Multiple-use Management Strategy Evaluation for Coastal Marine Ecosystems Using InVitro

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EXTENDED ABSTRACT

The general objective of the multiple-use Management Strategy Evaluation (MSE) framework is to develop and demonstrate practical science-based methods that support, under existing statutory arrangements, integrated regional planning and management of coastal and marine ecosystems. Multiple-use MSE has, so far, focused on four sectors: oil and gas, conservation, fisheries and coastal development. For each sector, a selection of development scenarios, provided by the relevant interest groups, is represented. These scenarios include prospective future sectoral activities and their impacts, and the sectoral response to management policy and strategies. The agent-based modelling software InVitro is well placed for analysing prospective social and ecological impacts of multiple-use management strategies in a risk-assessment framework such as MSE. An illustrative example is provided to demonstrate the tradeoffs that can be recognised and quantified using the MSE framework. The example explores the implications of a change in management strategy. This change not only has a direct impact on the targeted sectors, but also indirect impacts, not all of which are to be expected.

1. INTRODUCTION

Contemporary Australian society faces major challenges in the management of competing human uses of, and impacts on, natural and transformed ecosystems. Growing urbanisation, as well as industrial and tourism development, has increased the need for government to broker a balance among the activities of many users of the natural and built environment. In meeting these challenges, governments have encouraged an increasingly prominent role for science to provide information and analytical methods for supporting policy and management decisions. Significant issues for researchers are how science is engaged in government decision processes and how scientific advice is used. The past tendency to use scientific advice on an *ad hoc* basis, and to have it absorbed along with many other types of advice in an unspecified way, has prompted scientific research agencies to seek better ways of providing scientific support.

Among the barriers to uptake of scientific principles is a lack of a broad contextual framework within which non-scientists can assess the merits of particular scientific advice. It is to this broad contextual framework that scientists have turned their attention in attempting to communicate with a widening range of stakeholders. Such a framework requires active participation of stakeholders (including management agencies) and facilitates the generation of ideas, identification of problems and approaches for solving them, as well as anticipation of real-world impacts. It necessarily spans diverse fields ranging from biophysical, social and economic sciences, to jurisdictional, political, institutional and managerial processes.

An integrated management strategy evaluation (MSE) framework has been developed within CSIRO in response to their need for comprehensive science supporting coastal and marine environments. The purpose of the MSE framework is to advance the science and tools used to characterise, monitor, predict and manage ecosystems at the whole-of-ecosystem level, by recognising links across socio-economics, physics, biogeochemistry, trophodynamics, population and community ecology, and interactions across time and space scales. MSE has been applied successfully to fisheries, and has recently been developed for providing scientific decision support for multiple use management of coastal regions and estuaries.

The MSE framework is motivated and supported by the needs of management agencies, including:

- conceptual models and methods for bioregionalisation and biodiversity, as well as conservation assessment and mapping in support of ecologically sustainable development (ESD) and the design and monitoring of protected areas;
- observation, sampling and monitoring programs that are consistent and meaningful in their support of ESD of regional ecosystems, including human society;
- biosecurity risk assessment methods and evaluations of management strategies, economic instruments and policies, monitoring programmes, governance arrangements and alternative representations of scientific knowledge;
- socio-ecosystem models used as decision support tools by management agencies and industry;
- tracking of contaminant sources, dispersion and cycling, to assess potential ecological pathways and to determine the fates of selected contaminants; and, as a result of these scientific advances,
- implement management strategy evaluation methods to provide risk assessments, incorporate uncertainties in knowledge and predictions, and test the ability of proposed monitoring and management strategies to deliver desired outcomes.

Critical to integrated MSE is the clear definition of the three main elements: *strategy*, *specification* and *scenario*

A *strategy* is a deliberate existing or planned course of action by one or more people. It may be a management strategy that constrains human use in order to achieve environmental, social and economic objectives. It may be a monitoring strategy (or program) designed to observe and measure the state of the ecosystem through time and space in order to build a set of environmental, social and economic *indicators*. It may be a business or private strategy aimed at achieving business outcomes or personal advantage. It may be a particular set of policy instruments or governance arrangements. It may also be a combination of these and other types of strategies.

A *specification* is typically a computer representation (or model) of the real system. Uncertainty in knowledge usually leads to several alternative specifications of the system, which include the natural ecosystem and relevant components of human society. These specifications represent alternative hypotheses about how the system evolves in response to natural events and human actions.

A *scenario* is a future projection of various factors that impact on the system, but which are not included explicitly or dynamically in any of the computer representations (models) of the system. These factors are represented as data inputs to the model. The factors projected into the future include things such as human population growth patterns, industrial development, climate change and variability, and anticipated changes in recreational or industrial usage of natural resources.

For each combination of a *strategy*, a *specification* and a *scenario*, the MSE provides output data in the form of GIS layers (maps and images) and indicator variables. The display of these data may then be used to compare and contrast similar displays for different combinations of *strategy*, *specification* and *scenario*. Overlays of maps and images build up complete pictures of the spatial characteristics of the ecosystem at particular times. Such overlays can be updated through time to produce animated maps and images that allow the user to view the dynamical evolution of the system under alternative combinations of strategy, specification and scenario.

Specifications, scenarios and strategies can apply to all or part of the integrated social-natural system within the MSE framework, which is depicted in Figure 1. The left side of the figure displays the representation of the social ecosystem which accounts for the biophysical, socio-economic and management/policy/governance components of the system, as well as the performance measures used to evaluate how the system evolves. The right side of the figure displays the various human use sectors which, in this case, include resource extraction, urban and industrial development, tourism and recreation, and conservation and biodiversity. The coloured lines indicate the direction of influence among these components. Broken lines indicate indirect or secondary effects and solid lines indicate direct or primary effects.

2. In Vitro

The computer software for the MSE framework comprises a set of linked dynamical models, a user interface, visualization tools, and a data retrieval and storage capability. An example of a dynamic modelling software used for MSE is the agent-based model "InVitro". InVitro is a spatially explicit agent-based framework containing many embedded sub-models in continuous space with an individually variable time step.

Traditionally there have been two main types of ecological models: aggregate state models and individual based models. Separation of these model types is not always simple. Sometimes, within the latter form of model, the *individuals* represent schools, patches of homogeneous ground cover, flocks, patches of reef, or some other portion of the whole population that could be treated as equivalent to "an entity". From this it is clear that most of these aggregate state models can be seen as a proper subset of the set of all individual (or agent) state models. Consequently, we can treat these aggregate state models as agents within the system. This is the approach that has been taken in InVitro.

InVitro exhibits aspects of both of the traditional classes of ecological models, conceptually embedding them in a time-sharing universe. Agents are allowed to operate at time and space scales appropriate to the nature of the processes in question -- seasonal cycles, for example, are not forced to adhere to time steps more appropriate to larval migration or tides, and the spatial scale of interaction is set at the native resolution of the processes and their associated data sets. This treatment of a general model as an agent within a modelling framework has consequences: models may have inherently different spatial or temporal characteristics, and these must be made compatible. To achieve this, all the agents in InVitro act within the floating point representation of a continuous three dimensional spatial environment, and a temporal environment which arbitrarily has a fundamental step of one second. It would be inefficient to make all the agents run in a lock-step fashion with a temporal step of one second, so a scheduler was used as a means of executing larger blocks of time in a consistent way. Issues of concurrency also arise. What happens when agents are to interact? How are agents prevented from getting less or more time than they are allowed? These questions also arise in the context of operating systems, and the InVitro scheduler does bear a marked resemblance to such an operating system. Like most operating systems and ecological models, it does not exhibit

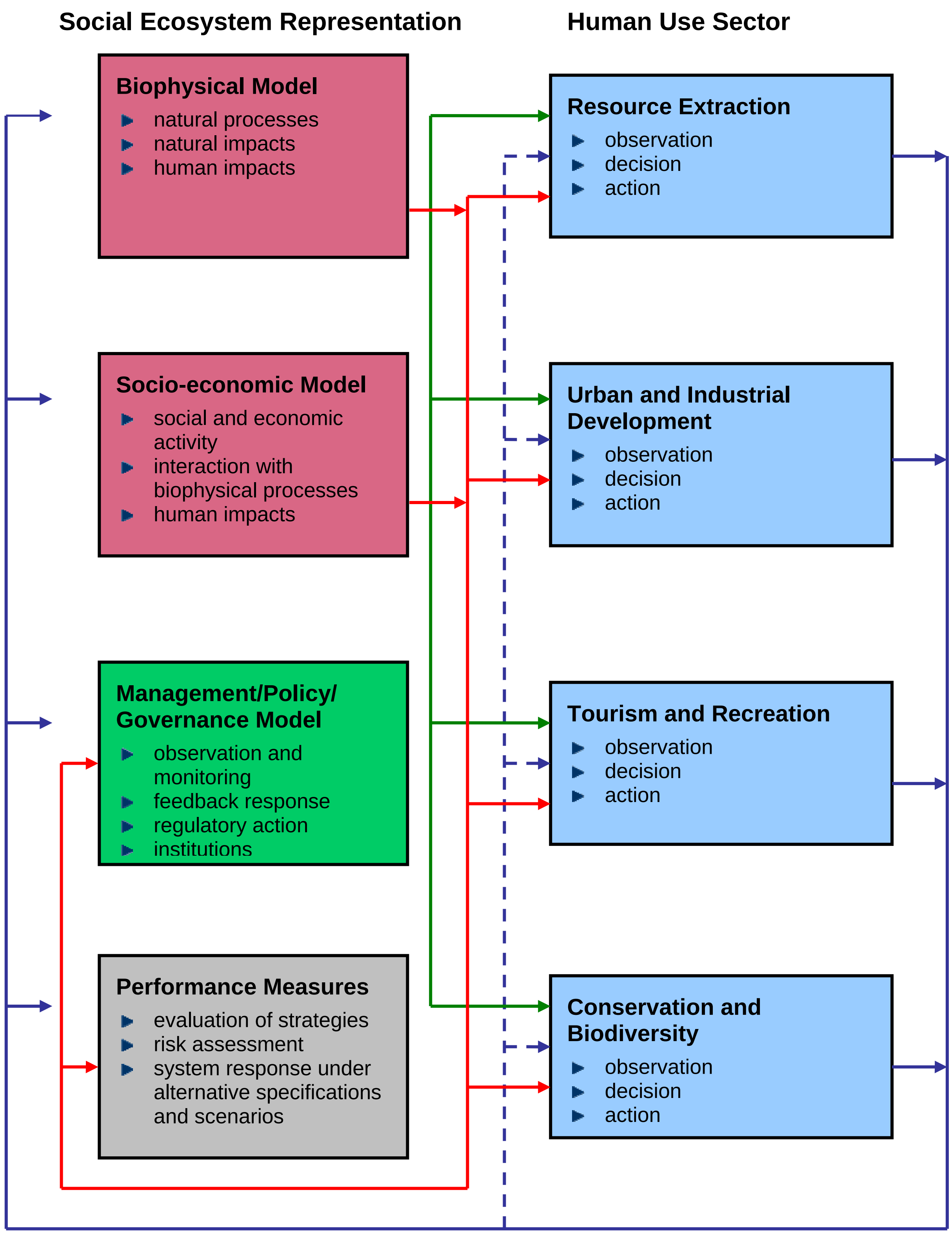

Figure 1. The MSE Framework
The biophysical and socioeconomic components of the social ecosystem characterise the complex real system that evolves through time. Their representation, as well as the representation of the human-use and management/policy/governance components, requires scientific specification and calibration. All of these framework components contribute to the mix of strategies, specifications and scenarios appropriate to the system. The coloured lines indicate the direction of influence among these components. Broken lines indicate indirect or secondary effects and solid lines indicate direct or primary effects.

truly parallel execution, and careful attention has been given to the issues of temporal order of action and interaction to ensure that dynamic processes occur *when* and *where* they should be.

Within the broad MSE-InVitro model there are submodels that reflect the bio-physical and anthropogenic activity in a coastal ecosystem; namely biophysical interactions, fishing, shipping, industrial/coastal development and contaminants. In particular, the software details the sectors of primary interest: oil and gas production, fisheries, conservation, and coastal development. These sectors are engaged with the issues of contaminant release, contact and uptake, sustainable harvest, ecosystem health, habitat quality and damage, economic growth and amenity. These are central to the assessment of various management strategies. Our explicit model components must, therefore, specify inter-group processes at appropriate space and time scales, a task made easier by the flexible handling of these factors by InVitro.

A practical part of capturing these critical scales is achieved in InVitro through the use of a hierarchical agent structure. The most significant division in this structure is the separation of *Monitors*, *Things* and *Environments*. A *Thing* is something which usually has a single location or sphere of influence. Typical *Things* are ships, schools of fish, turtles, and oil rigs. They may or may not be motile, and they can usually be thought of either as an individual or some aggregate representation of individuals (eg a fish school). An *Environment* is characterised by a fundamentally spatial nature - it covers an area, has some significant spatial structure, or its heterogeneous distribution may be of particular importance. Typical *Environments* include biogenic habitats (such as sponge beds and mangrove forests), bathymetry, plumes of contaminants, marine parks and road networks. *Monitors* are possibly periodic things which "happen" to either all the non-*Monitor* agents or some subset thereof. They are characteristically things like biomass assessors, water quality monitoring stations, models imposing recreational fishing mortality and management agents. *Monitors*, unlike other agents, are guaranteed that the agents they are interested in are temporally synchronous at the time the monitor acts.

It is possible to broadly summarise the components of a coastal marine ecosystem using these three classes, with each agent represented by one of these classes. However, processes or entities within the framework may have more than one representation, which may come from any of the three classes or may be multiple representations from within one of the three principal classes. For example, the framework has several quite distinct potential submodels representing fish - especially juvenile fish. These alternative representations can either lie closer to traditional population models or to individual-based models. The choice of representation used in any particular model simulation depends on what it is we wish to model, but each of these representations still needs to address the fundamental aspects of “being fish”. Each of the adult agents ought to be able to spawn to the chosen representation of juvenile fish, for example. The use of a range of alternative representations that interlock with the other components of the model is exemplified by the fish, but not restricted to them. For instance, currents might be represented as a mathematical model of tides, or as a time series of snapshots of the current field; either way they must still be accessible by, and to, the other agents. This multi-faceted, modularised form not only allows for the adaptation of the modelling framework to answering a variety of management questions, but has also facilitated an exploration of alternative model assumptions and structures.

3. MANAGEMENT OF THE AUSTRALIAN NORTH WEST SHELF REGIONAL ECOSYSTEM

Management of the Australian North West (NW) Shelf regional ecosystem is conducted by government agencies at federal, state and local levels. Management agencies correspond to the activity sectors in the main, although all four sectors are regulated by more than one agency. For each of the management issues identified in the course of the NW Shelf Joint Environmental Management Study (JEMS), the following are specified for MSE:

1. *management objectives* expressed in terms of their intended impact on the regional ecosystem and/or local environment;
2. *management strategies* for achieving specified objectives (including identification of feasible control variables, monitoring programs and feedback mechanisms, as well as specification of decision rules); and
3. *indicators and performance measures* from observation and monitoring for assessing how well management objectives have been achieved.

MSE has been carried out while considering biophysical uncertainty, although accounting explicitly for the response of managers to this uncertainty has not been done. Currently the MSE handles management response as part of the matrix of scenarios which evaluate uncertainties in system state, forcing and response. By way of example, we consider ecosystem response under two model specifications, three management strategies and two development scenarios. Space constraints prevent a full description of these in the present paper. Suffice it to say, we examine optimistic versus pessimistic model specifications; present infrastructure versus expanded industrial development; and status quo versus enhanced (improved individual sector) vs integrated (across sector) management strategies. .

4. RESULTS

4.1. Fisheries management

Under the current stock assessment protocol it is possible for the assessment model to become ill informed and diverge from the actual stock size (from the biophysical model) (Figure 2a). With the introduction of a vessel survey, which provides additional information on stock status, the agreement between the stock assessment trajectory and the actual trajectory can be improved substantially (Figure 2b).

4.2. Contamination

Status quo management of contamination means that the sector is effectively unlimited, which can lead to significant contact rates for animals in the vicinity of the outfalls (red line with dots in Figure 3). The enhanced management strategy for this sector ties allowed outfall rates to the level of contamination found in sample animals. If an animal is found with contaminant levels above the regulated trigger point, then the outfall rate is reduced, which ultimately leads to much smaller contact rates (green line with squares in Figure 3).

4.3. Coastal development – capacity and shipping traffic

While port revenue suffers with increasing vessel traffic flow under status quo management, there are clear revenue and risk minimisation benefits from increasing port capacity by 50-100% (Figure 4).

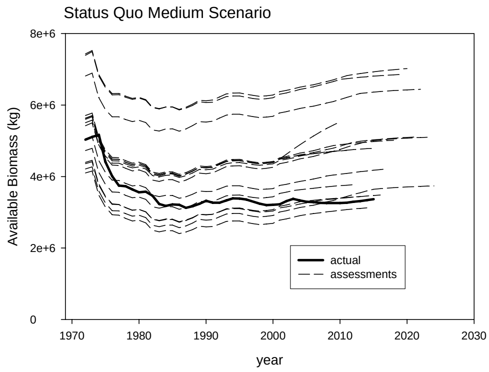

Figure 2a. The estimated (determined from the stock assessment in the management model) and actual stock sizes for the primary fishery target group (lsebae) under the status quo management strategy

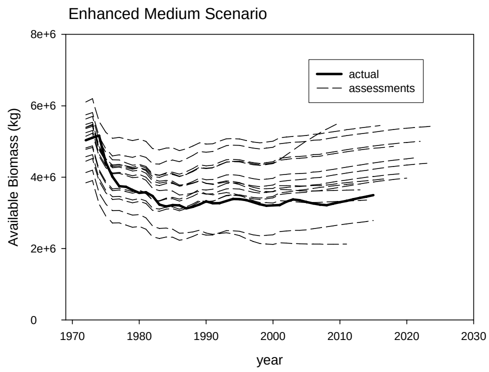

Figure 2b. The estimated (determined from the stock assessment in the management model) and actual stock sizes for the primary fishery target group (lsebae) under the enhanced management strategy

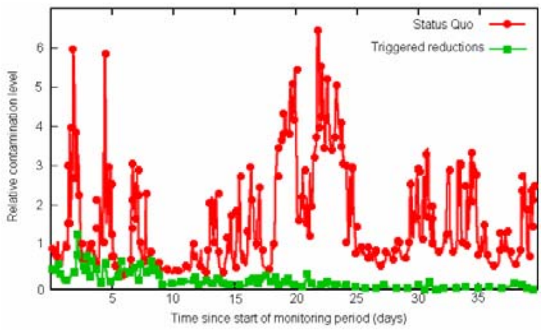

Figure 3. Relative levels of contaminant in prawns within 20km of an outfall under the status quo and enhanced management strategies

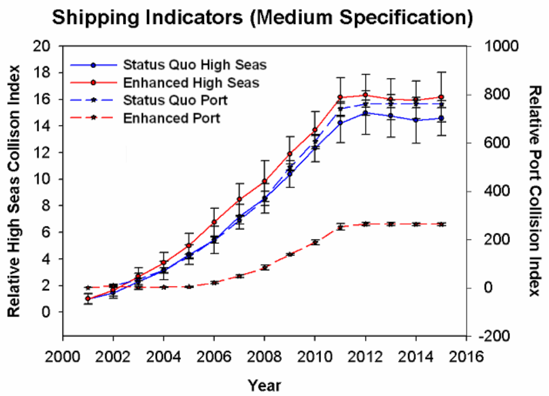

Figure 4. Collision risk relative to historical collision risk for the port of Dampier under the range of port capacity levels allowed by the status quo and enhanced management strategies

5. CONSERVATION IMPLICATIONS

While the enhanced management strategy for contaminant flows has positive conservation implications, conservation must be explicitly included in the management strategy for ecological stocks to benefit. Enhanced contaminant control methods lead to less mortality due to toxic contamination, particularly for juvenile animals (which often live in shallower water than the adults) and the local seabed habitat groups. In contrast the enhanced management of fisheries gives better economic returns, but does not lead to any substantial increases in stock size. It provides, however, better knowledge of the state of the fished stock, which leads to more targeted management and a redistribution of fishing effort. This gives some short to medium term relief to localised areas, but does not always lead to an overall reduction in fishing effort. Only the integrated management strategy, which includes conservation objectives, leads to significantly higher stock sizes and fewer incidental effects on bycatch groups (such as turtles, sharks and the seabed habitat). The enhanced and integrated management strategy for the shipping traffic has mixed implications (due to the requirement for additional dredging). However, as the new channels lie in an area which is already poor habitat for benthic animals, then the negative effects of dredge spoil are more than compensated for by the benefits of vastly reduced potential collision (and major spill) rates.

6. CONCLUSIONS

The MSE framework implemented within the context of an integrated agent based modelling system provides a powerful tool for evaluating the response of systems under a range management strategies, model specifications and scenarios of system dynamics.

The InVitro modelling system provides a highly flexible and modular tool that can simulate the gamut of behaviours of agents ranging from traditional to rule-based individuals. Likewise the characterisation of the environment can be structured in a variety of ways with extensive facilities to monitor impacts. Performance measures and indicators based on management needs and concerns allow stakeholders and managers to play a key role in defining explicit and objective evaluations that can improve their management practices. It also allows participants to appreciate the interactions amongst the different sectors.

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