Adaptive monitoring: an overview

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CONTENTS

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ABSTRACT

Ecological monitoring is often considered to be ineffective and unjustifiably expensive. The need for adaptive ecological monitoring designs was investigated. Very few reports on adaptive monitoring approaches were found in the literature. It is suggested that adaptive ecological monitoring be incorporated as an integral component of adaptive ecosystem management design to augment existing ecological management practices. This approach may help to effectively address conservation priorities while enhancing the conservation of New Zealand's natural heritage. An adaptive monitoring approach is, therefore, proposed that has implications for ubiquitous adaptive management practices. Three epigrammatic theoretical frameworks are presented which reflect how adaptive monitoring directs the intensity level of monitoring as well as the level of ecosystem management required to achieve conservation outcomes. I suggest that a study be performed to provide quantitative criteria based on biological and/or ecological theory underpinning changes and variability in species' communities and ecosystems.

Keywords: adaptive monitoring, threatened species, single species, communities, ecosystems

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1. Introduction

The biological diversity of New Zealand, similar to many other island archipelagos, has been depleted by a variety of human-induced disturbances (Atkinson 1989). The legislative mandate provided by the Conservation Act 1987 and other key statutes (e.g. National Parks Act 1980 and Reserves Act 1977) compels the Department of Conservation (DOC) to protect New Zealand's natural heritage. To this end, the Department adopted the mission: 'To conserve New Zealand's natural and historic heritage for all to enjoy now and in the future' (DOC 2001). To fulfil this mission, DOC has undertaken to develop a Natural Heritage Management System (NHMS) based on an Ecological Management Framework (Paula Warren, pers. comm., in Wassenaar & Ferreira 2002) to address ecosystems, species, biosecurity and legal land management requirements. Within this framework, Ferreira & Towns (2001) have developed a theoretically based management framework with an ecosystem approach for the Auckland Conservancy. I propose that this ecosystem approach be augmented with an adaptive monitoring design that can address conservation priorities while concurrently enhancing conservation of New Zealand's natural heritage.

2. Literature overview

A plethora of literature exists describing adaptive ecosystem management and the use of monitoring data to direct management action towards defined goals, add to existing knowledge about ecosystems and develop integrated management strategies for biological populations (Holling 1978; Walters 1986; Duffus 1994; Everett et al. 1994; Grumbine 1994; Bormann et al. 1995; Gunderson et al. 1995; Montgomery et al. 1995; Christensen et al. 1996; Yaffee et al. 1996; Shea et al. 2002). An equal volume of literature exists which describes monitoring strategies in one form or another (Hicks & Brydges 1994; Stevens 1994; Mulder et al. 1995, 1999). These often include the application of statistically inflexible sample surveys as noted by Ringold et al. (1999) and/or ecological modelling and GIS analyses (Mulder et al. 1995).

In contrast, there is a paucity of literature on adaptive monitoring *per se*. I am aware of only a few publications describing aspects of adaptive ecological monitoring (Mulder et al. 1995; Ringold et al. 1996, 1999; Possingham 2002). The difference between the traditional approach to monitoring design and an adaptive approach, as noted by Ringold et al. (1999), is that the adaptive approach 'overcomes barriers to monitoring design by adaptively implementing monitoring rather than waiting for new information or designing a system that does not anticipate new information'. To my knowledge, very little theoretical consideration has been given to adaptively altering monitoring programmes based on existing information.

2.1 ADAPTIVE MANAGEMENT

As noted by Ringold et al. (1999), adaptive management is a well-known term with various definitions in the literature (Holling 1973; Lee & Lawrence 1986; Bormann et al. 1993; Halbert 1993; McLain & Lee 1996; Salasky et al. 2002). Adaptive management has been used as a resource management tool since its inception in the early 1970s (Holling 1978). The basic concept of adaptive ecological management is relatively simple and attempts to incorporate both research and management action while integrating new information, considered 'learning', as an inherent objective (Ringold et al. 1999). 'Learning' adds to existing knowledge on how to better manage ecosystems by taking note of which management actions need to be adapted to increase management responses to future ecosystem changes or conditions. Adaptive managers thus aim to combine ecological research and management actions by integrating programme design, ecological management practices and ecological monitoring and using these to test assumptions methodically (Ringold et al. 1999). In this way, they can gain an understanding of how to adapt their management approach while concurrently answering questions about whether their approach works, and why it may or may not work (Salasky et al. 2002). Adaptive ecosystem management requires monitoring as essential feedback to management to ensure that necessary or appropriate action is taken, despite the fact that knowledge about the ecosystem being managed may be limited.

2.2 ADAPTIVE MONITORING

Adaptive monitoring is considered to be an iterative process that requires experience and knowledge of an ecosystem before implementing a monitoring programme, assessing results and interacting with users (Ringold et al. 1999). It provides essential feedback to management on information about the ecosystem and adds to the knowledge required to understand how to manage a system effectively. It also provides data that allow ecological objectives and defined goals to be evaluated so that specific management action can be taken where needed. It is, therefore, axiomatic that managers incorporate adaptive monitoring into their management design to facilitate ecosystem management.

In the context of DOC's management strategy, an adaptive monitoring approach can be distinguished by using monitoring data to define the next monitoring intensity level or action and where it should be applied. An adaptive monitoring approach would not only incorporate feedback on management action, but would also rely on feedback to applied monitoring practices. Monitoring intensity or follow-up action would depend on changes in expected trends that in turn, would indicate where current monitoring practices need to be modified.

The difference between the traditional adaptive monitoring approach and adaptive monitoring as it could fit into DOC's monitoring strategy, is that the latter approach supports adaptively incorporating changing monitoring priorities as needed, depending on data obtained from clearly defined indicators of change.

3. Adaptive monitoring framework: what is needed?

3.1 CONCEPTUAL JUSTIFICATION

It is evident from the paucity of literature on adaptive ecological monitoring/ design, that although most monitoring programmes are generally designed to take into account how changeable ecosystems are, they do not adequately allow for the complexity of unknown sources of variation inherent in natural systems. To try to overcome the inflexible principles that often define ecological monitoring practices, these uncertainties and unknowns need to be qualified and integrated. This notion is consistent with Brunner & Clark's (1997) and Ringold et al.'s (1999) concepts of introducing new approaches to ecosystem management practices.

3.1.1 Ecological considerations

An important component of adaptive ecological monitoring would be defining indicators that characterise the 'state' of a monitored entity. Depending on this 'state', intensity of monitoring can be adapted by either increasing, decreasing or terminating monitoring, depending on the biological objectives and defined goals of the monitoring programme. The adaptive monitoring design should also allow for new information derived from clearly defined indicators. However, the adaptive monitoring design should not be solely dependent on new information; instead, it should be mainly reliant on critical cut-off criteria/ thresholds of the monitored entity. Defining these critical limits is one of the most important components of an adaptive monitoring design.

The level or intensity of monitoring, if any, will be dictated by these critical limits which will indicate if/when thresholds are reached, and how long an ecological entity can persist before it disappears or recovers, or the point at which it will be sustained over the long term. The fluctuation between the upper and lower critical limits could be incorporated into an iterative feedback loop once specific cut-off criteria/thresholds are reached which will direct the level of monitoring, if any, that may be needed. Note that this could imply that a particular optimised adaptive monitoring design could be used as a type of generic model to describe adaptive monitoring in general (see Section 3.2). However, it is important to remember that a generic optimised adaptive monitoring strategy may not exist and that adaptive monitoring designs are species- or ecosystem-specific, dependent on each species' or ecosystem's specific cut-off criteria.

Often management has to take actions based on incomplete or sparse knowledge/data, especially when the objectives include the maintenance or monitoring of complex ecological patterns and processes over repeatedly disturbed areas and over long periods of time. At these times, adaptive monitoring designs allow the cut-off criteria/thresholds to dictate what needs to be done, irrespective of the inadequate knowledge available.

3.1.2 Managerial considerations

Managers need to consider a number of important factors when designing adaptive ecological monitoring strategies. In an adaptive monitoring design, the effort invested in monitoring at any time, as stated by Possingham (2002), is dependent on: the cost of different monitoring practices, the consequences of having too many or too few individuals in a population of the species of interest, available management options and the current perceived state of the population. Equally important are questions of how much effort should be invested in monitoring, where it is most feasible to monitor, whether monitoring at the selected time is necessary to justify spending money on the current monitoring programme of interest or, alternatively, whether the money should be allocated to other purposes. For an ecological monitoring programme to be successful over the long term, the perceived benefits of the information gained must justify the cost. Financial limitations will always restrict the extent to which a monitoring programme can be implemented and carried out, therefore it is important to accurately determine the costs in terms of the benefits of a programme. However, the benefits of implementing or maintaining an adaptive monitoring programme over the long term may not be easily qualified or quantified at the outset, frequently resulting in costs being underestimated. On the other hand, monitoring costs can be overestimated if changes in monitoring occur that require a decision be made to terminate monitoring, if continuing with monitoring would not be feasible. In this event, the money could have been more appropriately assigned elsewhere.

3.1.3 Management requirements

It is important to recognise that ecological and managerial considerations are closely linked to one another as well as to economic expenditure. Because of the costs involved in monitoring programmes where conservation benefit is not always immediately obvious, monitoring may be considered a luxury by some ecological managers. When putting a monetary value on monitoring, the following should be considered: how much it will cost to monitor effectively; and where and when monitoring can be appropriately initiated, adapted, sustained or terminated to ensure that monitoring practices are most cost effective without compromising New Zealand's natural heritage.

The economic component has been addressed through the Measuring Conservation Achievement (MCA) priority setting process developed by the Department (Stephens 1999; Stephens et al. 2002). However, this process does not allow for predictions on adapting monitoring programmes that are dependent on the manager and what he/she would use as input data.

Using Ferreira & Towns' (2001) suggestion that ecological stability would be a more achievable and more reasonable outcome in the context of the modern day species' pool, managers would benefit from:

- A feedback loop built into management decisions to evaluate whether ecological stability is being achieved. Note that ecological stability comprises several components e.g. variability, resistance, resilience and persistence (Pimm 1991).
- A cost-effective decision framework to evaluate ecological stability.

It follows that ecological managers should consider two major issues when evaluating conservation objectives and outcomes and making conservation management decisions. These two issues are:

- At what stage can things be considered to be going wrong, or at which point can it be accepted that things are not going wrong.
- At what point should management or monitoring be initiated or completed.

3.2 THEORETICAL ADAPTIVE ECOLOGICAL MONITORING FRAMEWORK

3.2.1 Monitoring single species

It could be expected that the population densities of a number of species at any given time, may not be changing. However, it could also be expected that although species' densities are neither increasing or decreasing, inherent variation in density characterises that species' population (Fig. 1A). In theory, stable populations can be expected to have constant densities and constant variability (Pimm 1991).

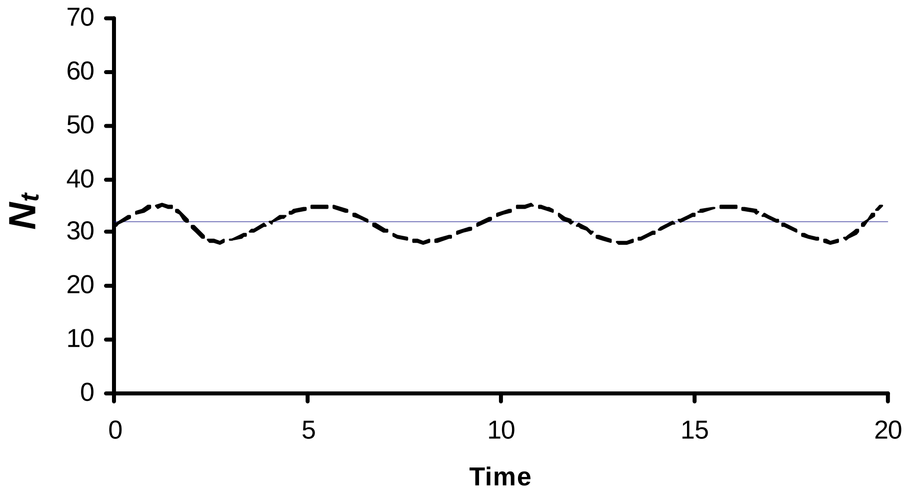
Species can become unstable through changes in density or changes in variability of density as a result of a variety of factors influencing population parameters, e.g. birth and death rates. In this case, I address the scenario where only variability is changing. This is of conservation concern as an increase in variability increases the probability that local extinctions can occur (Pimm 1991). Using this theoretical consideration, it is suggested that if variability increases, monitoring should be intensified. Alternatively, if variability decreases, monitoring should be adapted to a lower level of intensity.

I have constructed a theoretical example of a species where densities have been estimated at five localities initially on an annual basis. (Fig. 1B). After 5 years, no change in variability was observed so the monitoring intensity was reduced from annual to triennial. However, variability increased substantially after 10 years which necessitated an adaptation of the revised monitoring programme to more intensified annual monitoring. Following 2 additional years of intensified monitoring, it was confirmed that the increased variability was sustained, which resulted in more intensified research or management. In this theoretical example, population density variability decreased following research/ management, and after a further 5 years of sustained reduction of variability, the monitoring intensity was reduced.

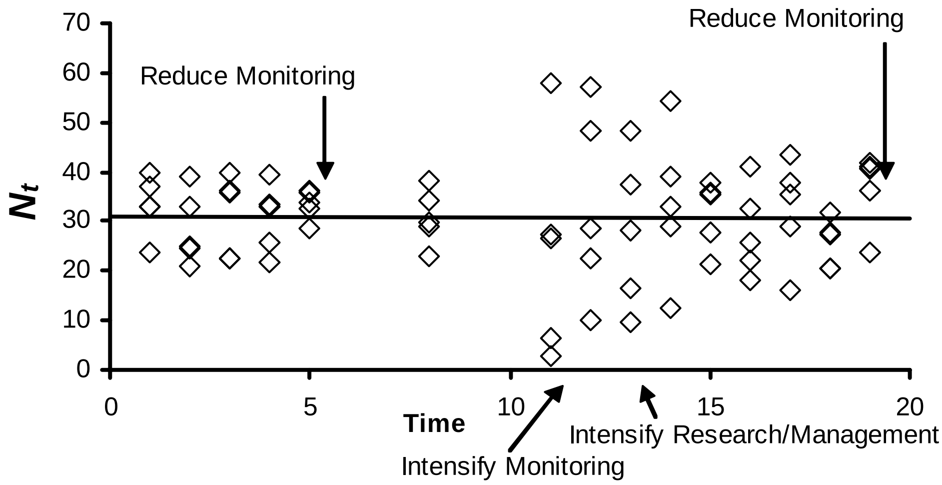
3.2.2 Monitoring threatened single species

It can be expected that a threatened species' population density will decline over time (IUCN 2001). It can also be expected that successful management directed at recovering a threatened species will result in increased densities over time (Fig. 2A). Based on this expectation, monitoring should be intensified when the population growth rate is negative due to changes in births, deaths, migrations or emigrations. Furthermore, as the population approaches $N_{t,E}$ which is the critical population size below which recovery is highly unlikely,

Figure 1. Theoretical considerations for species whose population densities are neither increasing nor decreasing. N_t represents population density at time *t*.



A, Expected fluctuations of density (dashed line) over time for a stable population (horizontal line).



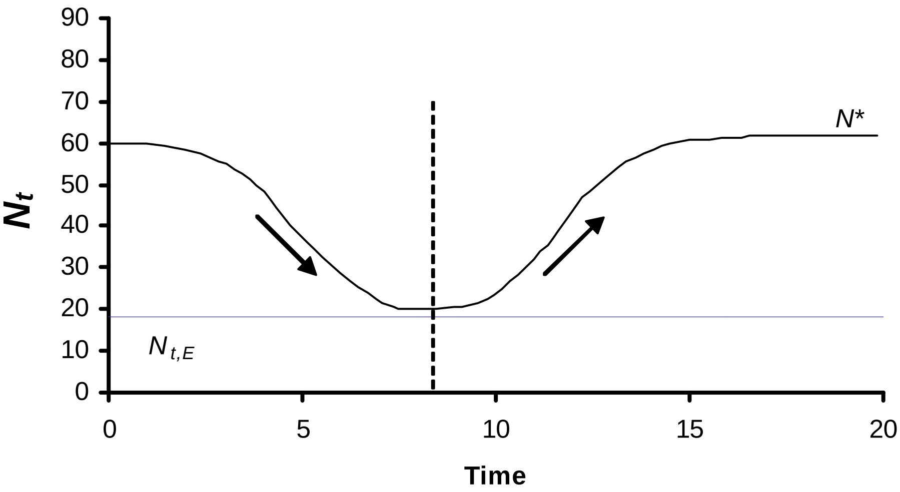
B, Theoretical example of applying adaptive ecological monitoring.

further monitoring (and in particular, research) should be implemented. In such an event, monitoring of parameters other than population size should be incorporated. Conversely, if the population increases, monitoring intensity should be decreased.

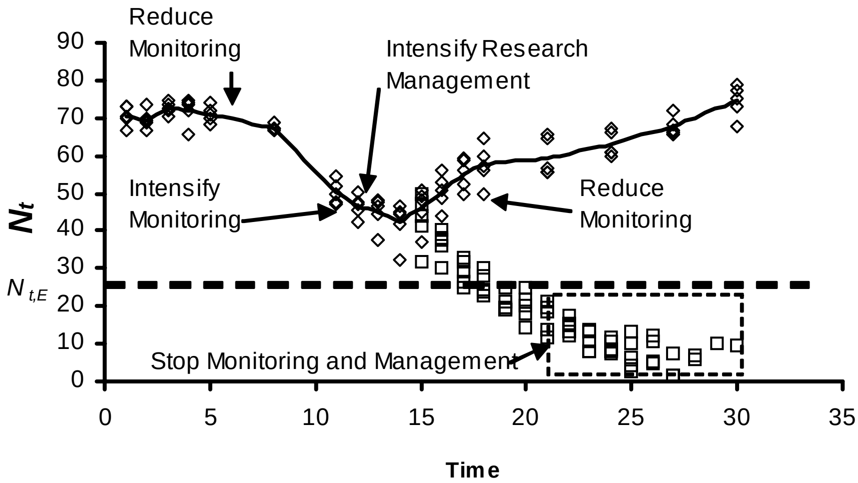
I have constructed a second theoretical example of a species where densities have been estimated at five localities initially on an annual basis. (Fig. 2B, diamonds). After 5 years, no change in density was observed so the monitoring intensity was reduced from annual to triennial. However, density decreased substantially after 10 years which necessitated an adaptation of the revised monitoring programme to more intensified annual monitoring. Following an additional year of intensified monitoring, it was confirmed that the population was continuing to decrease in density which resulted in more intensified research or management. In this theoretical example, density increased following further research/management, and after 5 years of subsequent sustained increase in density, the monitoring intensity was reduced.

Figure 2. Theoretical considerations for threatened species whose numbers are increasing or decreasing. N_t represents population density at time t. N^* represents equilibrium density and $N_{t,E}$ represents the critical population density at which recovery would be unlikely.

A, Expected pattern of a threatened species declining and the consequence of the response to the implementation of management (vertical line). Note, we do expect some variation.



B, Theoretical example of applying adaptive ecological monitoring for a threatened species declining. (represents an example where management made a difference; ' represents the same example, but management made no difference.



In a third theoretical example, extensive research and management did not result in an increase in population density (Fig. 2B, squares). In this case, the population continued to decline until all the sample sites were below the critical density $N_{t,E}$. This was the indicator to stop monitoring and management and accept that this species would become extinct in the wild (dashed block in Fig. 2B). This does not mean that the species would necessarily become globally extinct, as captive management programmes could still be an option.

3.2.3 Monitoring ecosystems and communities

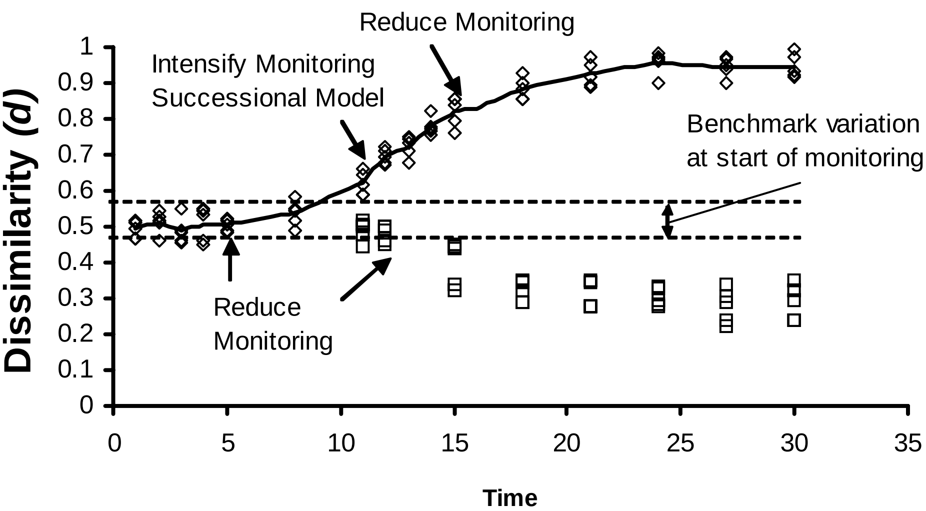
Hector et al. (2001) suggested that maintaining ecosystem structure (species and their densities) would maintain ecosystem functions. Ferreira & Towns (2001) suggested that if species composition was monitored at various trophic levels, it is likely that this measure of ecosystem structure will allow adequate evaluation of total ecosystem outcomes. Therefore, it is important that monitoring ecosystems should focus on measuring community structure at different trophic levels.

It is expected that a stable community will remain the same over time. This means that the similarity of a community over time to that of the same community at the start of monitoring (benchmark community at time *t*), will remain the same. Change in communities can be either divergent or convergent. Converging communities will theoretically have progressively less variability over time. This means that for instances where community similarity is increasing, monitoring intensity should be decreased.

Conversely, divergent communities will become progressively more different over time compared to their starting benchmark community. This divergence could either result from a degrading ecosystem or a developing ecosystem, i.e. one undergoing successional changes. Most ecosystems are variable (Pimm 1991) and one of the mechanisms of variability is successional changes (Barbour et al. 1987). In a conservation context, expected successional changes are desirable and would most probably maintain biological diversity at an ecosystem level. In cases of divergence, monitoring intensity should be increased to determine whether the system is degrading or developing successionally. Ecosystem changes should be evaluated against theoretical successional models for that system followed by increased research/ management for degrading systems and decreased monitoring intensity for developing systems.

In a fourth theoretical example, a community was monitored annually for 5 years during which measure of dissimilarity to the starting benchmark community (*d*) did not change (Fig. 3, diamonds). (In this example dissimilarity is used as an index that can vary between 0 and 1. A value of 0 suggests that two communities are exactly the same and 1 suggests that they are completely different.) Monitoring intensity was, therefore, reduced to a triennial basis. After 10 years, the community started becoming progressively more dissimilar to the starting benchmark community. Monitoring was reintensified (to annual) and a successional model was developed. Over the next 5 years, the divergent changes recorded as part of the intensified monitoring confirmed that the community was following expected successional changes. At 15 years, monitoring intensity was subsequently decreased to a triennial basis again.

Figure 3. Theoretical expectations for measures of dissimilarity (*d*) between a community and its starting benchmark community. (represents an example where a community became more different from the starting community over time; ' represents the same example, but the community becomes more similar through reduction in community variation.



Note that in the fifth and final example (Fig. 3, squares), the community became more similar to the starting benchmark community over time and monitoring intensity at a reduced (triennial) level was maintained.

4. Conclusions and recommendations

A literature survey indicated that very little consideration has been given to adaptive monitoring practices or design in conservation management. I suggest that an intensive theoretical study be implemented to fully investigate the brief, theoretical frameworks developed above. Such a study should focus on providing quantitative criteria based on biological/ecological theory underpinning changes and variability in species' communities and ecosystems.

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