## View from a Principal Scientist

Western Australia's North West Shelf (NWS) contributes $6 billion to the national economy and is an economically significant land and sea region in Australia. It produces the majority of Australia's domestic and exported oil and gas, and supports commercial fisheries, aquaculture, salt production, iron ore processing, shipping, and a rapidly expanding tourism industry.

The rapid growth of marine industries in and around the NWS has led to complex and somewhat fragmented, management and regulatory structures. The Western Australian Government recognised that a collaborative approach to integrated environmental management was essential to balancing and managing multiple-uses of the NWS ecosystem.

The North West Shelf Joint Environmental Management Study (NWSJEMS) was established in 2000 to develop and demonstrate practical and science-based methods that support integrated regional planning and environmental management of the NWS. A range of agent-based computer tools were developed to model the various complex biological and physical processes for predicting ecosystem and human impacts. However, the novel aspect of the Study was the application of The Management Strategy Evaluation (MSE) approach which linked these tools to provide, for the first time, a way of integrating the key environmental, social and economic processes. All of these modelled processes are complex and poorly understood, and the models used in MSE are designed to represent the uncertainty in understanding and predictions. In this way MSE was used to evaluate the effectiveness of prospective management strategies in achieving defined objectives for 4 major sectors operating on the NWS: petroleum, conservation, commercial fisheries and coastal development. This is the first time an attempt has been made to apply a complex systems science approach in the form of MSE to multiple-use management of a whole regional ecosystem.

The MSE approach provides decision-makers with the information and predictions of the range of consequences from prospective management actions from which to base a decision, given their own objectives, preferences and attitudes towards risk. It deals explicitly with multiple and potentially conflicting objectives, and with scientific uncertainty.

Applications of MSE are often to find a strategy that achieves the stated objectives robustly across all the scenarios that are represented. Alternatively MSE can be used to identify the particular scenarios under which an otherwise desirable strategy fails and to design an adaptive strategy to detect and correct such failure if it occurs in the real world. So the models in MSE have a fundamentally different function to models used solely for prediction. One of the key attractions of MSE is that it can proceed even if the models used contain many uncertainties and give highly uncertain predictions of the future because the emphasis is on finding strategies that can succeed despite these uncertainties.

The MSE models and information inputs are challengingly complex, but the NWSJEMS is demonstrating that the application of MSE to a regional ecosystem is achievable.

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# 13. Multiple-Use Management Strategy Evaluation for Coastal Marine Ecosystems Using *InVitro*

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## Abstract

The Management Strategy Evaluation (MSE) framework has been applied in a multiple-use setting to demonstrate practical science-based methods that support integrated regional planning and management of coastal and marine ecosystems. Multiple-use MSE has, so far, focused on 4 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, including surprises.

## Introduction

Environmental management is characterised by multiple and conflicting objectives, multiple stakeholders with divergent interests, and high levels of uncertainty about the dynamics of and interactions amongst the resources being managed. This conjunction of issues can result in high levels of contention and difficulties in the management process. MSE and risk assessment can assist in the resolution of some of these issues. MSE involves assessing the consequences of different management options and making clear the tradeoffs in their performance across a range of management objectives and uncertainties in resource dynamics (Butterworth et al. 1997; Cochrane et al. 1998; Butterworth and Punt 1999; Sainsbury et al. 2000).

The approach involves: close co-operation and collaboration with stakeholders and management agencies to map broad objectives into specific and quantifiable performance indicators; identifying and incorporating key uncertainties in determining effects on these performance indicators of proposed management measures and strategies; and communicating the results effectively to client groups and decision makers. At a technical level, the MSE framework facilitates dealing with multiple objectives and uncertainties in prediction (Butterworth and Punt 1999). At the implementation level, it fails if it cannot accommodate effective stakeholder participation and acceptance. MSE can be used to develop adaptive monitoring and management strategies, to develop effective management procedures, and to provide guidance on key gaps in scientific knowledge (as exemplified by Sainsbury 1991).

## Methods

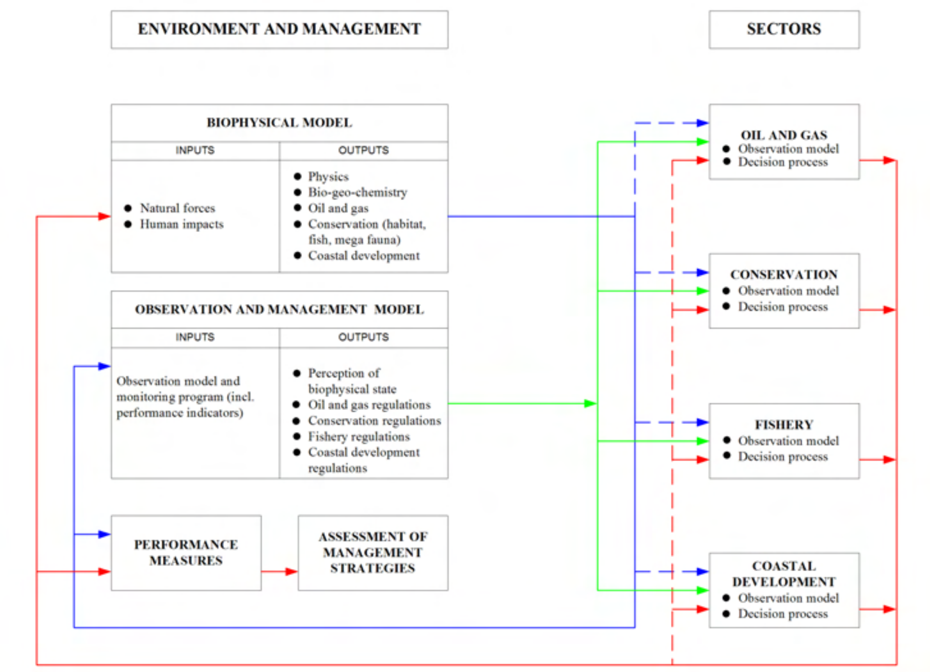
The core computational components of the MSE framework are: a model of the natural system; a model of each of the important sectors of human activity; and a model of how decisions are made, including associated monitoring activities. These models are used together to determine how the natural system might respond to both natural events and human activity. The computer program used for MSE traces the impact of a particular management strategy on the actions of sector firms or agencies, the effect that these actions have on the natural environment and the impact on the performance indicators and measures. In so doing, the program keeps track of details on sector response to management actions, sector performance, the way the natural system responds to sector-specific actions and important random or periodic events, and any strategy-mandated adjustments by managers as a result of sector and/or system response.

Central to the program's output is the choice of environmental and sector performance indicators. The set of indicators includes attributes of water quality, habitats and biodiversity, food-chain integrity, endangered species/habitats/communities, public amenity and ecosystem services.

The implications of a particular management strategy are recorded through many scenarios, each of which involves numerous model runs that evaluate specific cases of management action and specific uncertainty in resource and environmental dynamics. These simulations capture the response of performance indicators to major data, model, and process uncertainties so that it is possible to examine the performance measures that can be used to evaluate how well that management strategy meets management objectives. Multiple simulations with alternative management strategies provide the performance measures response profile with which one can compare strategies.

The flow diagram for the MSE framework is shown in Figure 13.1. The biophysical model emulates the physical and biological features of the natural marine ecosystem, including the bathymetry, currents, waves, type of sea-bottom, benthic flora and fauna, local animal populations and migratory animals. This model also includes a representation of the impact of natural forces and human activity. Outputs from this model include information about the state of the physical environment, about stocks of both renewable and non-renewable resources, and about other important features of the ecosystem. An assessment of variability is also included, thus providing an indication of the implicit uncertainty in models, observations and the bio-physical processes themselves.

**Figure 13.1. The MSE Framework**




The sectors represent human activity in petroleum exploration and extraction, conservation, fisheries and coastal development (which were developed by drawing on work in Sainsbury 1988; McDonald 1991; Iledare and Pulsipher 1999). Key players in each of these sectors observe the natural system imperfectly and make decisions about levels and locations of their activities. Sector activities have an impact on the natural system and also on public management agencies that monitor and regulate the activities of the sectors.

The observation and management model simulates the actions of public management agencies and the response of performance indicators are noted via a simulated management monitoring strategy. In this model management objectives are given quantitative interpretation, as are the management strategies and decision rules. Each of the sectors is then faced with implementation of a management strategy, which constrains their activities and, therefore, their impact on the natural system.

## InVitro

The computer software for the MSE framework comprises a set of linked dynamic models, a user interface, visualisation tools, and a data retrieval and storage capability. An example of a dynamic modelling software used for MSE is the agent-based model called 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 (Silvert 1981; Jørgensen 1994) and individual based models (Caswell and John 1992; DeAngelis and Gross 1992). 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 do we prevent agents 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 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 biophysical and anthropogenic activity in a coastal ecosystem; namely biophysical interactions, fishing, shipping, industrial/coastal development and contaminants. The software details particular sectors of 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 functional groups 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 that 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 mobile, and they can usually be thought of either as an individual or some aggregate representation of individuals (for example, 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 that *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 the NWS system using these 3 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 3 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. This is explained more fully below, but essentially the alternative representations of adult and juvenile fish 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. This 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.

## Environments

*Environment* agents are in some ways the most complex agents in the InVitro framework. These agents' representations are typically either vertex-based (lists of polygons, lines or points) or grid-based (grids or sets of coincident grids). Most of the archetypal environmental characteristics are modelled as *Environment* or classes derived from *Environment*, but a range of other data may also be modelled by these classes, for example, ocean currents, management control zones, primary production, contaminant plumes, and sampling regions. Anything represented using vertex-based agents may exhibit diffusion, advection, self-motility, or some combination of them all. They may also engender new polygons. Any of the *Environment* representations may also be reset at predetermined times to some given state.

It is easiest to convey some of the dynamics associated with *Environment* by example. One of the management options considered in the MSE-InVitro model is the use of Marine Protected Areas (MPAs). In MPAs, there are constraints on fishing and development, and the effects of external development on the habitat and populations within the MPA are monitored. These MPAs may consist of either a list of polygons or a set of time-tagged lists of polygons. In either case the polygons may be subject to independent management decisions (for example, 'The MPA is in very good shape, so we can allow recreational fishing'). The boundaries of the MPA may vary through time to accommodate changes to legislation or administrative policy using time-tagged source data. The presence of these data can prompt the underlying framework to reset the data to known, possibly quite different, conditions at predetermined times.

A particular subclass, *Tracers*, is used to represent both contaminant plumes and, via derived classes, most of the *Environment*-represented biological entities. By deriving the biological classes from the class used to track things like contaminants, the mechanics of the motion and oceanographic influences on the entities are made consistent. This is particularly important when trying to simulate organisms suspended in the water column and the outflow from some stationary source under the influence of tides (as shown by Condie et al. 1999; Walker 1999; Bruce et al. 2001).

## Ecology

The ecology in MSE-InVitro is primarily represented via a combination of *Environment* and *Thing* classes. The main groups of interest include fish (various species with varying life history characteristics, from prawns through to large fish and elasmobranchs), turtles, benthic habitat (beds of sponges, coral, seagrass and macroalgae) and mangroves. The first 2 are usually represented by *Things*, while the latter two are *Environments*. Regardless of the class used, the modelled processes include reproduction, growth, predation (either implicitly in the probability of mortality or explicitly with predator/prey interactions), foraging and larger scale migrations (for example, for spawning).

As mentioned above, there are several representations for some members of the virtual ecosystem. This is most evident for fish, for which there are two distinct representations for adults, and three distinct representations for juveniles. Adult fish may be modelled either as a more-or-less traditional population model (*Population* ), or as schools of varying sizes and locations ( *Fish* ). Juveniles are represented as separate from the adults rather than as simply the youngest age class as in traditional population models; this allows for ontogenetic changes in habitat, diet and behaviour. Juveniles can be modelled as new instances of *Fish*, or as *Larvae* (a mobile, polygonal list based representation), or *Blastula* (a region covering a fixed area of suitable habitat) with different possibilities for interaction with other agents.

The other major part of the ecological submodel in MSE-InVitro are the biogenic habitats ( *Benthics* ), such as mangroves and seafloor benthic communities. These are all currently modelled as sets of polygons with appropriate attributes. These polygons may be irregular and discontinuous, or they can be a fixed grid. If represented by a fixed grid, sub-grid scale processes are represented through a meta-population based size-age model which allows for changes in community structure and coverage within each grid cell. Thus both forms of *Benthic* deal with spatial coverage and the effects of competition, growth, predation and physical destruction.

## Fisheries

There are 4 fisheries represented in MSE-InVitro at present: trawling for scale fish, trap fishing, prawn trawling, and recreational fishing. The first 3 are modelled using explicit vessels with specific process models of the physical act of fishing. The trawlers trawl through the fish or prawn schools catching a proportion of the school and the trappers set their traps to catch fish. The vessels used in the process-based fishery representations choose likely locations for trawling based on past experience, and learn as conditions change, and should their expectation fall too low, they will *prospect for fish*. The steps involved in fishing (the hauling and processing of fish) are also modelled, and there is room for the mechanisms for returning discarded fish to the water as carrion. Turtles, sharks and all other suitably sized animals may also be caught in the net, and benthic habitats suffer damage along a swath beneath the path of the boat and may be cleared completely. In addition, to allow for realistic changes in fisheries behaviour, vessels are parameterised with their real physical constraints (hold capacity, fuel capacity, steaming speed, net characteristics, etc.), so that a change in regulation or technology (say, mesh size, zonation, or turtle exclusion gear) will flow naturally through the model behaviour. Other modelled vessel behaviour includes the explicit use of navigation channels, since this has bearing on the location of marine parks, the potential anthropogenic impact on marine parks and traffic congestion with respect to heavy shipping.

In contrast to the process representation of these fisheries, the recreational fishery is a simple catch equation. The recreational fishery is implemented as a *Monitor* that runs once a week and takes from each school a tithe that is a function of the human population in the nearest towns, distance of the schools to access points (jetties and boat ramps) and the distance from these points to the towns via a road network.

## Other human sectors

Heavy shipping is modelled as a manifestation of economic activity. Ships with deep draughts require deeper navigation channels and resultant spoil grounds, which have their own environmental impacts. Increasing congestion associated with increased production may prompt a range of management responses (controlled access to ports, additional transit channels, jetties/causeways, for example). Congestion is detected and reported to a Monitor which plays the role of the Department of Transport. It sits collecting information about port utilisation, shipping movements, near misses and collisions. Residence time and the size of a vessel in a port are related to the contaminant level within the port (for example, toxins associated with anti-fouling paint and fuel). Ships form the base class for the fishing vessels and share many of their properties. While the ships have largely predetermined paths once they leave the port's control, the courses of all vessels are subject to the control of the management strategy of the *fixture* (oil platforms, islands and shallow water, for example) they are approaching.

The coastal and industrial development sector is to some extent treated as one of the *forcing functions* of the system. One set of runs may proceed on the basis that there will be no increase in industrial activity (oil/gas, salt production, or coastal development), while another may have a 50 per cent increase in production over a given period. This is largely accomplished by increasing contaminants, increasing the economic worth of various activities, changing underlying environment (removal of habitat, causeways, roads, etc.), and increasing the human population.

The development sector is represented in the model by *Ports*, *Rigs*, *Roads*, *Jetties, Contaminant Plumes* (which are emitted by *Fixtures* or are present as a background part of the environment), *Transit Channels* (which may need dredging from time to time), the human population, and some notion of economic worth.

The modelling of contaminants in marine systems is a complex issue. Not only are there many mechanisms and rates of uptake for the diverse toxicants, but the combined effect of toxicants on mortality rates at a given level of contamination is quite complex. Contaminants are modelled as *Environment* agents that have a list of contaminants associated with them. These agents search for all other agents whose spatial extent impinges upon the contaminant agent and they then affect the agent appropriately. These contaminants are not necessarily all toxicants, some may be nutrients. Moreover, the issue of intoxication is fraught with difficulties. Not only are there quite different representations for the various agents (prawns are *Fish* schools with a fairly restricted radius, while *Benthic* sponge beds may cover quite large areas), but the contaminants with which an agent type is concerned may vary widely. Vessels may be quite concerned about contact with oil slicks, but relatively disinterested in contact with bitterns, while, to fish larvae, the bitterns are a poisoned chalice. The source of the contamination can also be important—the contaminant load from food may have a quite different rate of uptake and residence time than contamination through contact. Work is continuing on the implementation of mortality rates for given levels of contaminants across the set of contaminants deemed important for a given agent type. Issues such as dealing with the difference in toxicity from acute environmental contact and that from chronic tissue load are still unresolved. In part, these issues are a matter of extending the amount of data maintained in each individual's state vector and acting appropriately, but deeper problems remain in that much of the information we have about toxicity and environmental effects is available from specific laboratory studies of single toxicants.

There have been many prosaic issues for which solutions have required much effort and time. These include problems not encountered by the modelling group before—for example, getting the model to transparently accept either a single grid of data or a time-series of grids of data that update at the right time, or coalescing 3 different variants of essentially the same class into one class that *Does the Right Thing*. Ultimately however, the work has not only led to a greater understanding of the regional social-environmental system and the interaction of its defining processes, but has increased our understanding and appreciation of relationships among alternative model forms and the dynamics they can represent. It has given us a new perspective on the issue of scale, as well as insight and experience with truly complex systems and their emergent properties.

## Management of the Australian NWS regional ecosystem

Management of the North-West 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:

- *management objectives* expressed in terms of their intended impact on the regional ecosystem and/or local environment;
- *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
- *indicators and performance measures* from observation and monitoring for assessing how well management objectives have been achieved.

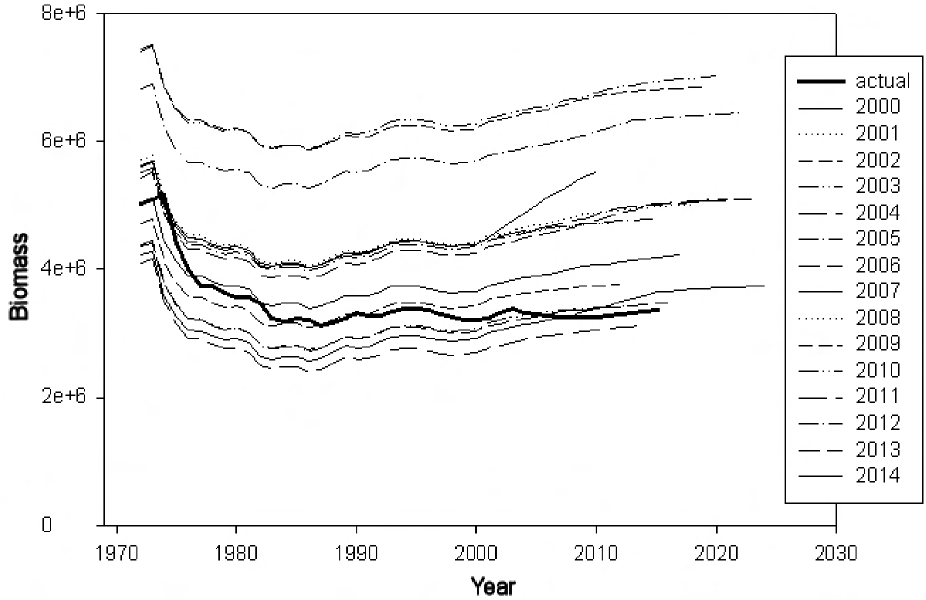
MSE has been carried out while considering biophysical uncertainty, although accounting explicitly for the response of managers to this uncertainty has not been done as yet. Currently the MSE handles management response as part of the matrix of scenarios which evaluate uncertainties in system state, forcing and response. By way of example, we consider ecosystem response under 2 model specifications, 2 management strategies and 2 development scenarios. Space constraints prevent a full description of these in the present chapter. Suffice to say, we examine optimistic versus pessimistic model specifications, status quo versus enhanced management strategies and present infrastructure versus expanded industrial development.

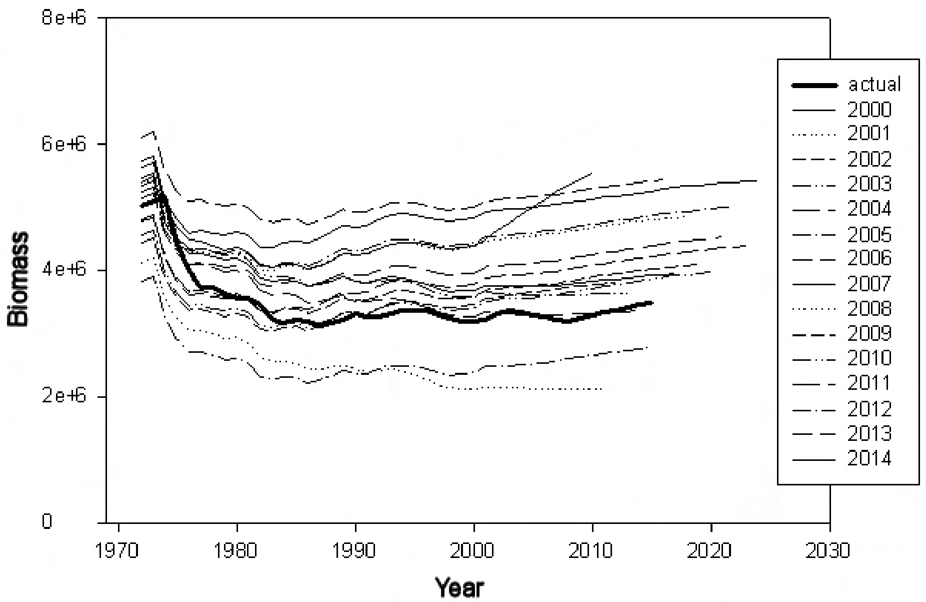
## Results

### 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 13.2, status quo). 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 13.2, enhanced).

**Figure 13.2. Estimated and actual stock sizes for the primary fishery target group (Lutjanids)**



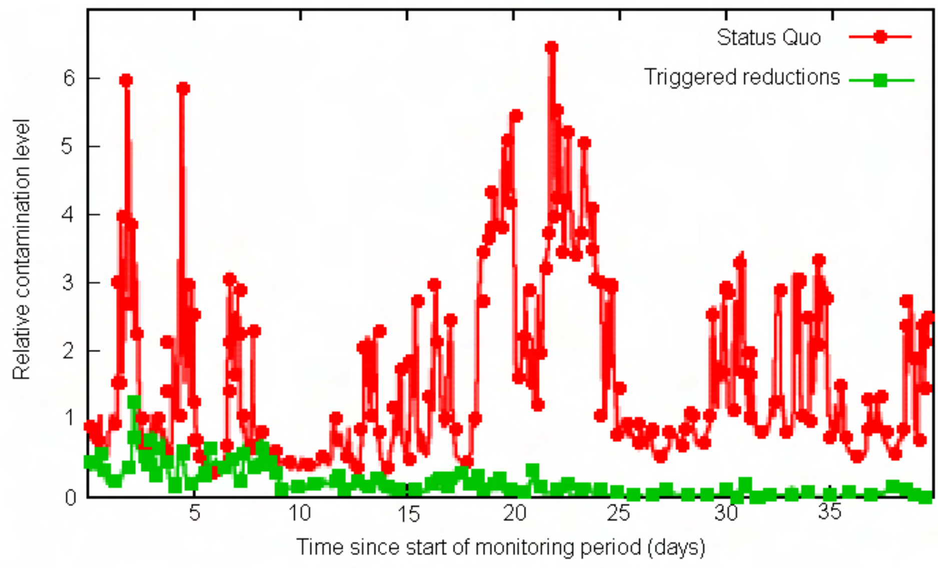




The estimated and actual stock sizes for the primary fishery target group (Lutjanids) under the (a) status quo and (b) enhanced management strategies.

## 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 (line with dots in Figure 13.3). 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.

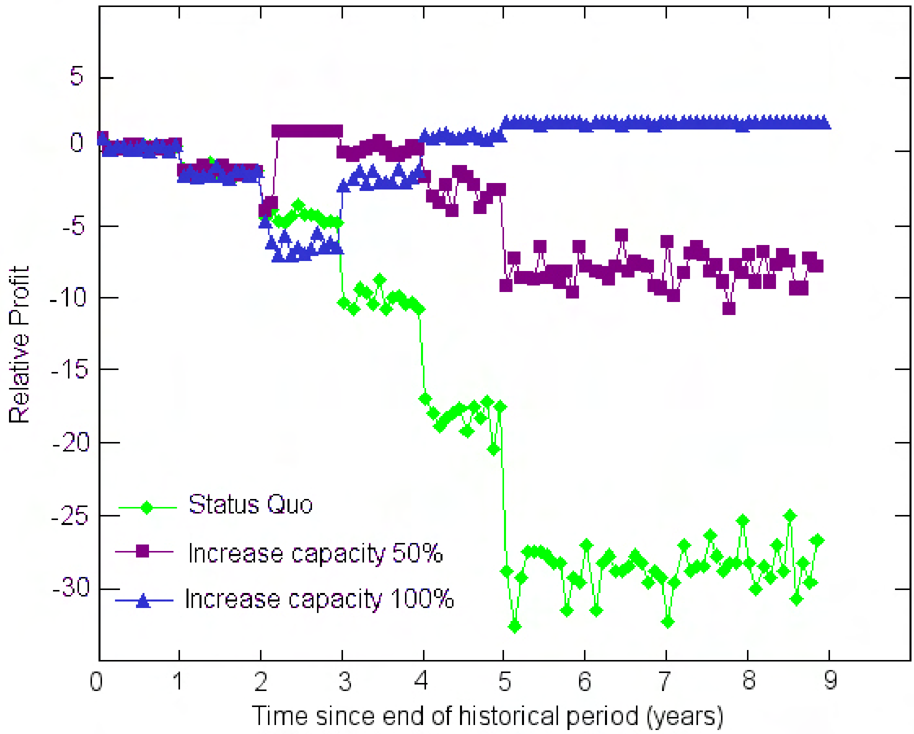
**Figure 13.3. Relative levels of contaminant in prawns within 20 km of an outfall under the status quo and enhanced management strategies**




## Coastal development—capacity and shipping traffic

While revenue suffers with increasing vessel traffic flow under status quo management, there are clear revenue benefits from increasing port capacity by 50–100 per cent (Figure 13.4).

**Figure 13.4. Profit relative to profit at historical capacity for the port of Dampier under the range of port capacity levels allowed by the status quo and enhanced management strategies**




## Conservation implications

The enhanced management strategies for fisheries and contaminant flows have positive conservation implications. A better knowledge of the state of the fished stock leads to more targeted management and less fishing effort, thus leading to fewer incidental effects on bycatch groups (such as turtles, sharks and the seabed habitat). Similarly, the 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.

The enhanced 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.

## 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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