Adaptive management: a synthesis of current understanding and effective application

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Summary Adaptive management (AM) remains a commonly cited, yet frequently misunderstood, management approach. The aim of AM is to improve environmental management through 'learning by doing' and understand the impact of incomplete knowledge, but AM more commonly consists of ad hoc changes in managing environmental resources in the absence of adequate planning and monitoring. Here, we trace and review the development of AM, the central roles of consultation, collaboration and of monitoring, and of quantitative models and simulations. We identify a series of formalized, structured steps included in one AM cycle and review how current AM programs build upon such cycles. We conclude that the best AM outcomes require rigorous and formalized approaches to planning, collaboration, modelling and evaluation. Finally, simulating potential outcomes of an AM cycle in the presence of existing uncertainty can help to identify management strategies that are most likely to succeed in relation to clearly articulated goals.

Key words *adaptive environmental assessment and management, modelling, uncertainty.*

Introduction

The development of adaptive management (AM) reflects growing concerns over the past 30 years about the effects of people on ecosystems (Holling 1978; McDonnell & Pickett 1993). Basic empirical ecological research or the development of general ecological theory alone was thought unlikely to improve the way that natural resources were managed (Holling 1978; Walters 1986), and investigations into how natural resources respond to management were deemed necessary. AM is an approach that includes scientific methodologies in the design, implementation and evaluation of managment strategies. The other essential components of AM build on methods from a wide range of disciplines, including the natural and social sciences and recognize the importance of institutional and social structures to management and policy decisions.

Ecological research can contribute to the understanding of environmental effects of management by suggesting plausible ecological mechanisms. For example, the management of algal blooms in some American lakes benefited from an understanding of trophic dynamics in lakes, and this ecological knowledge was used to manipulate trophic structure in order to reduce risks of algal blooms (Carpenter *et al*. 1999). Nevertheless, connections between ecological understanding and environmental management are rarely made explicit, and questions of particular management relevance, such as whether human exploitation of natural resources is essentially different from natural disturbances, remain unanswered (Fairweather 1998).

Understanding what adaptive management is and how it can be applied requires more than a mere definition of words. The terms 'adaptive environmental assessment and management' (AEAM) and 'adaptive management' (AM) are used interchangeably throughout the literature. Here we do not enter the debate on differences between these terms, as we do not believe that a re-definition of these terms will assist in identifying the benefits and common misunderstandings of this management approach. Instead, we review the development of AM in order to synthesize our current understanding and improve future application of this approach.

This synthesis will concentrate on the two primary reasons for the implementation of AM: to improve environmental management, and to understand the impact of incomplete knowledge.

The origin of adaptive management

The first synthesis of AM was a response to the burgeoning realization in the 1970s that natural resources were limited and their continued use demanded prudent management (Holling 1978). The integration of environmental, social and economic issues in the development of environmental policy and management strategies was identified as critical, as well as the iterative cycle in which managerial experiences gained in the application of environmental policy should contribute to further policy development (Holling 1978). Examples of AM were not restricted to natural resource management, but also included management issues dominated by economic and social issues, for example the development of an Austrian mountain village (Holling 1978).

The importance of design, consultation and incorporation of existing knowledge and uncertainties was stressed by Walters's (1986) separation of 'adaptive environmental assessment' (AEA) from management applications. In particular, Walters (1986) advocated quantitative modelling based on existing knowledge, combined with extensive stakeholder consultation and collaboration, to identify alternate management applications prior to their implementation. Once implemented, such alternate management strategies could then be monitored and evaluated in relation to each other. In this sense, some workers still regard AM as something of a hybrid between scientific research and resource management (Nyberg 1998).

The importance of models and simulations in adaptive management

The use of a modelling framework is central to AM (Walters 1986). Simple models are generally regarded as more appropriate than more complex and potentially more realistic models (Sainsbury *et al.* 2000). Complex models may be more vulnerable to misspecification than simpler ones, whilst simple models require less data, are quicker to develop, and, thus, may be easier to compare. The purpose of modelling in AM is not to build realistic representations of reality, but to develop simplifications of reality that are useful for the specific purposes identified within an AM program (Sainsbury *et al.* 2000).

Models are used to explicitly describe components of management and their relationships, to articulate assumptions and, most importantly, to incorporate specifically the levels and types of uncertainty in prior knowledge and data collection. The understanding of uncertainty and its consequences differ greatly amongst individuals, even at the level of managers and scientists and, most certainly, the public who may well (mistakenly) see an admission of uncertainty as incompetence (Marcott 1998). Mathematical models can include uncertainties and complexities in a systematic and quantitative way, something that the unaided human mind can not do easily (Anderson 1998). Uncertainties arise at many different levels from the dynamics of the natural system through to the behaviour of individual managers. Some uncertainties can be reduced through increasing knowledge, but others, such as inherent environmental variability, are likely to remain. Incorporating uncertainty, generally by utilizing some type of modelling approach, is crucial to all stages of adaptive management. Under conditions of data paucity, Bayesian modelling techniques can be used in model construction, but it is crucial that results are viewed with caution until larger amounts of data are available (Bergerud & Reed 1998; Marcott 1998).

One of the strengths of quantitative modelling is that it can be used to explore the consequences of combining several sources of uncertainty and investigate the propagation of uncertainty through time, specifically in relation to achieving defined management goals. Bearlin *et al.*'s (2002) simulation of the management of the reintroduction of an endangered freshwater fish, for example, suggested that uncertainties associated with current methodologies for determining fish densities in large rivers meant that any monitoring was unlikely to detect differences between alternative reintroduction scenarios, and, thus, efforts needed to be concentrated on reducing this uncertainty before decisions about improvements in management could be made.

Collaboration and consultation as important ingredients of adaptive management

Given the close connection between policy and management, AM practitioners stress the importance of stakeholder participation, including modellers, research scientists, resource managers and policy makers in AM, in particular in the early design and planning stages (Holling 1978; Walters 1986; Lee 1999; Cote & Kneeshaw 2001). Models representing existing knowledge of a given system are crucial to identifying uncertainties, but collaboration is also essential to ensure realistic bounding of management problems, constraints on possible actions, and identification of realistic outcomes. In contrast, complexities involved in collaboration with stakeholders are also often blamed for failures of the AM management approach (McLain & Lee 1996; Walters 1997; Rogers 1998; Johnson 1999; Lee 1999; Rogers *et al.* 2000; Moir & Block 2001; Moore 2001; Ladson & Argent 2002). For example, the AM program for managing environmental flows in the Colorado River has involved consultation with a very broad group of stakeholders with often contrasting interests (Walters *et al.* 2000). The success, or even just continuation of this project, will depend as much on managing complex social and political interactions and developments, as on elucidating the complexities in ecosystem structure and function in relation to alternative environmental management scenarios.

The management of rivers in the South African Kruger National Park is a more high-profile and complex application of AM (Rogers & Bestbier 1997; Rogers 1998; Rogers & Biggs 1999). This program recommended methodologies for cross-institutional collaboration that included the development of a broad, overarching vision and objectives, including value-based statements of overall priorities that are publicly acceptable and can be used as justification by upper management levels. Specific goals for on-ground management ('thresholds of probable concern') are included at a more detailed level to provide a way of assessing, on-ground, whether specific end-points were reached.

Adaptive management and science

The approach of incorporating policy and evaluation within management has not necessarily been regarded as a clearly identified part of management, in particular if policy makers and management are divided between different large institutions. Environmental management more often proceeds with established and accepted procedures, without evaluation of outcomes in relation to management objectives (Walters 1986). AM involves identification of goals, the use of measures that relate goals to outcomes, and assessment and evaluation of outcomes in relation to overall objectives of management (Cottingham *et al.* 2001).

The application of scientific methodology to management, in terms of designing, planning, implementing, and evaluating programs, remains one of the key ingredients of AM (Moir & Block 2001). Management actions are regarded as factors that are manipulated in order to distinguish between alternate hypotheses. The effects of management actions on the system are measured in relation to prestated objectives, where these objectives include the whole complexity of social, political and environmental interactions. Often scales are large, necessitating methodologies that can assist in choosing management strategies that are most likely to provide information on particular hypotheses in realistic and practical time frames.

'Learning by doing' has become the catch-cry for AM, possibly to seek acceptance of AM, in particular by scientists, but also by managers. 'Learning by doing' is a particularly attractive notion to scientists who are attempting to relate their work to management questions. Much ecological research in the past has been carried out at relatively small scales, both in time and space. Environmental management, on the other hand, is generally applied at large scales, such as catchments or forests, to which the results from small-scale ecological studies can not be easily translated. Thus, the idea of using a comparison between management strategies as a way of getting more information about ecological processes at large scales is particularly attractive to both scientists and managers (Carpenter 1990; Cottingham *et al.* 2001). However, AM targets management strategies by purposefully designing management in such a way that the success can be evaluated, preferably by comparing several strategies at the same time (Mapstone *et al.* 1996; Sainsbury *et al.* 1997).

AM does not replace scientific research on large-scale ecological questions – the distinction lies in the types of question asked; AM experiments specifically address management-related questions, while most ecological research addresses more general questions in ecology regardless of any management application. Linkages to management of course can be made, but the connection between the application of new scientific knowledge to management often lies outside the research methodology applied within a given project. For example, scientific research will contribute to the development of AM projects by contributing knowledge that can be used to model management systems in order to forecast how the overall system will respond to management (Nyberg 1998).

Links between ecology and management exist when management actions use ecological knowledge to reach a desired effect. For example, the manipulation of trophic dynamics by adding a top-level predator to reduce algal blooms in Lake Mendota, USA, was based on large-scale, field-based manipulations involving close collaboration between management and research agencies (Carpenter & Kitchell 1993). Unless explicitly designed to do so, AM does not address ecological hypotheses per se and expectations that learning by doing will automatically increase ecological understanding are unrealistic.

The central role of monitoring in adaptive management

One of the most important implications of the relationship between AM and science is the importance of monitoring. The purpose of monitoring in AM is not to check compliance with specific regulations or to check that the management action has actually been carried out (implementation monitoring). Learning of any sort can only occur if information is collected on the parameters identified in the development of the initial models of the system and in relation to the specific goals identified in the planning phase of a project.

Sometimes AM is equated with monitoring, such as in a review of AM on public lands in the USA (Moir & Block 2001). The common perception here is that monitoring is generally done very poorly, in particular as the types of issues and problems environmental managers deal with require at least 10–20 years of monitoring (Moir & Block 2001). However, restricting an AM approach to monitoring in a plan-act-monitor-evaluate cycle ignores the contribution that modelling and stakeholder collaboration can provide to environmental, social and political aspects of management problems. Active AM experimentally compares selected policies and management practises, in an organized, structured and experimental approach (Nyberg 1998). By restricting AM to only parts of the whole cycle (Fig. 1) evaluations of this management approach result in a 'litany of failures, with each failure being unique' – the Anna–Karenina syndrome (Moore 2001); as only single aspects of AM have been evaluated.

Applying an adaptive management approach

The AM framework structures management in a series of well-defined stages (Fig. 1) with the whole cycle being repeated

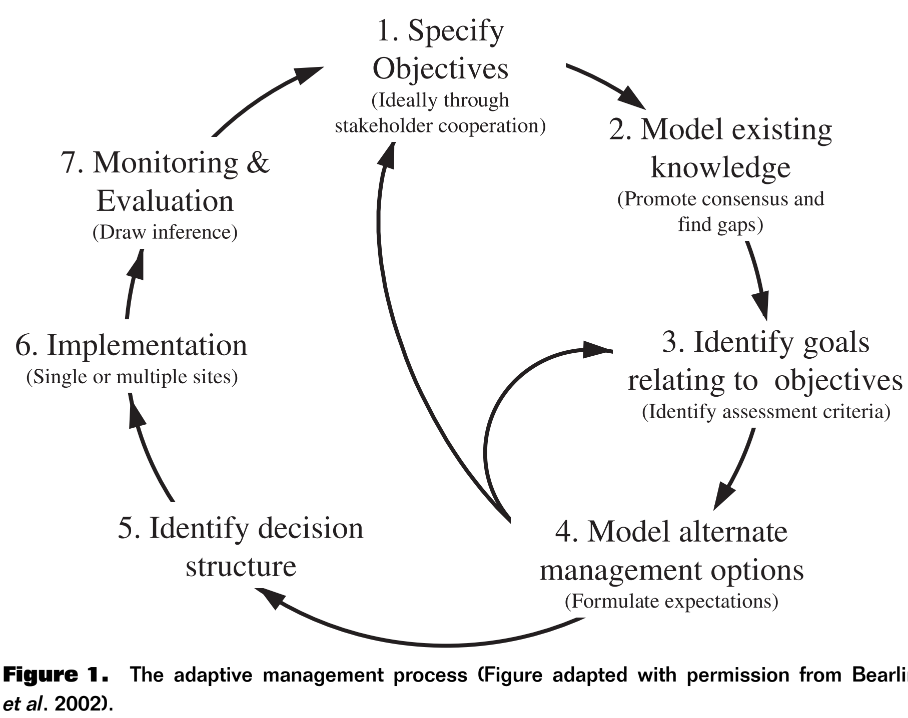

Figure 1. The adaptive management process (Figure adapted with permission from Bearlin *et al.* 2002).

through time. The process of identification and definition of management objectives (Fig. 1, steps 1, 2, 3 & 4) is a fundamental element of AM programs and is iterated and refined following initial modelling. Indeed the breakdown of this process has been blamed repeatedly for specific failures in natural resource management (Rogers *et al.* 2000). The development and exploration of a model representation of the system to which AM is to be applied, is critical to formulating hypotheses, identifying key components and relationships between them, making assumptions explicit, and, most importantly, considering the degree and types of uncertainty in data and prior knowledge. Quantitative models, in particular, are advocated to explore alternative management scenarios and to develop specific goals (Holling 1978; Walters 1986; Sainsbury *et al.* 2000).

Following the initial modelling of a system and of alternative management scenarios (Fig. 1, steps 2, 3 and 4), experiments can be designed that test specific hypotheses related to particular management strategies. It is the outcomes of these experiments that can be used to adjust policy and improve management. At this stage, management can proceed along one of two paths, passive or active adaptive management, both involving a decision about which hypotheses to test with management.

Passive adaptive management deals with one policy or practice at a time; if several hypotheses are considered in an AM framework then different management strategies are applied sequentially through time. Active adaptive management, on the other hand, compares several management approaches simultaneously (Nyberg 1998). It is this latter approach that is most akin to the traditional scientific approach of using controlled, randomised experiments with sufficient sample size and duration to test particular hypotheses and is thought to be the most efficient way of improving management (Murtaugh 1996). However, replication may not always be possible at the large scales that management needs to be carried out (Linnell Nemec 1998), but the formalized structure of an AM approach can still be gainfully applied.

In Australia, the management of aquatic resources has incorporated AM to various degrees, including some of the most comprehensive and successful applications of AM in general (Mapstone *et al.* 1996; Sainsbury *et al.* 1997; Sit & Taylor 1998). However, more commonly only some of the early stages of AM (in particular steps 2 & 3 in Fig. 1) are attempted (Grayson & Doolan 1995). Simulating later stages is done less often, despite clear benefits in relation to investigating the consequences of existing uncertainties on achieving project objectives (Bearlin *et al.* 2002).

The application of a large-scale, active AM approach for the groundfish fisheries in north-western Australia (Sainsbury 1988; Sainsbury 1991; Sainsbury *et al.* 1997) remains one of the best cases that includes all facets of adaptive management. The project was initiated by an observation of a decline in the fishery of two valuable species. As changes in the catch methods applied in the groundfish fishery accompanied this decline, it was of interest to know whether changes in management had caused the decline and whether this decline could be reversed. Four hypotheses were developed addressing possible reasons for the decline (Sainsbury *et al.* 1997). For two of these proposed scenarios, the reversal of the decline would require a decrease in fishing for the two target species. The other two scenarios involved the potential of an increase in productivity of the fish under some circumstances. Given the different implications for management under the alternative scenarios more knowledge was required for sustainable management of this fishery, but existing data were inadequate to distinguish between these hypotheses. Simulations of five different management strategies (called treatments) were used to differentiate between the hypotheses. Both historical data and Bayesian analyses were used to forecast the economic value resulting from each management strategy, and it was found that one strategy, applied for 5 years, would give greatest returns relative to the other strategies. Thus, decision analysis could be used to calculate the expected value of an experiment in an AM situation. This strategy was then applied in reality and monitored. The data gathered were evaluated after 5 years, which resulted in a changed protocol due to changed conditions (Sainsbury *et al.* 1997). The last reported outcome of this AM program has shown that despite institutional changes and changes in management jurisdiction, long-term experimentation was possible and gave outcomes that led to improvements in the management of this fishery.

The way forward

In summary, AM is often hailed as the panacea to, in particular large-scale, management problems. Yet, the AM approach is a combination of scientific methodologies and social and political analyses and can fail at many stages. Similar to any other scientific procedure it is particularly vulnerable to: (i) Inadequate planning and design (including inadequate management questions and misunderstandings between managers and scientists of what can be accomplished); (ii) Inadequate data (either in data leading to understanding processes in the system or previous data showing whether a particular management strategy works); (iii) Inadequate knowledge of how a system works, in particular in relation to management actions; and (iv) Inadequate follow-up in terms of monitoring and evaluation.

Social and institutional aspects of AM that are often seen as a stumbling block for this management approach include: (i) Risk aversion of some managers; (ii) Inadequate institutional structures and stakeholders participation; (iii) Incomplete or ineffectual implementation of a study plan; (iv) Lack of commitment to monitoring, evaluating and reporting; (v) Uncertain or inadequate funding for monitoring and analyses; and (vi) Institutional 'memory loss' regarding what has been learnt (Walters & Holling 1990; McLain & Lee 1996; Nyberg 1998; Ladson & Argent 2002).

In addition, the temporal and spatial scales that are relevant to many management problems make it difficult to clearly identify at which stage AM has failed or succeeded. The types of situations where AM has been attempted include the management of long-lived organisms (such as trees) and ecosystems in which the responses to management can occur at many levels and can be perpetuated through the system through time. Thus, monitoring on a temporal scale that is too short may just result in information about short-term and transient responses and noise, but provide little information on longer-term and/or threshold responses. In addition, short time scales are generally inadequate to evaluate the effects of relatively rare environmental events, such as particularly large environmental disturbances and catastrophes. While AM can help identify management strategies that are robust to uncertainty and to alternate model structures, it will still only do this within the range of models that have been explored.

The best outcomes from an adaptive management approach involve a series of formalized, structured steps within an AM cycle (Fig. 1), which include: (i) extensive collaboration amongst different groups of people involved in, or affected by management; (ii) modelling both of the system that is being managed as well as of alternative management scenarios; (iii) simulations of monitoring in relation to objectives; (iv) making decisions between a range of management options; (v) implementing, monitoring and evaluating alternative management options; and, finally (vi) assessing the outcomes of management in relation to specific initial goals.

Both AM and ecological research use field experiments to address specific questions. Whether AM can contribute to increasing ecological knowledge will depend on the questions that it is designed to answer. It is the formulation of objectives of AM projects that connect ecology and environmental management. The application of AM alone will not guarantee that ecological learning will result from this management approach. Individual stages of an AM cycle can be applied in isolation and still succeed in relation to the goals of that particular step. AM is not the panacea for large-scale management problems, but by being a more formalized and rigorous approach it may result in a more transparent and repeatable management approach.

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