

The Business of Biodiversity

Tela



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Tela is a series devoted to the exploration of the relationships between the environment, economy and society.

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Earthwatch Institute is an international, non-government organisation supporting scientific field research and environmental education. Its mission is to promote the conservation and sustainable management of natural resources and cultural heritage by creating partnerships between scientists, business and the community.

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The Business of Biodiversity:

Applying decision theory principles
to nature conservation

issue

9

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Abstract

Biodiversity is a fundamental part of Australia's natural wealth. It is part of the infrastructure that underpins industries like tourism and agriculture; it culturally defines the people of our island continent and enhances our quality of life. Given the importance of biodiversity and increasing alarm at the loss of this national asset, we have an enormous responsibility to use the resources allocated to biodiversity conservation wisely. This paper is about how we can make smart conservation decisions.

PAGE I

Why is this paper called "The business of biodiversity" when it includes no explicit economics? It is a paper about applying business-like thinking to managing biodiversity. While the currency of business is dollars, the currency of nature conservation is biodiversity. I argue that maximising our long-term biodiversity should be dealt with in a business-like way, with the only difference being the currency. A business-like approach to managing biodiversity involves using clear decision-making tools to determine actions and well-designed performance evaluation to measure the success of those actions. Both the decision-making and monitoring should be couched within the framework of active adaptive management.

Maximising biodiversity should be dealt with in a business-like way, using decision-making tools to determine actions and performance evaluation to measure the success of those actions.

I begin by arguing that many of our attempts to conserve biodiversity have been muddle-headed. I then use three examples to show how we can use decision tools taken from mathematics and economics to make smart conservation decisions. Once the best decision has been made with the information and methods available, the paper looks at the way monitoring (performance evaluation in a research context) can be used to trigger changes to management, and revise the original ideas and data used to make the initial decision.

Monitoring and research are part and parcel of all good business. I discuss the role of monitoring and research within the active adaptive management framework. A good monitoring program should efficiently measure environmental variables that will influence the way we make decisions. The results of monitoring need to be tied back to actions and

to refinement of the theories and models that are used for making decisions. Good monitoring programs for biodiversity management should be framed within rigorous experimental design. Conservation management with a well-designed monitoring program is applied environmental research.

Conservation agencies and managers need to be more accountable for their actions by: enunciating clear goals, using appropriate decision-making tools, measuring and reporting on performance, and showing how their research and evaluation of performance has and will improve future decisions.

Conservation biology needs to incorporate the tools of decision making that take into account constraints, trade-offs and uncertainties to deliver the best possible long-term outcome. Research and performance evaluation must be integrated into any conservation planning and actions. People responsible for biodiversity need to prove to the community at large that they can deliver ecosystem management and conservation solutions that are effective and efficient at achieving goals. Agencies and land managers cannot continue to use public and private resources for conservation without being accountable to their shareholders – the Australian public – for our communal biodiversity asset.

Introduction

Past, present and future losses of biodiversity are considered by many scientists to be Australia's single greatest environmental problem. Biodiversity is the diversity of life; it includes the variety of species, the genes they contain and the ecosystems of which they form a part. In its broadest sense, biodiversity includes all the ecological and evolutionary interactions between the genes, species and ecosystems, including ecosystem processes.

Biodiversity is a natural asset that contributes to quality of life in a wide variety of ways. The contribution of biodiversity ranges from cultural inspiration, aesthetics to medicinal drugs. It is the infrastructure that underpins industries like tourism, forestry and agriculture. The pollination of crops is just one of many biodiversity services fundamental to agriculture, while the koala has been valued at delivering over one billion dollars per annum to the Australian economy. There are many other economic and ethical reasons why we have a responsibility to look after Australia's biodiversity. The loss of Australia's native biodiversity, our variety of habitats, species, and genetic information within those species, is basically irreversible. It will take hundreds of thousands of years for evolution to recover an equally diverse flora and fauna after the current, human-induced, mass extinction. A decline in ecosystem functions will incur more immediate costs although ecosystem functions may recover faster than species diversity. This loss of Australia's natural biological wealth will bewilder future generations of Australians – it contravenes our notion of inter-generational equity; it is robbing our children of opportunities.

Biodiversity includes all the ecological and evolutionary interactions between the genes, species and ecosystems, including ecosystem processes.

This paper is not another lament for biodiversity loss, nor a plea for more spending on nature conservation. There are numerous books and articles that cover those issues. This paper is about our failure to manage our biodiversity conservation efforts efficiently and effectively because of a lack of clear thinking and vision. First I discuss examples of our current approach to biodiversity conservation. Then I present a new way of tackling the problem, which has begun to emerge in recent years. This new approach is about smart decision-making. It utilises the decision theory tools of engineering and economics. It is a problem-solving approach that integrates decision-making with performance evaluation

and research, within the framework of active adaptive management. This paper is about the business of conserving our biodiversity.

This paper is about our failure to manage our biodiversity conservation efforts efficiently and effectively because of a lack of clear thinking and vision.

The title, the business of biodiversity, may suggest that this is a paper about the interface of economics and natural resource management. It is not. How to value biodiversity, and how much time and money to spend protecting it, are important questions that are not discussed here. Instead I assume that external forces fix the amount of time and money invested in biodiversity conservation. Given this economic constraint, the question remains: how should our available time and money be spent to best effect and most efficiently?

1. Some Fundamental Problems in Biodiversity Conservation

There are a number of fundamental questions that need to be answered to manage our biodiversity. These problems range from the micro-management to the macro-management scale. At the micro-management scale the objective is generally easy to state and the problem is confined to one individual or a small group. For example we may be interested in answering the following questions. Where should a shelter belt be planted on a grazing property? What weed should be eradicated from a small patch of bush first? How many nest boxes need to be erected, and where, to maximise the breeding success of the Red-tailed Black Cockatoo? How can the flow regime of a creek be restored? What sort of forest management is needed for the long-term persistence of Leadbeater's Possum?

At the macro-management scale the problem is usually one of resource allocation between many individual programs, each of which will have many small-scale decisions to make. How should threatened species recovery funds be allocated amongst Australia's species? How much should be invested in different conservation programs of a state-based national parks service? Within a large multi-use national park how should the budget be allocated between fire management, feral predator control and visitor management?

Many problems have not been efficiently solved because the problem is not properly posed, objectives are not clearly stated, or relevant ecological theory and data are not used within a decision-making framework.

In this section I introduce some of these fundamental questions and examine how they have been addressed in the past. I argue that many problems in biodiversity conservation have not been efficiently solved for three reasons.

- The problem is not properly posed.
- Objectives are not clearly stated.
- Relevant ecological theory and data are not used within a decision-making framework.

I do not intend to imply that these arguments have not been put before. Many Australian scientists and government agencies have been world leaders in the development of systematic

conservation planning and ideas about landscape management. Despite their efforts I believe there is still considerable room for improvement in the application of clear thinking to conserving biodiversity.

As examples, I consider three problems. The first two are at the micro-management scale. Where should habitat be restored on one or two properties to maximise biodiversity benefits? How should decisions about a captive breeding/reintroduction program for a threatened species be made? The third problem is at the macro-management scale. How should resources be allocated between recovery programs for different threatened species?

Habitat restoration in landscapes

Where in the landscape should habitat be restored to maximise biodiversity benefits? Across much of southern Australia (and parts of northern Australia) many landcare and practical conservation groups are expending efforts to restore habitat on properties and in catchments to stem the tide of biodiversity loss and rehabilitate deteriorating ecosystem services. This question of landscape design is pivotal to these action-oriented groups and the programs, like the Natural Heritage Trust, that provide some of their resources. Here I consider a single land manager who has sole control over a single property. The ideas can be scaled up to groups of properties, catchments and even large bio-regions.

What is the objective? This a fundamental question that is rarely answered.

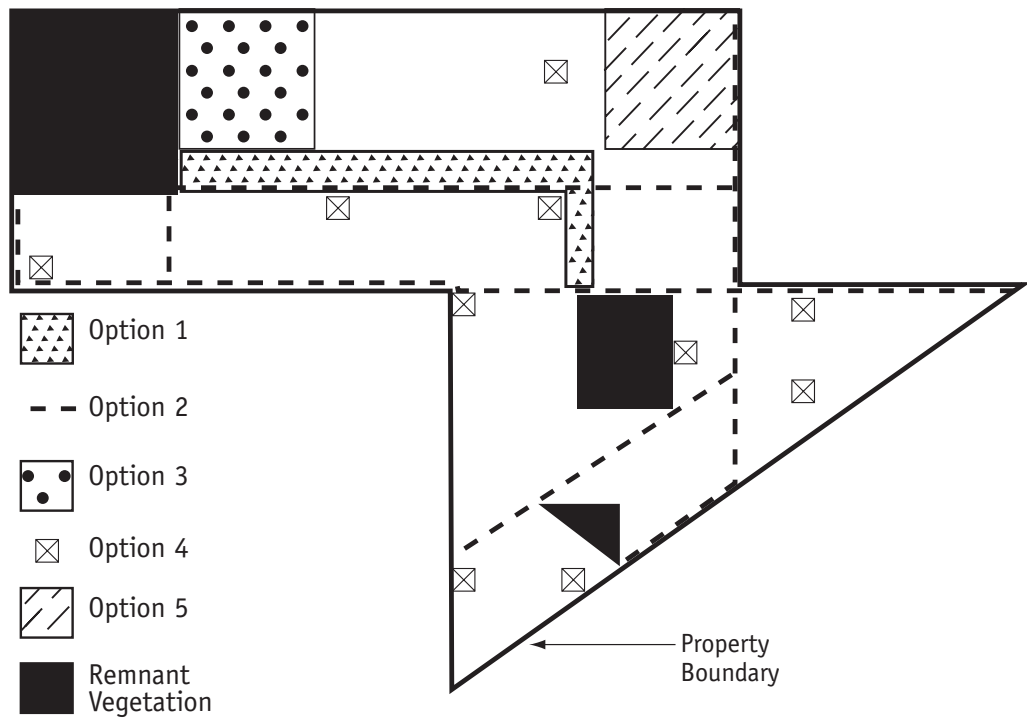
A land manager interested in habitat restoration has finite resources and tight financial constraints. Given these constraints, assume that she has decided to restore a certain number of hectares of native vegetation on her property. The question for the economically minded conservationist is: Where should that restoration occur to maximize long-term biodiversity benefits? To make the problem more real, let us consider a specific example.

Farmer Jill is interested in restoring 100 ha of native vegetation on her sheep/wheat property. Let us assume that all of the remnant vegetation in the property is currently in three patches, one 150 ha, one 60 ha and the other 20ha (Figure 1). Assume Jill's primary objective for the restoration is to retain and recover as much biodiversity as possible in the long term. (Other objectives like agricultural productivity, aesthetics and soil and water management will be

ignored. One can use a variety of multi-criteria decision-making tools to include these other objectives). Advice from other landowners, state agencies, and local naturalists is conflicting. One source is obsessed with wide vegetation corridors, and suggests connecting the two largest patches with a single corridor. Another likes the idea of a dispersed network of narrow vegetation corridors, linking all the remnant patches, but also linking this property to vegetation in other properties and providing additional strips of trees. A birdwatcher tells her that there is a small population of Malleefowl in the 150 ha patch, and that unless the patch is increased to 250 ha the small population will expire. A local plant enthusiast recommends restoring ten small (10 ha) patches of native vegetation throughout the property with a focus on creating a representative sample of the different vegetation communities that once occurred over the property. Finally a geographer notes that one of the vegetation types that once occurred in the north-east corner of the property is nationally endangered. The geographer suggests restoring the corner that once was vegetated by the endangered habitat. He argues this will best promote conservation objectives at a national scale.

All five scenarios can be supported by sensible, but very different ecological arguments. In the 1980s, when ecologists and conservationists in Australia and around the world were obsessed with habitat corridors, option 2 would almost certainly have been fancied. As ecologists discovered that narrow vegetation corridors are hard to manage and promote edge species that are generally common elsewhere, the emphasis may have shifted to option 1. In the 1990s the notion of conserving a representative sample of habitats gained popularity. This philosophy underpins vegetation clearance legislation in some states and was a fundamental plank of the Regional Forest Agreements. At a local scale the notion of conserving representative habitats would favour option 4, a smattering of small vegetation blocks. If Jill views her responsibilities to biodiversity conservation at a regional or national scale then she may take the advice of the geographer and opt for restoring as much as possible of the nationally endangered habitat, option 5. Classical island biogeography theory, which dates back to the 1960s, would favour the big is better approach implicit in option 3. Given that the question of where to restore habitat is such a common and fundamental question all over Australia, is it not a concern that so many plausible options exist? Surely the vast body of ecological theory and data has something to say about what Jill should do. Let us briefly consider some of the theory and data that exist.

Figure 1. A hypothetical property showing remnant vegetation and five different plans for restoring 100ha of locally indigenous vegetation. Each option reflects influences from a different mixture of conservation theories.



Option 1 connects the two largest blocks of remnant vegetation with the widest corridor

Option 2 emphasises the importance of numerous narrow corridors

Option 3 makes the biggest remnant bigger

Option 4 adds many small patches to represent the variety of former soil and vegetation types equitably

Option 5 adds a new patch to represent a nationally endangered vegetation type

There is a range of theories that generally address the question of optimal landscape configurations, beginning with “island biogeography theory” (MacArthur and Wilson 1962), and more recently, with “metapopulation theory” (Hanski 1999) and “source–sink theory” (Pulliam 1988). Let us see what answers these theories provide to the question of optimal landscape reconstruction.

Island biogeography theory generated a series of rules that one can find in any conservation biology textbook, most notably:

- Big reserves are better than small reserves. This supports option 3, and to a lesser extent option 5.
- Connected (or close) reserves are better than unconnected reserves. This supports options 1 and 2.

Metapopulation theory deals with a single species. It is a theory of how fragmented populations behave and tells us that there are several ways to increase the likelihood that a fragmented population of single species will persist. Given the vast array of species in remnant vegetation, this means that from a practical point of view it is only possible to consider just one or two species that are believed to be significant – like the Malleefowl. The theory suggests several ways in which a metapopulation of a single species can be secured.

- Decrease local extinction rates which usually means making patches bigger (option 3)
- Increase between patch colonization rates which can be achieved through corridors (option 1 and 2)
- Spread the risk of species disappearing from all habitat patches by having more habitat patches. In this example this philosophy favours option 4 and to a certain extent option 5.
- Increase the number of patches occupied by any species. This rule would favour adding corridors (options 1 and 2), or actively moving species from one habitat patch to another which is not a habitat restoration strategy.

Source–sink theory is also concerned with single species and emphasizes the importance of identifying habitat where population growth rates are consistently positive. Hence the rule:

- Protect source populations and ignore sink populations. Practically this information is rarely available.

There is also the empirically derived conservation rule that argues against habitat edges:

- Because habitat edges favour common species, and present management problems, reserves with a low edge to area ratio are better than reserves with a high edge to area ratio. This argument would favour option 3 and to a lesser extent option 5.

More recently some ecologists studying fragmented ecosystems have argued there is a patch threshold size for each species. Below the patch threshold size a species is unlikely to persist. If a particular species is of concern and the patch threshold size is known, then that information can be used to determine restoration priorities. Indeed this is the argument that the birdwatcher is using to advocate option 3. However, there is considerable debate as to whether such thresholds exist and what they are for particular species.

Finally there has been a growing trend to favour proportional conservation of different habitats – the idea of equitable representation of habitats. This philosophy tends to ignore issues of size and shape and could be used to argue for options 4 and 5.

The different theories suggest different habitat restoration options. For some of the theories it is not clear which option should be favoured. If Jill had decided to resolve her problem of conflicting advice by learning more about the science of ecology, she would have become deeply frustrated. The reason these conservation biology theories have limited utility for such practical decisions is that they have not been couched within a decision-making framework. The theories were never intended to solve problems. To solve a problem we need to embark on a different path, a decision-theory path where the first task is to state a clear and measurable objective. In this example Jill first needs to determine what biodiversity she is trying to maintain or recover. What is the objective? This is a fundamental question that is rarely answered. Later in this paper I argue that stating a clear objective is step one in solving a land management problem, step one in the decision-making process.

Even when an explicit objective is specified, none of our theories provide explicit predictions as to how the objective is most likely to be met. If the biodiversity objective is to minimize the likelihood that Malleefowl become extinct, alternative habitat reconstruction scenarios could be tested in a population viability model (something which is rarely done given the lack of data and the demands on the time of managers). Even if the resources for population viability analysis were available, why single out Malleefowl from a myriad of potential candidates?

If the biodiversity objective were to restore a representative sample of habitats, and a map of the original vegetation types of the property exists, this objective could be met. However Jill would not know exactly where to do the habitat restoration for each vegetation type. There would be too many options and no rules about the size, shape and distribution of patches to enable us to choose between them.

Given the vast conservation literature on habitat fragmentation generated over the past decade, it is an embarrassment that so little of this research (empirical or theoretical) provides answers to the most basic practical questions concerning optimal habitat reconstruction for biodiversity conservation. The theories generate a list of generally useful things the land manager might do, but they offer little insight into how best to choose among the alternative options. It is no wonder that our different experts gave different advice; it probably depends on which of the many theories they have heard, and how those theories were presented. Given the importance of this problem in Australia now, I make no apology for belabouring the example. The remaining examples will be shorter. I return to this example at the end of the paper and suggest a program of active adaptive management (research and management combined) to provide answers for this pressing dilemma.

Reintroduction of threatened species

A second common question in conservation biology relates to the problem of reintroductions and captive breeding. There is a large amount of science focused on reintroduction and captive breeding but few protocols exist for answering basic questions like:

- When, in the decline of a threatened species, should some individuals be captured and a captive breeding program initiated? For example as the number of Californian condors in the wild declined, when was the best time to capture all or some of the remaining wild individuals.
- How many individuals should be captured to found a captive breeding program? If a captive breeding program is started, how much of the wild population should be captured, and what ages and sexes should be targeted for capture?
- If the captive breeding program succeeds in increasing the size of the population, when should individuals be released back into the wild, how many and in what combinations of sex, age and group composition? This is the question facing many of the more successful captive breeding programs for Australian mammals, like the Bilby.

Which species should receive funding?

Vulnerable species rarely receive funding but critically endangered species, given a well-presented recovery plan, are funding certainties.

There are two ways to answer these questions – one is to consider the empirical evidence from past actions, often using information on other species. We have learnt a lot about the captive breeding and reintroduction of many species from all over the world. Unfortunately there are few general rules because each species is different, and because failure leads to species extinction, there is limited empirical data on failures. Empirical reintroduction research yields essential data and experience, but provides only a limited framework for extending experience with a particular species or site to new species or uncertain circumstances.

Population ecology theory provides some general principles. We know that the reintroduction of a large number of individuals will typically be better than a smaller reintroduction, and a

captive breeding colony that was founded by many wild individuals will prosper more than a colony founded by few individuals. However these principles do not answer any of our three basic questions. Indeed, scanning the conservation biology literature, I found only two attempts to use decision-theory to help us make a decision about captive breeding and reintroduction (one for Sumatran Rhino and one for Grizzly Bear, both authored by Lyn Maguire). Again this is remarkable, given that conservation agencies and zoos are making such decisions on a regular basis all over the world.

Threatened species funding: the triage dilemma

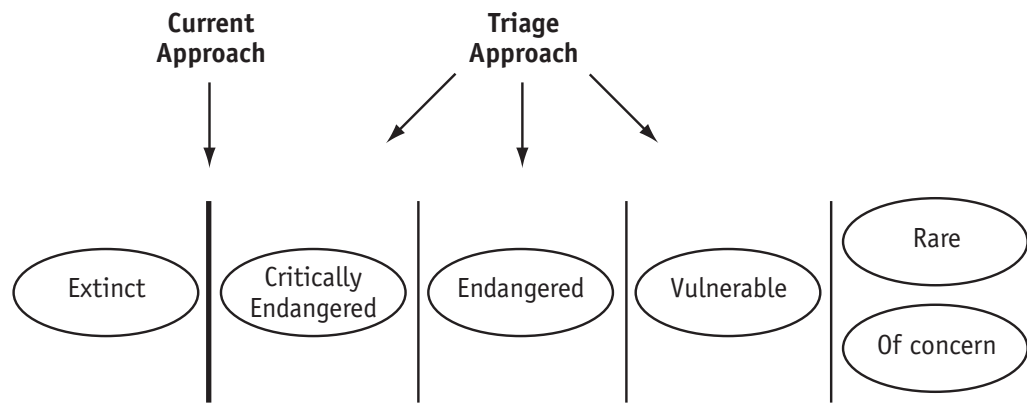
The two problems discussed above are very specific. The first problem is specific to a small spatial scale, a single property; the second problem is specific to a single species recovery program. Decision-making problems are also prevalent at grander scales, at the scale of choosing between projects or programs. A common macro-scale problem in government agencies is how to spread funding across a number of projects. One example is how to spread funding across threatened species recovery programs. Here I discuss how that allocation is generally carried out, and raise the controversial issue of ecological triage, where some species should be probably left to fend for themselves.

The triage approach tries to minimise the total loss of species over a long time frame rather than trying to save everything.

The International Union for the Conservation of Nature (IUCN) has a systematic method for ranking threatened species. The most highly ranked species, called “critically endangered” are those most likely to become extinct in the short term. Endangered species are those less likely to become extinct than critically endangered species. Vulnerable species are species likely to become endangered. Other categories of threat refer to species that may be simply rare, or for which we have inadequate information.

The Endangered Species Unit of Environment Australia enters partnerships with state agencies to allocate funds to the nation’s threatened species. Because of the huge number of threatened species, and the limited funding, only a small fraction of federally listed species receive support. The question is – which species should receive the funding?

Figure 2: Over most of the world the current approach to single species conservation is to invest most effort in the species most likely to become extinct. This approach has registered high profile successes as species like the Giant Panda and Helmeted Honeyeater are brought back from the brink of extinction. However while millions of dollars are spent on these species hundreds of other, currently less threatened species, slide inexorably into the endangered and critically endangered categories.



To date the general trend has been to invest most funding in the species most likely to become extinct as determined by the IUCN rankings (or ranking by some similar method). Vulnerable species rarely receive funding but critically endangered species, given a well-presented recovery plan, are funding certainties. If the decline of Australia's species diversity is thought of as a movement of species through the different categories from "secure" through "rare" or "of concern" to "vulnerable", "endangered" and finally "critically endangered", then our current strategy is somewhat like Hadrian's last stand, buying time before the inevitable avalanche of extinctions (Figure 2).

This approach to endangered species funding led some conservation biologists to propose the notion of "ecological triage". In a triage approach species are placed in three categories – threatened species that are likely to become extinct even with huge expenditure, threatened species that can be recovered quickly for a reasonable cost in a relatively short time frame, and those species that are threatened but are currently a long way from extinction. The

advocates of ecological triage argue that most funding should go to the middle group of species, the ones that can be secured for low costs quickly. The highly endangered species for which recovery actions are uncertain and expensive are left to fend for themselves. They may recover without assistance, they may become extinct, or a cheap and efficient means of ensuring recovery may be discovered. Either way, the cost of saving them is too high and the chances of success are too low.

The triage approach to threatened species funding allocation acknowledges the fact that many species will become extinct. It takes a longer-term and more pragmatic view of conservation, looking to a time where few species are endangered and the rate of species extinction slows to the "normal" pre human-induced rate. Later in this essay I formalise the notion of triage within a decision theory framework. For now we need only note that the triage approach, which is trying to minimise the total loss of species over a long time frame, is not being used in place of the politically more palatable approach of trying to save everything.

In summary, decision-making about the environment generally lacks rigour. Actions to conserve biodiversity are informed by scientific information that has not passed through a decision-making filter. At all levels, biodiversity decision-making is in urgent need of an economic filter, where the principle of maximising benefits for minimum cost is applied. In the next section I introduce three examples that apply decision-theory thinking to some specific problems. These three examples are intended to illustrate good biodiversity business.

2. What is decision theory and how can it be used in conservation?

Decision theory is a framework within which those responsible for managing a system attempt to achieve explicitly stated objectives. Engineers and economists have used decision theory for decades to help make decisions. In some cases, decision theory relies on complex mathematical tools that go under the generic name of "mathematical programming" tools. However decision theory can be much broader and often includes qualitative tools such as "ecological risk assessment" or "multi-criteria decision analysis." The common thread within the theory is a disciplined protocol for problem solving that includes the following seven steps.

1. **Specify the management objective**, or at least list the indicators of management performance. For example: minimize the risk that numbats become extinct in the next 50 years, or conserve 20% of every reef type in a marine ecosystem. Where there are multiple objectives, utility theory can be employed to deal with the problem of how to maximize multiple objectives that are measured in different currencies (e.g. money, biodiversity loss, and risk to human health).
2. **List the management options** and express them as control variables (e.g. release x animals in year t , expend y dollars on baiting predators, dedicate a new protected area).
3. **Specify the system properties** that describe the state of the system (e.g., population size, predator abundance, amount and type of habitat currently in the protected area system).
4. **Develop a conceptual model of the dynamics of the system** being managed, and if possible develop equations to describe the dynamics of the state variables (e.g., equations for numbat and predator population dynamics, a map of the likely threat of global warming on coral reefs). This step will often involve collaboration between field biologists and ecological modellers.
5. **Specify constraints** that bound the decision variables and state variables (e.g., a recovery program budget, the social acceptability of predator reduction strategies, consideration of the economic impact of marine reserves on the fishing industry).
6. **Be honest about what we don't know**. Specify the range of uncertainty for all the parameters. Is the current size of the numbat population really known? Can we put bounds on the uncertainty in our reef classification system?

7. **Find solutions to the problem.** Once the problem is defined in steps one to six the manager may often need a decision-making protocol and/or mathematical programming package to find the best, or at least some good, solution(s).

To illustrate how decision theory thinking might be integrated with traditional conservation biology approaches, I present three examples.

Example 1: Optimal fire management for a large conservation park

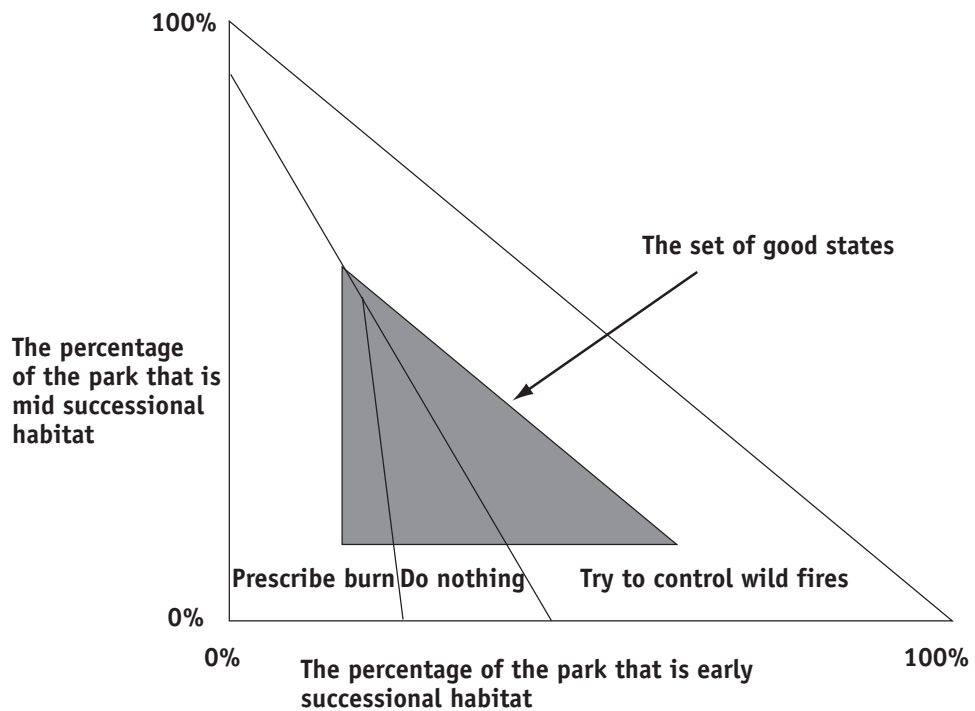
Managing disturbance processes in conservation areas is a contentious issue throughout the world. In many large and semi-natural terrestrial systems fire is the main force that disturbs vegetation and it is often managed with fuel reduction burning, attempts to reduce ignition frequency, and prescribed burning to increase fire frequency. The pro and anti-fire advocates often take highly polarized positions based on preconceived ideas, conflicting goals, and non-predictive mental models of an area's natural history. The fear of making the wrong decision often means managers decide to do nothing. Here I summarize the work of Richards, Possingham and Tizard who used decision theory to determine an optimal fire management strategy for a large conservation reserve. The kind of ecological process management method described here could be adapted to other questions of process management, like flow regime management in streams, and total grazing pressure in the pastoral zone.

One of the greatest benefits of decision theory is that it provides a protocol to help distinguish among, and integrate, various goals held by multiple sectors of the public.

Ecological theory tells us that different species like different habitats. These different habitats occur as successional states at different times after a fire. Let us call these habitats early, mid and late successional habitat. To conserve all species in a large park a mosaic of these three vegetation types is required. Let us now fit the description of the problem into the seven-point framework of decision theory.

1. **Specify the management objective.** The broad objective is to maintain a balance between the different successional states of the park. Specifically, assume that at least 20% of the park should be in each of the three successional habitat states – early successional habitat, mid successional habitat, and late successional habitat. This specific target for each habitat type is a surrogate objective for the ultimate objective of retaining species diversity. The habitat-based objective is efficient because it can be measured and is believed to reflect other aspects of biodiversity.
2. **List of management options.** Each year the park manager has three options: do nothing, attempt to stop all wild fires, and prescribe burns in some of the park to create more early-successional habitat.

Figure 3. A state-dependent decision diagram for fire management in a large conservation reserve. The result is based on an objective of trying to keep at least 20% of the park in each of the three successional states, early, mid and late. Do nothing means that fires are neither initiated nor extinguished.



3. **State variables.** The state of the system is the fraction of the park in each of the three successional states - early, mid and late.
4. **State dynamics.** The two forces that drive the dynamics of the state of the park are fire and vegetation succession. Using probability theory, Richards et al calculated the chance that the park will move from any one mixture of habitat types to any other mixture of habitat types through a combination of fire and succession. The chance of moving from any state of the park to any other state of the park will be different under each of the three management strategies. The final model describing how the system changes with time is called a Markov chain model.
5. **Constraints.** The ability of the manager to enact any of the three management options is not constrained, although Richards et al did assume that the fire suppression option would not be completely effective.
6. **Uncertainty.** Richards et al. varied the definition of early, mid and late successional habitat, and the relationship between fire frequency and habitat state, to test the robustness of their conclusions. For more detailed fire management a whole host of uncertainties regarding ability to control fire, risk to life and property, and even variability in the political climate, could be used to enhance the robustness of the results.
7. **Solution Methods.** Stochastic dynamic programming, a common mathematical programming method, was used to find the optimal solution to the problem.

The main outcome is a state-dependent fire management diagram that tells a manager what to do given a particular state of the park. Where the resources to explore options for a particular park are limited, Figure 3 could be thought of as providing a rough rule of thumb for fire management in a large semi-natural park, although its robustness would require considerable further testing (see point 6 above).

Unexpectedly, a manager often needs to do something even when the park is in a “good” state, and sometimes a manager should do nothing when the park is in a “bad” state. Exactly when a manager should take the action of “do nothing” is not easy to predict without a model. The stochastic dynamic programming method is able to accurately integrate decisions in a randomly determined world over a longer time frame than human intuition. Returning to the debate amongst many fire managers as to whether there are too many or too few fires, there is no fixed optimal policy - it depends on the state of the park.

One question raised by this work was the social and economic cost of adopting different policies. This was not dealt with in detail, yet may be important in some cases. Utility theory would need to be applied to generate relationships between different “values” – conservation value, economic cost, and social perception of fire. This issue is discussed in the context of another example below.

Example 2: Reserve system design

Australia has been a pace setter in systematic reserve planning through the leadership of scientists such as Bob Pressey. However there are many people, both in Australia and overseas, who advocate ad hoc approaches to reserve system design. The emphasis is on grabbing anything you can get as quickly as possible without thinking about the long term consequences of being inefficient.

There is growing literature on the systematic design of nature reserves. Most ecologists are aware of the problem outlined in the seven-step decision theory framework below, yet it has taken twenty years to get clear formulations of the problem. The most recent push for marine protected areas often ignores the advances made in systematic reserve system design in terrestrial ecosystems. This will be to the detriment of both conservation and industry interests.

So far the formulations include some ecology, but very little economics. The social and economic aspects of reserve system design are in most need of further research and can be easily incorporated into the seven-point framework below.

1. **Specify the management objective.** The objective is to ensure adequate representation of a suite of biodiversity features (usually species or habitat types) in a reserve system for the minimum cost. The cost of a reserve system can be any combination of its area, direct economic cost for acquisition, opportunity cost for other uses like fishing or forestry and long-term management cost. An alternative objective is to maximise the representation of biodiversity in a reserve system given a constraint on the total reserve system size, or a fixed budget for acquisition.
2. **List of management options.** The control options are to acquire, or not, each parcel of land or sea (called a planning unit) for the reserve system. There is a control variable for each planning unit. Current interest in off-reserve conservation and marine zoning

would mean that the list of options for any parcel of land or sea should be broader than in or out of a reserve, and include non-purchase conservation options (like covenanting) or partial protection options (through zoning).

3. **State variables.** The key data are whether or not a biodiversity feature occurs in a planning unit. For example how much of each habitat is in each planning unit. Other state variables would be whether a planning unit has already been dedicated as a reserve, or is somehow unavailable for reservation. How much an industry needs to be compensated for the reservation of any planning unit needs to be included. The cost to industry of the entire reserve system is unlikely to be simply the sum of the cost of reserving each planning unit.
4. **State dynamics.** There are normally no dynamics in reserve design problems, although this is an area of active research. To include climate change and changes in the ranges of key species would add an interesting dynamic layer to the reserve system design problem.
5. **Constraints.** The primary constraints are the biodiversity constraints. Usually the problem is formulated so that all biodiversity targets (e.g., conserve 15% of habitat A, or 500 individuals of species B) must be met. Planning units are constrained to one of a few states: already in the reserve system, available for conservation designation, or unavailable. In the alternative problem of conserving as much biodiversity as possible, the constraints are economic constraints, such as total budget for acquisition, or social constraints, such as only 20% of the region can be conserved.
6. **Uncertainty.** There are many ways in which uncertainty can impinge on this problem. The most common occurs where some of the GIS data layers have errors, or the species lists are incomplete and inaccurate. This would mean that there are errors in the state variables that describe how much of each conservation feature is in each planning unit. Recent work has been carried out on the impacts of uncertain, incomplete or unreliable data.
7. **Solution Methods.** These sorts of problems often become so large that classical mathematical programming methods fail. Simple heuristic algorithms, like the greedy algorithm, or less classical optimisation methods, like simulated annealing, have been used.

Where reserve system design is implemented, it quickly becomes apparent that human society is not a single entity with a single value system. Whereas a conservationist may value a particular site because it contains habitat for an endangered species, a timber company may value that site because of the potential revenue that might be generated from harvesting trees, and a horse-riding group may value the site for its recreational values. Perhaps one of the greatest benefits of decision theory is that it provides a protocol to help distinguish among, and integrate, various goals held by multiple sectors of the public. For conservation, social and economic stakeholders it quickly becomes clear that the costs and benefits of an entire reserve system are more (or less) than the sum of the parts.

To be more specific, in various marine regions around the world scientists, managers and agencies are working on designing reserve systems to conserve representative samples of marine habitats in fully protected zones. If conserving biodiversity is all that matters, this problem is hard, but not as hard as a problem that takes into account other values. Real world marine reserve design has to include the interests of others: commercial fishers, recreational fishers, the tourist industry, etc. Another complication for reserve system design is multiple zoning, where any planning unit needs to be assigned to one of several zones, each of which has implications for conservation, scientific, social and economic values. Multiple zoning problems raise many questions. From the biodiversity perspective, would two previously exploited reefs closed to fishing, but not tourism, compensate for one reserved reef opened up for fishing? A question like this is hard to answer for a single species, let alone for biodiversity in its entirety. We are a long way from developing fully integrated and adaptive reserve system planning tools, yet most countries need them now. By adopting the disciplined approach to problem formulation described above it is possible to provide a framework within which different stakeholders can start to integrate their objectives.

Example 3: Threatened species funding

Allocating funds among different species recovery plans is a common problem for conservation agencies. This decision-making is at a different scale to the other two problems described above. Here government faces the task of allocating funds between recovery programs, where each recovery program must resolve a number of micro-management decisions. As discussed earlier in this paper, most agencies spend most

of their money on the most threatened species. I argued that this is unlikely to be optimal in achieving the objective of minimising total species loss. By formulating the problem within the seven-point decision theory framework this becomes clear. It is worth noting that the formulation developed here can be generalised to other problems of resource allocation.

1. **Specify the management objective.** Assume that the objective is to minimise the total number of species that become extinct over some time frame, say 200 years. This assumes that the species listed, usually vertebrates and vascular plants, are all regarded as having equal value. Some agencies implicitly choose to value the survival of some species more than others. This occurs particularly with regard to invertebrates and non-vascular plants that are rarely listed, and their recovery almost never funded. The valuing of species can be made explicit in the decision theory framework if the agency wishes by weighting species differently in the objective function.
2. **List of management options.** As with all allocation problems, the decision to be made is how much money to allocate to each of a range of projects. Specifically we want to know how much to spend on each threatened species (for many the answer may be nothing).
3. **State variables.** The state variables will be the list of threatened species, how much has been spent on each species so far and some measure of how well those species are doing.
4. **State dynamics.** The state dynamics are the expected dynamics of the species given a certain level of funding, and possibly some notion of future budgets. Specifically we need to estimate how much each species's chance of extinction is expected to decline with a certain level of future funding (Figure 4).
5. **Constraints.** The constraint is the size of the budget (now and in the future).
6. **Uncertainty.** There will be considerable uncertainty about the likelihood of any species becoming extinct, or recovering, given a particular allocation of recovery funding. Such uncertainties need to be explored and allocations will need to be continually updated as new information comes to hand. Clearly there is a need here for a research component to reduce this uncertainty and I discuss that issue in the next section of the paper.

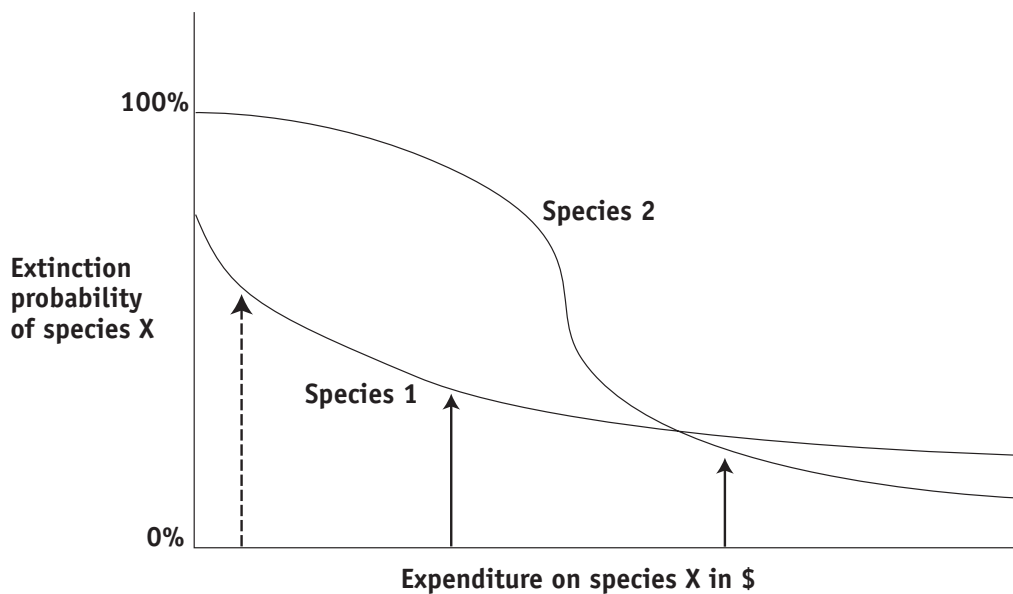
7. **Solution Methods.** A variety of solution methods can be used, from classical optimisation where the objective is to minimise the expected number of extinctions, to a multi-criteria decision approach where certain species may need special treatment for social and economic reasons. Working through the formulation of the problem may be all that is needed to make agencies rethink their funding allocation policy.

To my knowledge no country has adopted a quantitative decision-theory approach to threatened species funding allocations. To illustrate the approach for a specific case consider Figure 4 where a fixed sum of money could be allocated between conservation efforts on two species. Where the total available funds are low we should allocate them to the least threatened species because that generates the biggest gains – ecological triage. Where the funds are substantial then the best strategy is to spend a small amount on species 2 and most of the funds on the most threatened species, species 1.

Working through the formulation of the problem may be all that is needed to make agencies rethink their funding allocation policy.

Stepping back from the problem even further one might question how funds are allocated between large conservation programs like: threatened species management, habitat restoration, reserve acquisition, habitat retention, feral animal control, weed management and restoration of flow regimes in rivers and streams. The near extinction of a native species is often the consequence of an interconnected suite of threatening processes. Propping up small populations of vertebrates may be popular with the public and the media but it may not provide the best long-term conservation outcome. Since prevention is better than cure, a forward-thinking Australia needs to devote more effort to provide incentives to stop threatening processes. I believe that it is more cost effective to provide incentives to stop the degradation and loss of native vegetation, rather than to create new habitat or restoring degraded habitat. Similarly Australia should spend more on quarantine measures that stop invasive weeds, new diseases, marine pests and other aliens entering the continent, rather than funding the invariably futile efforts of eradication.

Figure 4. The relationship between the probabilities each species becomes extinct is a function of the amount of money spent on that species. If no money is spent on either species then the extinction probability is 100% for species 2 and 80% for species 1. As expenditure increases on each species the extinction probability decreases but in different ways. If the budget is very low all the money should be spent on species 1 (dotted arrow) because the marginal gains are higher, even though it is not as threatened as species 2. If the budget is large the money should be spent on both species so that the marginal reductions in extinction probabilities are equal (solid arrows).



It is more cost effective to stop the degradation and loss of native vegetation than to create new or to restore degraded habitat, and to stop exotic species entering the continent than to fund the invariably futile efforts of eradication.

The reader will have noticed that the seven steps to decision-making fall short of taking action. Two further essential steps now need to be considered; taking action then monitoring the consequences of the decision-making. Monitoring and consequent re-evaluation and reformulation of our underlying data and models and theory should lead us into the cycle of active adaptive management. It is where managers and researchers meet.

3. Monitoring and active adaptive management

Once a decision has been made, action needs to be taken. With all actions a cost efficient monitoring program should be considered, with the aim of evaluating and refining the solution or management action chosen. Here I argue that a well-designed monitoring program is a form of research and performance evaluation that is essential for improved decision-making. These are steps 8 and 9 in our biodiversity management protocol.

8. **Manage the system.** Take the action identified by application of steps 1-7. This is not a particularly contentious step, although later I argue that the way a system is managed may need to take into account how the performance of our management is evaluated, and how we might try to minimise uncertainties identified in step 6 of the decision-making protocol.
9. **Evaluate the consequences of management.** Usually we are told to monitor the consequences of our actions – but why?

Why monitor?

There has been a disturbing move away from environmental monitoring. Monitoring has become a dirty word in some circles of Australian biodiversity management. State and federal conservation agencies are reluctant to talk about monitoring to their political masters, and the funds for monitoring have dwindled. Some sectors of government and the general public have become convinced that monitoring has wasted a lot of valuable time and money when we already know the answers to most environmental problems. Monitoring can be seen as a waste of resources, or worse still, an excuse for inaction. For the research community monitoring is not seen as sexy science. Why has monitoring got a bad name and is it really a waste of time and money?

A well-designed monitoring program is
a form of research and performance evaluation
that is essential for improved decision-making.

To see the value of monitoring let us return to our business theme. Assume that you run a chain of retail outlets that sell a limited range of products. A wholesaler offers you a new product to sell that is compatible with your current products. You would immediately carry out some limited market research on the new product (or assume the manufacturer's market

research is accurate). Imagine now buying and selling that product without monitoring the costs and benefits! No business would be so irresponsible. Each week or month the managers would look carefully at the performance of the new product and continually re-evaluate the decision to continue with the product. Monitoring, which in this case might be called performance evaluation, is an essential part of good business. Despite this we continue to carry out many conservation actions without evaluating the performance of those actions; we continue to think of monitoring as an expensive luxury divorced from real actions. There are at least two main reasons.

Imagine buying and selling a product without monitoring the costs and benefits! No business would be so irresponsible.

First, some monitoring has been implemented for no real purpose. Monitoring that cannot influence management and actions can be interesting but does not fit within the framework of efficient business. For example it may be interesting to count the number of ducks in a series of wetlands, but unless those counts influence our decisions about water management or hunting quotas then the monitoring is of intellectual interest only. Too often scientists and managers have been guilty of monitoring things that can never change actions and arguing that this is applied science. This is not part of good applied science because it cannot be used to help to refine decisions so it has given monitoring a bad name. Counting ducks for the sake of developing new theories about waterfowl population ecology could be regarded as more pure science – which I hasten to add can generate enormous benefits. However that discussion is outside the scope of this paper.

Second, many monitoring programs are poorly designed.

- The questions they are intended to answer are not well defined. The number of ducks on a wetland might be accurately counted but we are not sure whether we are looking for overall changes in duck abundance, seasonal changes in habitat use, or the impact of hunting.
- Their ability to change actions is not clearly stated. There needs to be a clear relationship between monitoring information and action. In our retail outlet scenario we may have a threshold level of sales below which we cut the product. For ducks there may

be a threshold number of individuals observed in the wetland system above or below which we do, or do not, have a hunting season.

- The experimental design is inadequate for discerning relevant changes. In the retail scenario if the errors in sales figures are large and we look at reports from a limited number of stores we may never be sure if the product is generating a profit or loss. Similarly we may not be counting enough of the wetlands in a region to be sure whether a particular species of duck is declining or increasing. While in business the issue of the statistical power to be confident of our conclusions is often not an issue, monitoring ecological systems where there is often a high degree of natural variability in the things that are monitored means that the power to detect real trends is often lacking. This issue is a large and active area of research in environmental statistics.

What is good monitoring?

Good monitoring needs a good experimental design that is targeted at reducing the uncertainties identified in step six of our decision-making protocol. Good monitoring is equivalent to well-designed research, or in a business sense, performance evaluation of adequate power to detect the changes that will trigger action.

Ideally monitoring targets the biodiversity assets and processes of greatest concern and/or uncertainty. When monitoring the impact of fire on biodiversity there are many species and ecosystem processes that could be measured. By using the context of our fire management problem described above the most important things to monitor become clear. First, what action should be taken depends on the fraction of the park in each of the three successional states. Monitoring this is essential. In general, if the state of a system influences the choice of management action then this state must be monitored. Second, there is uncertainty about the relationship between the successional states and habitat suitability for rare and threatened species. Easily and reliably monitored high profile species should be monitored and their response to different habitat and different sorts of fire determined. This will help to reduce uncertainties in the definition of the different habitat types, the way in which the habitat model works, and the relatively arbitrary 20% target for each habitat type.

No monitoring design can feasibly encompass all ecological processes and species. Therefore, the design of monitoring programs requires careful consideration of candidate species and processes for measurement. Selection of things to monitor should be made

in the light of the management objectives and the model of the ecosystem of interest. Although biodiversity has many dimensions, since there is a limit to the number of things we can measure, and there is pressure for quick answers, it is popular to rely on monitoring surrogates such as indicators, keystones, or umbrella species.

For monitoring programs to be useful they must be efficient, informative and reliable. For example, given an objective of detecting a population decline, and a fixed level of effort or resources, how many sites should be monitored? How many samples are required to detect a trend in population size when there is uncertainty in observations and significant environmental variation? How likely is it that a particular sampling procedure will detect a rare species?

Most frequently used statistical techniques do not answer these questions because they are rooted in the tradition of null-hypothesis testing. Typical management programs hinge on the implicit assumption that if no problem is observed, none exists. The burden of proof rests with monitoring programs. If monitoring programs fail to detect an impact on a rare species, these impacts are assumed to be absent. In these circumstances, the reliability of the monitoring system becomes critically important. This reliability, in turn, depends on statistical power, the ability of a method to detect real outcomes, often against a background of natural environmental variation, measurement error, and ignorance of biological processes.

Given the importance of reliable monitoring, the persistent failure of conservation biologists and managers to explicitly incorporate reliability considerations in the design of monitoring programs is notable. The task of stipulating an appropriate level of statistical power and an acceptable effect size is not simply a statistical decision. It entails judgments about the biological importance of an effect. These judgments may, in part, be influenced by the social, political and economic implications of the ensuing management or policy decisions. Such considerations are critically important because analysis indicates that without reliability calculations, experimenters often are overly optimistic about the reliability and representativeness of their samples.

In summary, only when monitoring is framed within the context of making decisions and taking actions will it be fully valued.

Active adaptive management – the circle is completed

Many environmental managers argue they are implementing the principles of adaptive management. They say that their management actions are flexible and responsive to new information – given new evidence they are willing to change. This is passive adaptive management and is only half the answer to integrating decision-making, monitoring, research and action.

Active adaptive management is management with a plan for learning. It is management seen as a well designed experiment to increase knowledge. An active adaptive manager will vary management in different times and places, monitor performance, and use that information to refine future decisions. Knowledge is seen as a commodity that reduces uncertainty and makes the task of making the best decisions more accurate.

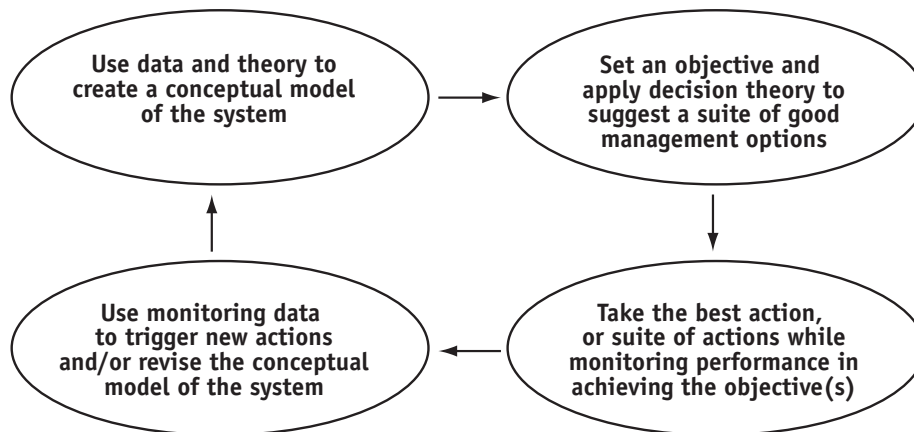
Active adaptive management is management with a plan for learning.

To illustrate this idea let us return to our very first example of habitat restoration and see how decision-making, research, monitoring and action can be integrated to advance our ability to answer this pressing problem of landscape design. Early in the paper I argued that we do not have the theoretical nor empirical information to determine how Jill should best revegetate her property to promote biodiversity. For Jill to make a decision she first needs a more specific objective. Assume that Jill's objective is to recover the diversity and abundance of one of the more conspicuous, and easily monitored parts of biodiversity - birds. Because small bird populations can persist on the scale of a rural property this is a reasonable objective and will influence our further monitoring. (Some will argue that birds are a good surrogate for biodiversity in general, others will argue that there are no simple and adequate surrogates for biodiversity.) In particular Jill would like to ensure the persistence of her dwindling Malleefowl population.

First consider the five options illustrated in Figure 1. Given the existing literature on how birds respond to landscapes, Jill can probably reject options 2 and 4 that create landscapes that are far too fragmented at the scale relevant to large vertebrates like the Malleefowl. If her targets had been invertebrates or vascular plants then these two options may well have been worth exploring further. Jill has refined her decision space using the best available

information but can't choose between options 1, 3 and 5. She needs more data but the kind of ecological data needed demands long-term research. Rather than wait for the research Jill contacts some regional groups involved in habitat restoration, such as the regional landcare groups, the state primary industry and environment departments, and Greening Australia. She works with them to identify five groups of four properties across the mallee whose owners or managers are interested in doing some habitat restoration and learning about how best to do that restoration. In each group of four she asks them to restore habitat consistent with one of the four options, where the fourth option is to do nothing. Before the restoration commences local bird watchers are enlisted through the Birds Australia atlas to set up two hectare monitoring sites in each property. These are monitored continuously throughout the experiment. The restoration is commenced and implemented with the help of the revegetation agencies over five years. During this time the results are continuously monitored.

Now that the experiment is under way, management is taking place, and the monitoring is happening four times a year. How does the regional community know when to stop? How will Jill know when she can be confident that one or two of the restoration methods is superior? There are a variety of statistical methods that can now be used to answer these questions. The methods rely on well thought-out experimental design and are similar to methods used by medical scientists to determine which one of several drugs is superior for the treatment of a particular disease. The basic idea is to run the experiment no longer than is necessary for us to be able to throw away one, two or three of the options. Assume that after 8 years our continual analysis shows that landscape restoration option 5 is just not working. Creating a new, large but isolated patch of different habitat has failed to enhance bird diversity compared to the other two treatments. Options 1 and 3 are clearly outperforming the do nothing (control) option. The regional community is at the end of the first cycle of active adaptive management. They have acted, monitored and partially refined their decision-making. They can confidently and publicly recommend that some sorts of habitat restoration bring significant biodiversity benefits and that restored habitat needs to be connected to remnants to generate the best results. But uncertainties remain about the relative merits of broad corridors over bigger patches, while new ideas about the role of buffer zones emerge and need to be tested. The experiment is revised to examine this question further, the restoration plans for existing properties are revised and new properties are brought into the experimental design to expand the program and provide more statistical power. And so the cycle continues (see Figure 5).

Figure 5. The active adaptive management cycle

What can we do when it is not possible to replicate management actions? For example where only one population of a threatened species remains and we need to experiment with different management options, how can we vary or replicate our management? Although lack of replication presents a problem, the principles of active adaptive management can still be applied. I will not explain this in detail here since the methods and tools have been exhaustively explored for fisheries management. Suffice it to say that the approach involves construction of a population or habitat management model, and an explicit variation of management from year to year to test the validity of that management model. As each year passes monitoring data is used to update the model and hence the management decisions.

The principles of active adaptive management, which to some may seem like common sense, can be implemented for almost any environmental problem where actions can be replicated in time and space. For example the same ideas can be used to look at the value of feral predator control, nest boxes, alternative logging scenarios, or weed management. This is rarely done, and the elements that are most often missing are: adequate control sites (where nothing is done), a clear specification of what should happen given pre-existing data and theory (an explicit verbal or mathematical model), and clear rules for stopping or modifying actions based on the results of monitoring.

4. The business of biodiversity

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If you feel uncomfortable with the notion of taking a business-like approach to conservation, then consider the following parting analogy. Imagine you are the director of one branch of a large business. You have been given a multi-million dollar annual budget to manage an income-generating asset. Let us call this asset the koala. If at the end of ten years you are unable to clearly state how many koalas there are, whether the koala asset is growing or declining, indeed whether or not there even would be any asset left after 20 years because of lack of monitoring, then you would be considered incompetent. Worse still if you have no clear framework for allocating resources to increase the size of the koala asset, and you have no explicit decision-making protocol for minimising threats to the asset, you will probably be in search of a new job. By these standards it would seem that most of the world's biodiversity managers, whether they be responsible for a park, a threatened species, or a program of habitat restoration, are not up to scratch. Many of us are in the field of conservation biology to "save the planet". While this is laudable we would be naïve to believe that our management actions do not impinge on the values of other sectors of society and are free from the economic constraints that apply to all other human endeavours. The expectation is that all public resources are used efficiently and accountably to conserve the public asset that is biodiversity.

Conservation biology needs to incorporate the tools of decision making that take into account constraints and trade-offs to deliver the best possible long-term outcome. We need to take a more business-like approach to providing management prescriptions for conservation. Research and performance evaluation must be integrated into conservation planning and actions. We need to prove to the community at large that we can deliver ecosystem management and conservation solutions that are effective and efficient at achieving goals. We cannot continue to use public and private resources for conservation without being accountable to the shareholders in the biodiversity asset – the public.

Private, local, state and federal funds for conserving biodiversity are inadequate for delivering equitable opportunities to future Australians. We are increasingly questioning the interplay of research and on-ground action. The time for a more business-like approach to managing biodiversity has never been more appropriate.

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Further Reading

PAGE 36

Burgman M. and Lindenmayer D., 1998, *Conservation biology for the Australian environment*, Surrey Beatty, Australia.

Cocks K., 1992, *Use with care: managing Australia's natural resources in the twenty-first century*, New South Wales University Press, Australia.

Cocks K. and Baird I., 1989, "Using mathematical programming to address the multiple reserve selection problem: An example from the Eyre Peninsula, South Australia", *Biological Conservation*, 49: 113-130.

DETR, 2000, *Case Studies in Business and Biodiversity*, Earthwatch, UK.

Lambeck R., 1997, "Focal species: A multi-species umbrella for nature conservation", *Conservation Biology*, 11: 849-856.

Lindenmayer D. and Possingham H., 1994, *The risk of extinction: ranking management options for Leadbeater's Possum using population viability analysis*, Australian National University – Centre for Resource and Environmental Studies, Australia.

MacArthur, R. and Wilson E., 1967, *The theory of island biogeography*, Princeton University Press, USA.

Maguire L., 1986, "Using decision analysis to manage endangered species populations", *Journal of Environmental Management*, 22: 345-360.

Maguire L. and Servheen C., 1992, "Integrating biological and sociological concerns in endangered species management: Augmentation of grizzly bear populations", *Conservation Biology*, 6: 426-434.

Margules C. and Pressey R., 2000, "Systematic conservation planning", *Nature*, 405: 243-253.

McIntyre S., Barrett G., Kitching R. and Recher H., 1992, "Species triage – seeing beyond wounded rhinos", *Conservation Biology*, 6: 604, 606.

Pressey R., Humphries C., Margules C., Vane-Wright R. and Williams P., 1993, "Beyond opportunism: key principles for systematic reserve selection", *Trends in Ecology and Evolution*, 8: 124-128.

Ralls K. and Starfield A., 1995, "Choosing a management strategy – 2 structured decision-making methods for evaluating the predictions of stochastic simulation-models", *Conservation Biology*, 9: 175-181.

Richards S., Possingham H. and Tizzard J., 1999, "Optimal fire management for maintaining community diversity", *Ecological Applications*, 9: 880-892.

Shea, K., Amarasekare, P., Mangel, M., Moore, J., Murdoch, W. W., Noonburg, E., Parma, A., Pascual, M. A., Possingham, H. P., Wilcox, W. and Yu, D. 1998. Management of populations in conservation, harvesting and control. *Trends in Ecology and Evolution* 13:371-374.

Taylor R. ed, 1996, *Australia: State of the Environment*, CSIRO Publishing, Australia.

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