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Review Article

Integrated modelling to support decision-making for marine social–ecological systems in Australia

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Policy- and decision-makers require assessments of status and trends for marine species, habitats, and ecosystems to understand if human activities in the marine environment are sustainable, particularly in the face of global change. Central to many assessments are statistical and dynamical models of populations, communities, ecosystems, and their socioeconomic systems and management frameworks. The establishment of a national system that could facilitate the development of such model-based assessments has been identified as a priority for addressing management challenges for Australia's marine environment. Given that most assessments require cross-scale information, individual models cannot capture all of the spatial, temporal, biological, and socioeconomic scales that are typically needed. Coupling or integrating models across scales and domains can expand the scope for developing comprehensive and internally consistent, system-level assessments, including

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higher-level feedbacks in social–ecological systems. In this article, we summarize: (i) integrated modelling for marine systems currently being undertaken in Australia, (ii) methods used for integration and comparison of models, and (iii) improvements to facilitate further integration, particularly with respect to standards and specifications. We consider future needs for integrated modelling of marine social–ecological systems in Australia and provide a set of recommendations for priority focus areas in the development of a national approach to integrated modelling. These recommendations draw on—and have broader relevance for—international efforts around integrated modelling to inform decision-making for marine systems.

Keywords: Australia, integrated modelling, marine systems, social–ecological systems.

Introduction

Models are fundamental tools for assessing the status of marine ecosystems and the effects of human activities in the marine environment (e.g. Borja *et al.*, 2009, 2012, 2013; SoE, 2011). Modelling can inform: (i) mitigation of impacts on marine ecosystems (Barange *et al.*, 2010; Wild-Allen *et al.*, 2010), (ii) maintenance of ecosystem services and their dependent social systems (Fulton *et al.*, 2015a), (iii) adjustment of human activities to avoid or limit actual or imminent impacts, such as in adaptive management (Hollowed *et al.*, 2013; Fulton and Gorton, 2014), and (iv) adaptation of human activities and industries before problems arise for ecosystem services (Fulton and Gorton, 2014; Hobday *et al.*, 2016). Fulton *et al.* (2015b) suggest that a suite of models of different size, complexity and scope can be more effective than individual models in supporting management for complex environmental problems. Models of different complexity can address different needs, but can also be combined as components of a flexible toolkit (Smith *et al.*, 2007; Plagányi *et al.*, 2011a; Hollowed *et al.*, 2013) and can be deployed at different stages throughout an assessment process or project. Maintaining flexibility in modelling approaches is likely to assist in addressing uncertainty (e.g. via ensembles of models) and in providing capacity to tackle new questions as they arise (Hollowed *et al.*, 2013).

Integrated modelling across scales (individual, patch, local, regional, global) and across 'dimensions' (physical, ecological, economic, social/cultural, management) is a related approach, and like toolkits, provides flexibility for supporting decision making across a broad range of contexts, questions and needs (Figure 1). Integrated modelling has been defined to include a set of interdependent science-based components (models, data, and assessment methods) that together form the basis for constructing an appropriate modelling system (EPA, 2008). This is distinct from integrated assessment modelling (Levin *et al.*, 2009; IPCC, 2014; Smith *et al.*, 2016) which is an analytical approach rather than a framework for coupling models across scales and dimensions. Here, we specifically consider integrated modelling to be interdisciplinary (i.e. capturing more than one discipline or 'dimension'—many models typically combine physical and ecological dimensions; Table 1) across multiple scales (e.g. local-to-regional scales). The key benefits of such an approach are the ability to capture two-way effects in the coupling of models as well as feedbacks between dimensions and scales. It also enables predictions to be made at a range of spatial scales depending on the decision-making context.

Recent thematic issues provide some guidance for improving integrated modelling of aquatic ecosystems. Laniak *et al.* (2013, and papers within) provide a useful summary of methods and call for a global community of practise for integrated modelling science and technology. Gal *et al.* (2014, and papers within) consider common problems related to software portability and integration, and provide resources that can help break down barriers between users of different modelling packages. The development of consistent methods (standard protocols) for enabling integration of models—such as those considered by Laniak *et al.* (2013) and Gal *et al.* (2014)—will provide increased opportunities to test the performance and skill (the ability of a model to represent real-world processes and dynamics; *sensu* Olsen *et al.* 2016) of models at different scales, and enable models to be shared more easily across the modelling community. The development of standards may also allow increased efficiency in developing and configuring models for undertaking assessments across many scales.

The Australian marine context

Australia is a marine nation; more than 85% of its population live within 50 km of the coast, and its surrounding oceans have a strong impact on terrestrial climates (NMSC, 2015). Australia's 'marine economy' is projected to grow three times faster than its national gross domestic product over the next decade (AIMS Index of Marine Industry, Australian Institute of Marine Science in NMSC, 2015). The Australian Government's National Marine Science Plan 2015–2025 highlights seven challenges for the next 10 years: marine sovereignty and security; energy security; food security; biodiversity conservation; sustainable urban coastal development; climate change adaptation; and resources allocation. It emphasizes the need to develop and refine decision-support tools that translate knowledge and data into useful information—including realistic projections—for effective decision-making in relation to these challenges. Finally, the report identifies the need for a coordinated national marine environment and socioeconomic modelling system.

Aims

The aim of this review of integrated modelling for marine systems in Australia is to guide the development of a toolbox of integrated models that is well documented and accessible. A key outcome is to identify priorities to meet the need for a coordinated national approach to integrated modelling for marine social–ecological systems—as has been articulated in the National Marine Science Plan. The review is based on an assessment of the literature and input from experts in the Australian marine science community. It summarizes integrated modelling efforts for marine social–ecological systems in Australia, including methods that are used for integration and comparison. It also lists priority needs for facilitating further integration, particularly with respect to standards and specifications.

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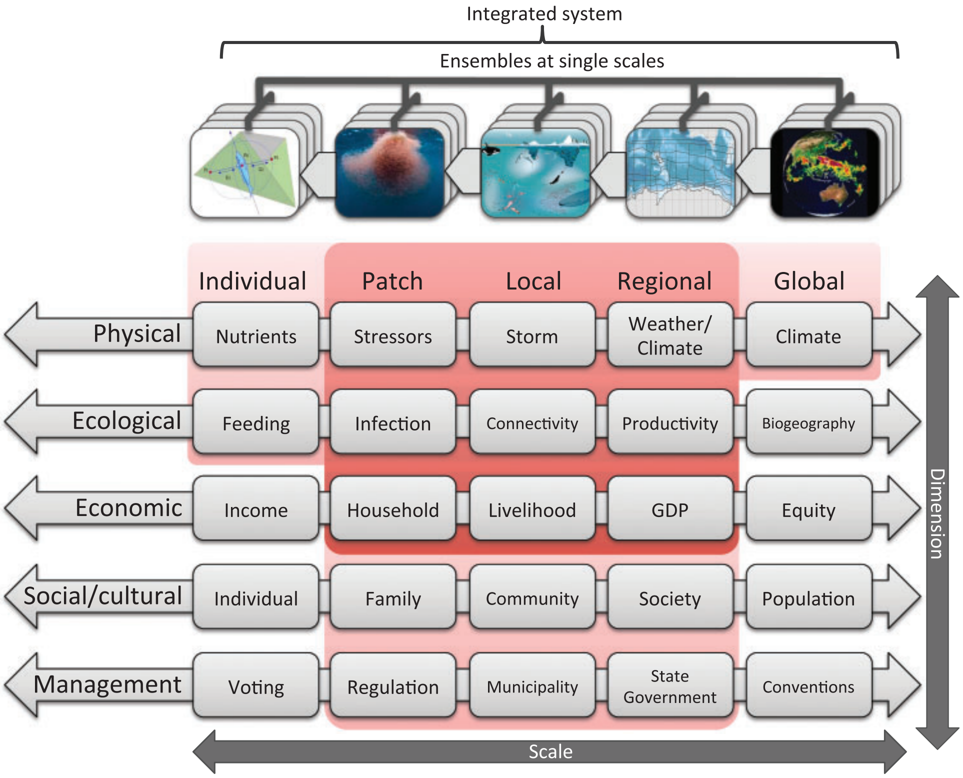

Figure 1. Schema for representing components of integrated marine social ecological systems across five spatial scales (horizontal dark grey arrow) and across five dimensions (vertical dark grey arrow) that loosely align with different disciplines. Examples are provided for the types of processes and factors that may be considered at each level (text in boxes—note that examples provided are not exclusive of other scales, but are usefully considered at the scale indicated). Horizontal light grey arrows indicate the continuum of spatial scales for each dimension (rather than discrete scales). Underlying shading provides a qualitative assessment of the spatial scales and context—that have generally been the focus for modelling work in Australia (darker shading = primary focus, lighter shading = limited consideration only). The images at the top of the figure indicate the potential for ensembles of models at each scale to be connected in an integrated system. The examples shown are: an individual based models for particular species (individual scale); models of swarms/schools (patch scale); foodweb models (local scale); end-to-end models such as Atlantis (regional scale); global climate models (global scale).

Review of integrated modelling in Australia

A review of integrated modelling in Australia was conducted through joint processes of seeking written contributions from invited experts followed by a 2-day workshop (twenty-seven experts from ten Australian research organisations and representing the following fields: physical and climate modelling, biogeochemical modelling, marine ecosystem modelling, socioeconomic modelling, observing systems and databases—eighteen of the twenty-seven contributors attended a workshop in Hobart, Tasmania on 25th and 26th August 2015). Experts were invited to provide 300 word contributions via a wiki (www.soki.aq) that addressed: (i) the development and/or use of models and model output, (ii) integrating different methods (including any standards used for coupling and comparing models), and (iii) suggestions on supporting networks for integrated modelling in Australia, including connecting existing modelling efforts. The specific objectives of the workshop were to (i) summarize the kind of integrated modelling that is currently done in Australia, and methods that are used for integration and comparison, and to (ii) identify what needs to be done to facilitate further integration (particularly with respect to standards and specifications), including helping to develop a 'toolbox' for integrated modelling and enhanced collaboration. Notes and outputs from the workshop were compiled using the wiki and were augmented by an assessment of the literature, where the criterion for consideration of particular models/papers was that they integrated across two or more spatial scales and/or 'dimensions' (as in Figure 1).

Through the workshop and literature review we identified a broad range of methods that are currently employed in Australia for modelling social–ecological systems including, *inter alia*, qualitative and Bayesian network modelling (Metcalf *et al.*, 2011), mass-balance foodweb modelling (Goldsworthy *et al.*, 2013), agent-based modelling (Gray *et al.*, 2006), fluid dynamics for regional ocean currents (Schiller *et al.*, 2014), coupled population dynamics modelling (Little *et al.*, 2007) and dynamic energy budget modelling (Cropp *et al.*, 2014). We also note increasing effort around development of seasonal forecasting models for decision support in marine fisheries and aquaculture (Hobday *et al.*, 2016), as well as decadal-scale predictions for climate (Risbey *et al.*, 2014; Salinger *et al.*, 2016). There are regional differences around Australia in the number of models available—and in modelling effort to date—for marine social–ecological systems (Figure 2). Stock assessment models, which can encompass several stocks, environmental drivers, and harvest sectors are also

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Table 1. Summary of the scope of integrated models in Australia (for models summarized in Figure 2 and using the five 'dimensions' shown in Figure 1).

	1. Bustamante *et al.* (2011), Dichmont *et al.* (2013)	**2. Okey (2006)**	**3. Plagányi *et al.* (2014)**	**4. Plagányi *et al.* (2011b)**	**5. Gray *et al.* (2006), Fulton *et al.* (2011a)**	**6. Bulman (2006), Fulton *et al.* (2011a)**	**7. Griffiths *et al.* (2013)**	**8. Gehrke (2007)**	**9. Gribble (2009)**	**10. Morello *et al.* (2014)**	**11. Little *et al.* (2007, 2009b)**	**12. Herzfeld *et al.* (2015)**	**13. Lozano-Montest *et al.* (2011, 2013)**	**14. Doubell *et al.* (2013)**	**15. Goldsworthy *et al.* (2013)**	**16. Gillanders *et al.* (2015)**	**17. Fulton and Gorton (2014)**	**18. Bulman *et al.* (2006)**	**19. Goldsworthy *et al.* (2003)**	**20. Marzloff *et al.* (2013)**	**21. Matear *et al.* (2013)**
Model name	EwE	EwE	MICE	MICE	InVitro	EwE	EwE	EwE	EwE	MICE	ELFSim	eReefs	EwE	BGC	EwE	EwE	Atlantis	EwE	EwE	TRITON	BGC
Physical			**LR**		**PLR**							**LR**		**R**		**LR**	**R**				**R**
Ecological	**LR**	**L**	**LR**	**LR**	**IPLR**	**LR**	**LR**	**LR**	**LR**	**PL**	**R**	**L**	**LR**	**R**	**LR**	**LR**	**LR**	**LR**	**LR**	**PL**	**R**
Economic	**LR**	**LR**	**LR**		**PLR**						**L**						**R**				
Social/cultural					**PLR**												**R**				
Management	**LR**				**PLR**	**LR**					**L**						**R**				

Numbers given to each paper/model correspond with the numbers used to identify these models in Figure 2. Dynamic components of each model are highlighted in grey (components that are modelled implicitly as fixed terms in a particular model are not considered). Abbreviations in each cell refer to Individual (I), Patch (P), Local (L), Regional (R) and Global (G) scales shown in Figure 1. EwE: Ecopath with Ecosim; MICE: Models of Intermediate Complexity; BGC: biogeochemical.

used for fishery assessments around Australia, but we do not consider these further here. True regional-scale (i.e. whole of Australia) models are currently under development. Plagányi *et al.* (2011a) provide a useful and complementary review of the types of tools that are used to model climate-change effects on Australian and Pacific aquatic ecosystems; this summary is not revisited here.

The models identified in Figure 2 differ not only in formulation but also in scope, where scope refers to scale (individual, patch, local, regional, global), and dimension (physical, ecological, economic, social/cultural, management). We developed a schema for considering where models sit in terms of scope (Figure 1), with processes or functions at each scale-by-dimension combination. This schema recognises that modelling really occurs over a continuum of scales (shown as horizontal arrows in Figure 1) and that the relevant spatial scale may not necessarily be the same across dimensions (i.e. for each row within a column). Indeed, 'scale' may not correspond closely with a geographical zone for human-related dimensions (i.e. economic, social/cultural, and management), but rather with the degree of connectivity and relatedness between individuals. For example, the 'Patch' scale defines a space somewhere between the 'Individual' and 'Local' scales (both of which are relatively intuitive), and captures a range of processes and functions across the different dimensions. In the physical and ecological dimensions, this patch scale might capture different physical/chemical drivers, which can come into play (i) across a heterogeneous patchy benthic habitat (e.g. shear stress varying as a function of reef complexity, and presence of habitat-formers), or (ii) within clusters of individual animals, or plants (e.g. disease transmission/infection). In the economic, social/cultural and management dimensions, the patch scale might describe groups of individuals that interact directly, display similar behaviours, or share identical activities. 'Regulation' as a management process at the patch scale would then pertain to a group of individuals such as fishers that target a certain species, using a particular type of gear or vessels of a particular size class (vs. the local scale which might cover all fishers in a particular municipality). Clearly, multiple examples exist for each component box in Figure 1; a single example per box is provided for illustrative purposes. The schema is intentionally flexible depending on the context, without fixed definitions for each dimension × patch combination.

With respect to the scope of existing models for marine systems in Australia, we suggest that the focus to date (highlighted in red in Figure 1 and summarized in Table 1) has been on the patch, local, and regional scales in the physical, ecological, and economic dimensions, while the social/cultural and management dimensions are represented in highly simplified forms. Figure 1 also shows how ensembles of models at the same scale might be connected in an integrated system. As yet, there are no clear examples of formal ensemble approaches (such as that described by Gårdmark *et al.*, 2013) for marine systems in Australia, although there are several cases where less formal, multi-model approaches have been used to inform management (Johnson *et al.*, 2014; Fulton *et al.*, 2015b).

The schema shown in Figure 1 can be used to visualize four aspects of the formulation and application of integrated models, namely:

(i) The mechanics of model integration (see Figure 3a and discussion below);

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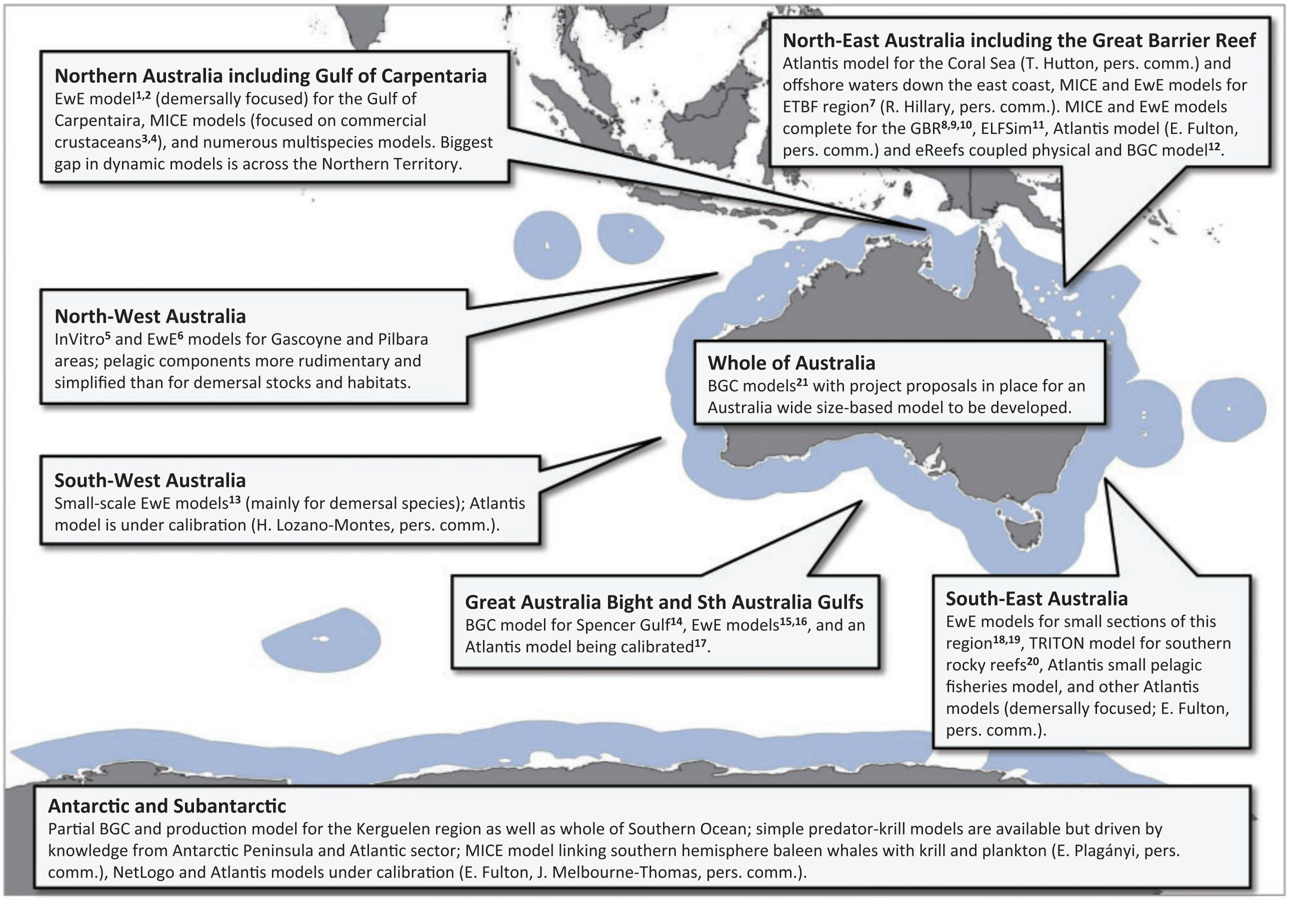

Northern Australia including Gulf of Carpentaria
EwE model[1,2] (demersally focused) for the Gulf of Carpentaira, MICE models (focused on commercial crustaceans[3,4]), and numerous multispecies models. Biggest gap in dynamic models is across the Northern Territory.

North-East Australia including the Great Barrier Reef
Atlantis model for the Coral Sea (T. Hutton, pers. comm.) and offshore waters down the east coast, MICE and EwE models for ETBF region[7] (R. Hillary, pers. comm.). MICE and EwE models complete for the GBR[8,9,10], ELFSim[11], Atlantis model (E. Fulton, pers. comm.) and eReefs coupled physical and BGC model[12].

North-West Australia
InVitro[5] and EwE[6] models for Gascoyne and Pilbara areas; pelagic components more rudimentary and simplified than for demersal stocks and habitats.

Whole of Australia
BGC models[21] with project proposals in place for an Australia wide size-based model to be developed.

South-West Australia
Small-scale EwE models[13] (mainly for demersal species); Atlantis model is under calibration (H. Lozano-Montes, pers. comm.).

Great Australia Bight and Sth Australia Gulfs
BGC model for Spencer Gulf[14], EwE models[15,16], and an Atlantis model being calibrated[17].

South-East Australia
EwE models for small sections of this region[18,19], TRITON model for southern rocky reefs[20], Atlantis small pelagic fisheries model, and other Atlantis models (demersally focused; E. Fulton, pers. comm.).

Antarctic and Subantarctic
Partial BGC and production model for the Kerguelen region as well as whole of Southern Ocean; simple predator-krill models are available but driven by knowledge from Antarctic Peninsula and Atlantic sector; MICE model linking southern hemisphere baleen whales with krill and plankton (E. Plagányi, pers. comm.), NetLogo and Atlantis models under calibration (E. Fulton, J. Melbourne-Thomas, pers. comm.).

Figure 2. Overview of models for marine social–ecological systems that have been developed, or are currently under development, in seven different regions around Australia (after Constable *et al.*, 2015). Conceptual (qualitative) models have been developed for all regions (Dambacher *et al.*, 2012; Melbourne-Thomas *et al.*, 2013). EwE: Ecopath with Ecosim; MICE: Models of Intermediate Complexity; BGC: biogeochemical. Superscript numbers refer to models identified in Table 1.

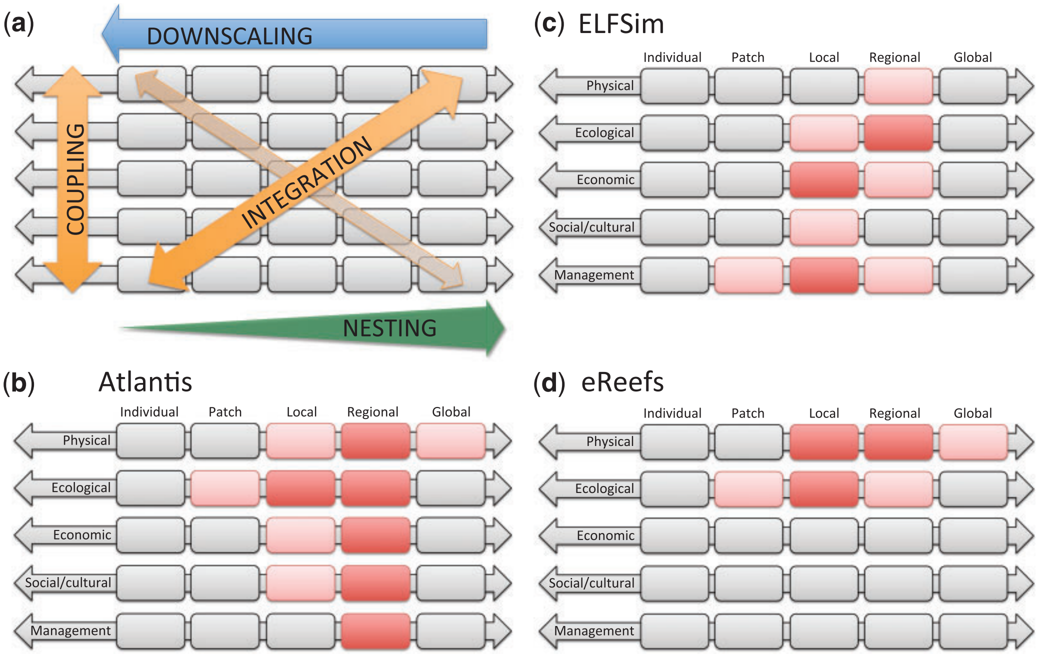

Figure 3. Features and applications of the schema shown in Figure 1. (a) Shows the terminology used for linkages across models at different scales and for different dimensions. (b)–(d) Illustrate how the schema can be applied to visualise the scope of existing models, where darker shading indicates the focus of a particular model, and lighter shading shows levels that are considered but not fully represented. (b) Shows the typical scope of an Atlantis model implementation (Fulton *et al.* 2011b), (c) for the ELFSim model (Little *et al.* 2007, 2009b), and (d) for the eReefs model system (Herzfeld *et al.* 2015).

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(ii) The scope of existing model frameworks (we use the term 'model framework' to mean a particular model's code-base, parameters and any default inputs, as opposed to a particular implementation of that model) (see Figure 3b–d and discussion below);

(iii) The scope of a particular model implementation, existing, or proposed (e.g. for a particular location, such as the Ecopath with Ecosim model for the Great Australian Bight ecosystem; Goldsworthy *et al.*, 2013 and the 'Model of Intermediate Complexity for Ecosystem assessments' (MICE) model of the pelagic ecosystem in the Coral Sea; Plagányi *et al.*, 2014); or

(iv) The scope of a particular question or management need (e.g. management for a particular region, Begg *et al.*, 2015; or marine protected area design, Fulton *et al.*, 2015a).

Features of the schema for model scope that relate to the mechanics of model integration are highlighted in Figure 3a. Model downscaling (where finer scale predictions are derived from larger-scale models) and nesting (embedding smaller scale models in a larger and/or coarser domain) occur across scales, as illustrated by horizontal arrows in Figure 3a. The shape of these arrows indicates that a single model (or output from a single model) might be downscaled, whereas nesting usually refers to the process whereby a finer scale model is 'nested' in a larger scale model (and/or the large-scale model provides boundary conditions). Examples of downscaling include the Climate Futures for Tasmania project (Corney *et al.*, 2013; White *et al.*, 2013) and recent work on downscaling future climate scenarios for Australian boundary currents (Sun *et al.*, 2012); while the eReefs project (Herzfeld *et al.*, 2015) for the Great Barrier Reef includes a nested approach to model resolution and the model domain. The term 'coupling' refers to the joining of models across dimensions (vertical arrow in Figure 3a), so that a model of one dimension will be driven (one-way) or interact with (two-way) models of other dimensions. A typical example is biophysical and socioecological coupling (e.g. the Effects of Line Fishing Simulator, or ELFSim model; Little *et al.*, 2007, 2009). Model integration (diagonal arrows in Figure 3a) occurs across both scales and dimensions.

We provide an example of application (ii) of the schema (as listed above, i.e. to visualize the scope of existing frameworks) for three different model frameworks—Atlantis, ELFSim, and eReefs—that were selected because they are relatively well documented and they span contrasting areas with respect to scope. The Atlantis model framework (Fulton *et al.*, 2011b) is intended as a tool for exploring alternative ecosystem-scale management options using management strategy evaluation (Sainsbury *et al.*, 2000), and includes representations of each significant component of the adaptive management cycle. This framework typically has its focus at a regional scale, extends into the management dimension and includes some local and patch representations for physical, ecological, economic, and social/cultural dimensions (Figure 3b). In contrast, the ELFSim model framework (Little *et al.*, 2007, 2009), which was designed as a decision-support tool to assess harvest strategies for reef fish species on the Great Barrier Reef, extends into the management dimension at multiple scales but is narrower in its representation of biophysical processes than Atlantis (Figure 3c). Finally the eReefs model system (Herzfeld *et al.*, 2015), which integrates marine biophysical models, fine scale coastal relocatable models as well as catchment models, extends across multiple scales with a sole focus on the biophysical dimensions (Figure 3d). We suggest that using the schema to describe and contrast models in this way could support further comparisons of model frameworks and could also be used as a part of an agreed standard for describing and comparing integrated models. We further suggest it can be used to distil the scope of models required by end-users in planning discussions and as such, inform what needs to be developed in the toolbox of an integrated model in order to meet the requirements of end-users.

Key directions for enhanced modelling capability in Australia

Based on our review, we identified three aspects of integrated models in Australia that could be developed further, in particular to better support the applicability of these models in environmental decision-making for marine systems. First, two-way (rather than unidirectional) coupling of processes across scales and dimensions is likely to enhance the realism and predictive capacity of integrated models. For example, physics and biogeochemistry typically drive higher trophic level dynamics in end-to-end models, but feedbacks may not yet exist in models from these higher trophic levels to physical and chemical processes, despite the potential importance of such feedbacks for overall system responses (e.g. nutrient cycling by higher predators; Ratnarajah *et al.*, 2016). Similarly, human use can impact ecosystem (e.g. coral reef) health, which in turn can directly affect industries such as tourism or fisheries; these feedbacks can be challenging to capture in models (e.g. Melbourne-Thomas *et al.*, 2011; Fulton *et al.*, 2015b).Clear specification of the nature of linkages across scales and dimensions—including definition of functions for effect and subsequent response between components—is an important aspect of model development in this context.

A second, related aspect of integrated models that could be developed further is the number of linkages that extend into the social/cultural and management dimensions. Model representations of human components are typically less complex than the representation of biophysical processes in models for marine systems and earth systems more generally (Fulton, 2010; Plagányi *et al.*, 2011a; Mooney *et al.*, 2013). While modellers are moving towards including the socioeconomic components of end-to-end models with the same degree of sophistication as the biophysical components, defining linkages and capturing feedbacks between these components in an integrated system remains challenging. For example, feedback between the human and ecological components of integrated models has conventionally been through a small number of variables (particularly fish catch), although this is now being expanded to include broader social psychological concepts such as sense of place indicators (Wynveen *et al.*, 2010; Larson *et al.*, 2013; E. van Putten, personal communication) and beliefs and values (Boschetti, 2012). Österblom *et al.* (2013) articulate a series of key linkages between human and biophysical dimensions in the context of modelling social–ecological scenarios for marine systems (although scale is not treated explicitly by these authors).

A third and final aspect of integrated models that could be considered further relates to the handling of uncertainty in individual component models, the coupling of models, as well as error propagation (which becomes substantially more difficult as

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Table 2. Operational needs for using integrated models to support decision making for marine social–ecological systems in Australia.

Need	Examples	Recommendation
Standard scenarios for integrated models (where possible—see text)	International Fisheries and Marine Ecosystem Model Intercomparison Project (FISH-MIP, 2015)	Movement towards the use of standard scenarios will facilitate ensemble modelling approaches for marine social-ecological systems
Standard forcings for integrated models (where possible—see text)	Example sources for physical forcings (1) C-CAM (McGregor, 2005) (2) Bluelink (3) Climate Futures for Tasmania (White *et al.*, 2013)	As above—standards for model inputs (forcings) and outputs will facilitate ensemble approaches
Recognition of the ongoing need for human expert skill as a component of integrated modelling toolboxes	See Figure 4	Formalisation around the level of engagement of experts that might be needed to best use models to support decision making in a given application
Protocols for documentation and discoverability of models	UK marine ecosystem model summaries http://www.masts.ac.uk/research/marine-ecosystem-modelling/model-summaries/	Develop protocols for documentation, including articulation of key assumptions for components of integrated models
Mechanisms to acquire suitable data for model parameterisation, fitting and evaluation/validation	IMOS (Integrated Marine Observing System), SOOS (Southern Ocean Observing System), Marine Virtual Laboratory (MarVL)	Establish links between an integrated modelling facility and existing observing systems and data portals for the region

multiple models are coupled or linked together). Comprehensive discussion of these challenges is beyond the scope of this manuscript (see Hollowed *et al.*, 2013 for discussion in the context of climate change impacts on marine fish and fisheries). However, based on our experiences with these integrated models to date, we offer some suggestions:

(i) To the extent possible, models should be fitted or validated using independent field-based data and observations—while few ecosystem models demonstrate any validation or measure of goodness of fit (Allen *et al.*, 2007), it is possible (e.g. Marzloff *et al.*, 2013; Olsen *et al.*, 2016) and should become the accepted best practice.

(ii) Given that suitable data are mostly unavailable for many of the components that need to be included in larger integrated models, and historic information can be of limited use in making forward projections under conditions that have not been observed in the past, alternative approaches to considering uncertainty need to be explored, such as:
   (a) using multiple models of the same system to test whether they predict similar outcomes either qualitatively or quantitatively;
   (b) sensitivity analyses to test sensible alternative scenarios given that a full formal sensitivity analysis is not currently feasible with large models (e.g. Ito *et al.*, 2013; Plagányi *et al.*, 2013); or
   (c) using an ensemble approach (analogous to climate ensemble modelling approaches) in which an envelope of potential future outcomes is projected (e.g. Hill *et al.*, 2007; Gårdmark *et al.*, 2013).

(iii) Retrospective analyses of performance (in which model fitting and/or validation are conducted or updated as new information becomes available), should be strongly encouraged, especially in locations where rapid change is underway so that insights can be gained into the relative strengths of the models to remain informative in such highly dynamic conditions.

Operational needs

While the key directions discussed above contain recommendations for extending the scope and skill of the existing suite of integrated models in Australia, experience to date has also allowed us to identify a set of priority operational needs for improving capability in integrated modelling for marine social–ecological systems in Australia (Table 2). These priorities are:

- The use of standardised scenarios (e.g. shared socioeconomic pathways; Schweizer and O'Neill, 2014; O'Neill *et al.*, 2015) and, where possible, standardized forcing data (e.g. datasets in the ISI–MIP project; Warszawski *et al.*, 2014).
- Recognition of the ongoing need for human expert skill/knowledge as a component of integrated modelling toolboxes, and some formalisation around the degree of engagement of experts that might be needed for a particular problem or in a particular context (see Figure 4 and discussion in text below).
- Protocols for inter-operability and documentation of the components of integrated models.
- Mechanisms to acquire suitable data for model parameterization, fitting, and evaluation/validation.

We recognize that appropriate scenarios, as well as scales and resolutions for forcing data under a particular scenario will be dependent on (i) the management need or intended application of a particular model, (ii) the scope of the model (as per Figure 1), and (iii) its formulation (e.g. grid format, default time steps, number of state variables etc.). Nevertheless, with increasing moves towards ensemble modelling approaches for marine social–ecological systems (e.g. Gårdmark *et al.*, 2013) there is a matching need for standards and protocols around scenarios and input data (as well as model output). Global efforts for model inter-comparison are currently underway, notably the Fisheries

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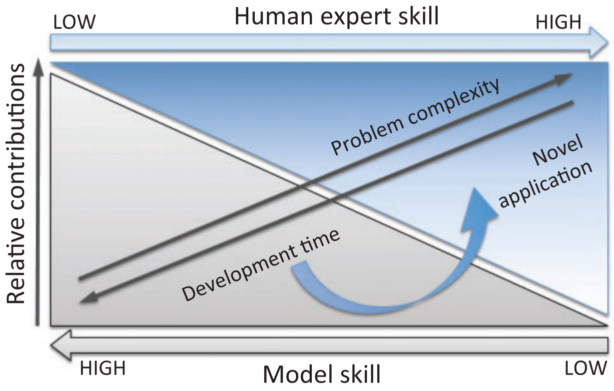

Figure 4. Model and expert skill (domain knowledge and/or technical know-how) components of a modelling toolbox. The relative contribution of model and human expert skill to address a given question may vary and is likely to depend on the development time (or 'maturity') of a particular model as well as the complexity of the model and hence the level of human expertise required to run it and interpret outputs. The pattern of shading in the upper (human expert skill) triangle indicates that a higher relative contribution of human skill requires a higher level of experience for a particular system and/or model type. When a given model is used for a novel application an updated assessment of model skill is required, which involves a movement back to the high human expert skill space.

and Marine Ecosystem Model Intercomparison Project (FISH-MIP, 2015), the MareFrame project to increase the use of ecosystem-based approaches to fisheries management for European fish stocks (http://mareframe-fp7.org/) and efforts within the ICED (Integrating Climate and Ecosystem Dynamics; www.iced.ac.uk/) community to develop standard scenarios for Southern Ocean ecosystem models. Within Australia, sources for forcing data in climate change scenarios for marine ecosystem models include C-CAM (the Conformal-Cubic Atmospheric Model; McGregor, 2005), Bluelink (http://wp.csiro.au/bluelink/), and output from the Climate Futures for Tasmania project (Corney *et al.*, 2013).

As particular models or model toolkits are developed, implemented, and/or adapted, the relative importance of model skill (a model's ability to represent real-world processes and dynamics) and human expert skill (which may comprise domain knowledge, the technical "know how" of using/developing a model, or both) is likely to change (Figure 4). Here, domain knowledge relates to expertise regarding the scope of a model while technical skill relates more to familiarity with the model platform and ability to run and adapt the model. The relative contribution of model and human expert skill to address a given question may also vary and is likely to depend on the development time (or 'maturity') of a particular model as well as its complexity (and hence the level of human expertise required to produce simulations and interpret outputs; Figure 4). Any particular model in a model toolbox could usefully be tagged with a model skill level, which might help avoid situations where a tool from the low end of the tool skill-spectrum is presented as having high skill due to a lack of awareness on the part of the user. While human expert skill can be supplemented by documentation to a point, there is still a need to engage expert users with sufficient depth of knowledge for a particular discipline, or set of disciplines, in order to best use models to support decision making for management. Formalizing the application of expert skill in integrated modelling for decision-making might help avoid cases where this expertise could be suboptimal or even subversive. Importantly, when a given model is used for a novel application an updated assessment of model skill is required, which involves a movement back to the high human-expert-skill space (right-hand side of Figure 4).

Finally, and in support of both standardized scenarios and increased use of toolkits, we highlight the need for protocols in the documentation of integrated modelling projects. In particular, there is a need for a standard format for the documentation of model formulation and reporting of outcomes. Ideally this standard would include relatively simple model descriptions so that policy makers and end users can readily access and understand the variety of models available, and their intended uses (including whether they are intended for tactical or strategic applications). A useful example for the European context can be found at http://www.masts.ac.uk/research/marine-ecosystem-modelling/model-summaries/. There is an ongoing need for improved communication between disciplines that contribute to integrated models. In particular there needs to be greater awareness of the assumptions underlying models for the different dimensions shown in Figure 1 (rows) and how to usefully weight different components for particular applications. This type of collaborative approach clearly requires a broad thinking, flexible research community, as well as longer-term support for projects.

Considerations for the future

We have identified a set of important gaps in available capability together with priority operational needs (Figure 1; Table 2) in integrated modelling for marine social–ecological systems in Australia. As modelling capability, together with demand for models to support decision-making, continues to expand, this is likely to drive increased pressure to expand the scope of existing models. Three important questions in considering whether to add components to existing models or to increase the complexity of particular components are: (i) is the current representation adequate for the purpose of the model? (ii) are there observational data to inform and test these representations? and (iii) is the addition of a particular component or process likely to significantly change the behaviour of a model or the projections of future state? (this can be tested using perturbations, for example). Changing the scale at which a model is applied (e.g. from local to regional, Figure 1) may also mean that new variables or processes come into play. Models will generally have their highest skill level with respect to the theoretical or management question for which they were created, applied and evaluated. New instances targeted for different questions, or with additional components, are likely to require additional evaluation of output against observations. Further, the approach to evaluation and model checking may need to reflect the context, i.e. be more or less stringent for particular applications, cover different time periods or test different aspects of model skill. These issues may cause tension with funding bodies that may not wish to continually fund model development instead of the delivery of outputs. Changes to model formulation may also affect stakeholder/end-user 'acceptance' of models; we note the effects of stakeholder trust in models on the decision making process is an important issue that has not been broadly considered (Boschetti *et al.*, 2012; Lehuta *et al.*, 2016).

Similar considerations apply for modelling decisions that relate to adding linkages between components in integrated

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models, that is, better connecting the boxes in Figure 1. Defining linkages that are robust and realistic is a particular challenge for integrated modelling. We suggest a strategy of prioritising effort into (i) closing simple two-way couplings and links and (ii) working towards addressing large but critical gaps (e.g. links to management components in integrated models; Figure 1). Recent progress with adaptive hybrid models, whose submodels may change their representation based on their own state and the states of the other submodels within the system (to maximize overall performance within the global state space of the system; Gray and Wotherspoon, 2015), may be particularly useful in this respect. However, such modularity can be compromised by model architecture specificity and platform specific approaches (e.g. coding conventions that are difficult to maintain across model platforms). Moving towards the point where it is standard practice to publish code and supporting data will help address this issue.

We suggest that an Australian facility for integrated modelling could not only support standards for documentation and archiving, as discussed above and identified as a priority in the recent National Marine Science Plan, but might also help minimize needs for re-investment since existing model components could be strategically re-deployed for different scales and applications (with the caveats related to model testing described above). Such a facility would usefully be linked to existing observing systems and data portals for the region; namely IMOS (Integrated Marine Observing System) and SOOS (Southern Ocean Observing System). Examples of such projects and initiatives exist in the international community (e.g. the Marine Ecosystem Evolution in a Changing Environment project, MEECE—http://www.meece.eu/ and the Ecosystem Based Management Tools Network http://www.natureserve.org/conservation-tools/ecosystem-based-management-tools-network) and open source coding communities are widespread and well developed (e.g. R www.r-project.org and Blender www.blender.org). An Australian example—currently implemented for hydrodynamics and surface waves—is the Marine Virtual Laboratory (MarVL; marvl.org.au). These examples could be used to guide the development of protocols and the virtual infrastructure needed for model redeployment. In this context, we underscore the importance of maintaining links between the modelling community, the public and policy-makers, and stress the ongoing value of accessible and understandable descriptions of available models and their applications.

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