-330.

Stewart-Koster B., Bunn S.E., Mackay S.J., Poff N.L., Naiman R.J., Lake P.S. 2010. The use of Bayesian networks to guide investments in flow and catchment restoration for impaired river ecosystems. Freshwater Biology 55, 243-260.

Stone-Jovicich, S.S., Lynam, T., Leitch, A., Jones, N.A. 2011. Using Consensus Analysis to Assess Mental Models about Water Use and Management in the Crocodile River Catchment, South Africa. J Ecology and Society 16(1), 45. [online] URL: http://www.ecologyandsociety.org/vol16/iss1/art45/

Sydelko, P.J., Majereus, K.A., Dolph, J.E., Taxon, T.N. 1999. A dynamic object-oriented architecture approach to ecosystem modelling and simulation American Society of Photogrammetry and Remote Sensing Annual Conference: Portland, OR, USA, pp. 410-421.

Tress B., Tress G., Fry G. 2006. Chapter 17. Ten steps to success in integrative research projects, in: Tress B., Tress G., Fry G., Opdam P. (Eds.), Volume 12 From Landscape Research to Landscape Planning: Aspects of Integration, Education and Application. Wageningen University Frontis Series: Wageningen.

Tress G., Tress B., Fry G. 2007. Analysis of the barriers to integration in landscape research projects. Land Use Policy 24 (2), 374-385.

Villa F., Athanasiadis I.N., Rizzoli A.E. 2009. Modelling with knowledge: A review of emerging semantic approaches to environmental modelling. Environ Modell Softw 24(5), 577-587.

Voinov A., Cerco C. 2010. Model integration and the role of data. Environ Modell Softw 25(8), 965-969.

Wainwright J., Mulligan M. 2004. Environmental modelling: finding simplicity in complexity. John Wiley & Sons Ltd: Chicester, UK.

Wickson F., Carew A.L., Russell A.W. 2006. Transdisciplinary research: characteristics, quandaries and quality. Futures 38(9), 1046-1059.

Winder N. 2003. Successes and problems when conducting interdisciplinary or transdisciplinary (= integrative) research, in: Tress B., Tress G., van der Valk A., Fry G. (Eds.), Potential and Limitations of Interdisciplinary and Transdisciplinary Landscape Studies. Alterra Green World Research and Wageningen University: Wageningen.