Adaptive monitoring: a new paradigm for long-term research and monitoring

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Long-term research and monitoring can provide important ecological insights and are crucial for the improved management of ecosystems and natural resources. However, many long-term research and monitoring programs are either ineffective or fail completely owing to poor planning and/or lack of focus. Here we propose the paradigm of adaptive monitoring, which aims to resolve many of the problems that have undermined previous attempts to establish long-term research and monitoring. This paradigm is driven by tractable questions, rigorous statistical design at the outset, a conceptual model of the ecosystem or other entity being examined and a human need to know about ecosystem change. An adaptive monitoring framework enables monitoring programs to evolve iteratively as new information emerges and research questions change.

Why long-term ecological research and monitoring are needed

Ecologists and managers of natural resources readily acknowledge the importance of long-term research, which often includes monitoring, for the improved understanding and management of complicated ecological systems. Long-term data are important for many reasons, including evaluating responses to disturbances such as climate change or experimental manipulations; providing baselines to evaluate change; and detecting and evaluating changes in ecosystem structure and function, as can occur in response to management interventions.

Numerous scientific articles, books, management plans and other documents have been written about the need to do long-term research and monitoring (e.g. [1–11]). Although there have been some successful long-term ecological research and monitoring programs (e.g. [12–16]; Box 1), there is also a prolonged history of poorly planned and unfocused monitoring programs that are either ineffective or fail completely [17–19].

Here we briefly outline some of the deficiencies in long-term research and monitoring programs. Then, based upon our collective experience spanning 70 years in establishing natural resource monitoring programs, we propose a new paradigm, adaptive monitoring, to resolve some of the problems underlying poorly planned and unfocused monitoring programs.

Perceived and real problems in long-term research and monitoring

Monitoring programs often have a bad reputation [10], and many fail. Norton [18] described how nearly half of all the monitoring programs undertaken in New Zealand went unreported, indicating that the failure rate can be high. Some members of the scientific community have traditionally viewed monitoring as a management activity that is unrelated to scientific research (e.g. Ref. [20]). However, many other authors, including us, have argued that well-conceived and well-executed monitoring is an important component of long-term scientific research programs and, as such, is very useful to natural resource managers and policymakers [8,10,21]. As we argue here, the features of good science and, hence, good research are often the same features that characterize good monitoring and good environmental management.

Many factors have undermined the credibility of long-term research and monitoring programs. Here we outline what we consider to be three of the key ones. First, they have often been driven by some short-term funding opportunity or a political directive rather than being underpinned by carefully posed questions and objectives [22]. Roberts [23] argued that too often monitoring has been 'planned backwards on the collect now (data), think-later (of a useful question) principle.' Two examples of this are the Alberta Monitoring Biodiversity Program [24] and the Programa de Pesquisa em Biodiversidade (PPBio program) for biodiversity monitoring in southeastern Queensland, Australia [25].

A second problem (related to the first) has been that long-term research and monitoring programs have often been poorly designed at the beginning of a study. Although good design is an inherently statistical process, professional statisticians are often left out of the experimental design phases of monitoring programs. Key issues are then overlooked, such as calculations of statistical power to detect trends, the importance of contrasts between treatments (e.g. where there is a human intervention and where there is not) and the value of innovative rotating sampling to increase the number of sites in a monitoring program and improve power for detecting effects [26].

A third issue is that the design of long-term research and monitoring programs is often prefaced by protracted (and usually unresolved) arguments about what to monitor. One response has been to monitor a large number of things (the so-called laundry list), but resource and time constraints frequently mean that this approach is done

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Box 1. Successful long-term monitoring programs

Although there are many examples of failed ecological monitoring programs, there are also several highly successful ones. Examples include agricultural research and monitoring at Rothamsted in the United Kingdom [43]; at the Hubbard Brook Experimental Forest in New Hampshire (USA) [44]; and the Moreton Bay Waterways and Catchment Partnership in southeast Queensland, Australia [45].

These (and other) successful examples of long-term monitoring have several features in common [2,10], including: (i) well-formulated and tractable questions that were posed at the outset of the work; (ii) an ongoing development of new questions as initial ones were answered or as the insights from research indicated that important new ones needed to be posed and addressed; (iii) robust experiment design; (iv) high-quality data collection and careful attention to field data and field sample storage; (v) well-developed collaborative partnerships among scientists, resource managers and members of other key groups; (vi) access to ongoing sources of funding; and, importantly, (vii) strong and enduring leadership.

badly. An alternative response by some workers has been to argue that 'indicator' species or groups should be the targets of monitoring programs. A review of biodiversity surrogates and indicators [27] showed that a vast array of species and >20 major taxonomic groups have been proposed as indicators, ranging from fungi and bryophytes to invertebrates and most major vertebrate groups. Moreover, credible scientific relationships between a surrogate and the entity for which it was purported to be indicative were rarely quantified, making it difficult to judge when particular species or groups were and were not appropriate indicators. It seems to us that the best response to the common question 'What should be monitored?' is 'What is the crucial question?' As we outline further below, driving monitoring programs by questions is the most efficient and effective strategy to obtain meaningful ecological results. Although question setting is inherently difficult, driving monitoring programs by well-formulated and tractable questions is the best way to avoid inefficient and ineffective monitoring and squandering of limited resources.

Adaptive monitoring

The three broad kinds of problem that we outline above suggest that, by contrast, there are some key features that should accompany successful and effective monitoring programs. Such programs should: (i) address well-defined and tractable questions that are specified before the commencement of a monitoring program; (ii) be underpinned by rigorous statistical design; (iii) be based on a conceptual model of how an ecosystem might work or how the components of an ecosystem that are targeted for monitoring (e.g. a population) might function; and (iv) be driven by a human need to know about an ecosystem (e.g. the effects of a pollutant or changes in climate) so that they 'pass the test of management relevance' (*sensu* [28]). That is, the program is useful for assisting improvements in the management of natural resources.

We propose a new approach to monitoring programs that encompasses these features and we believe that it is relevant to an array of monitoring approaches, ranging from ecosystems to the components of ecosystems such as populations of individual species. We term this new paradigm 'adaptive monitoring' and show the key steps in Figure 1. The adaptive monitoring framework is motivated by questions that are carefully posed at the outset. Indeed,

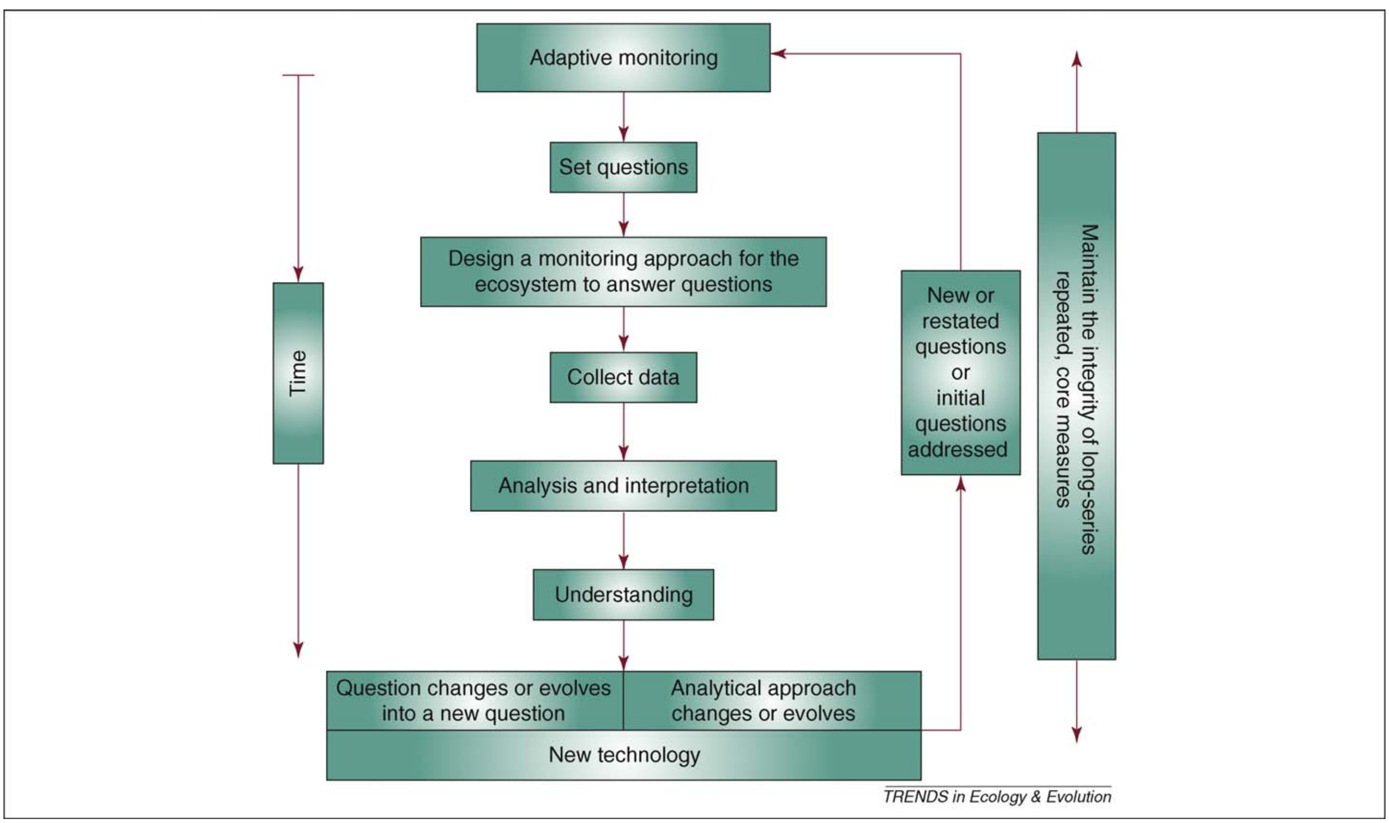

Figure 1. Adaptive monitoring provides a framework for incorporating new questions into a monitoring approach for long-term research while maintaining the integrity of the core measures. Initial key steps are the development of critical questions and a robust statistical design.

as in all successful science, defining the questions is a key step. Close attention to which questions to set could quickly indicate that long-term research and monitoring are not needed. For example, some kinds of behavioral ecology question can be resolved by short-term investigations, such as conspecific influences on bird vocalization [29].

Setting clear objectives and framing tractable questions will help resolve differences of opinion about what to monitor because that will be based on the questions asked. It also will circumvent arguments about whether particular entities are 'indicators,' again because the entities selected for monitoring will be those that are appropriate for answering the questions being posed.

A fundamental part of the adaptive monitoring paradigm is that the question setting, experimental design, data collection, analysis and interpretation are iterative steps (Figure 1). A monitoring program can then evolve and develop in response to new information or new questions. For example, it might be appropriate to alter the frequency of monitoring and data collection when key entities are changing at rates that differ from those initially anticipated. An adaptive monitoring approach also enables questions to change when the initial questions have been answered, or for when new questions need to be posed, or, if new protocols are embraced when, as for example, might occur when new technology develops to enhance field or laboratory measurements, within an overall monitoring framework. An important caveat here is that the adoption of new sampling or analytical methods must ensure that the integrity of the long-term data record is neither breached nor distorted.

The importance of setting questions

A rigorous approach to setting questions and identifying target entities will aid the development of an appropriate experimental design to underpin an adaptive monitoring program. Posing good questions lies at the heart of good science and also good long-term research and monitoring. However, developing good questions is difficult and here we propose two ways to help improve question setting.

First, we believe that it is essential to develop a robust conceptual model of the ecosystem that is being targeted for long-term research and monitoring. This step provides the framework around which to pose questions and gather data to answer those questions. We show in Figure 2 an example of the conceptual model that was the foundation for the successful long-term research and monitoring program at the Hubbard Brook Experimental Forest (HBEF) in New Hampshire, USA [16,30]. Long-term monitoring at HBEF revealed significant losses of base cations from the forest ecosystem via stream water [31]. Within the context of the conceptual model (Figure 2), it was possible to evaluate these losses in terms of the impact of acid rain on the ecosystem.

Second, developing appropriate questions around a conceptual model must occur through a partnership among scientists, statisticians, policymakers and natural resource managers. A true partnership is essential because policymakers and resource managers will often not know how to frame questions in ways that can be resolved by well-executed, long-term research and monitoring, or might initially pose too many questions without prioritizing them. Conversely, scientists will often not fully comprehend

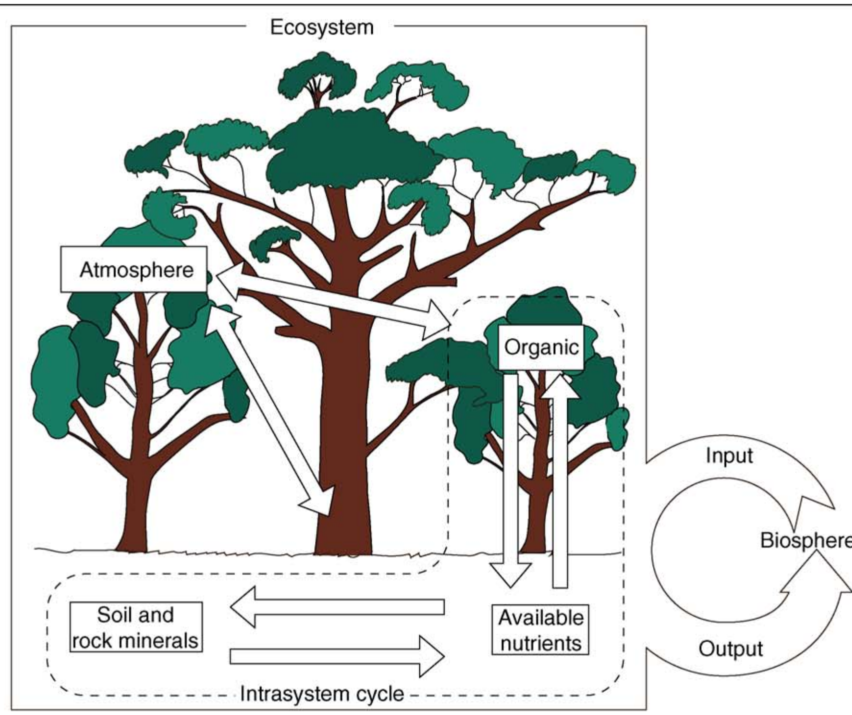

Figure 2. A conceptual model for biogeochemical relationships and input and output fluxes in a terrestrial ecosystem. This conceptual model was used successfully for decades to guide thinking and research for the Hubbard Brook Ecosystem Study in the White Mountains of New Hampshire, USA, in particular how management interventions might alter the ecosystem and how carefully formulated questions might be used to guide tests of the impacts of management practices. Redrawn, with permission, from Ref. [30].

the kinds of problem faced by policymakers and resource managers that need to be addressed by long-term research and monitoring [28]; neither will scientists necessarily be fully aware of the policy options and range of management interventions available for testing and monitoring in a particular ecosystem [21]. Thus, without guidance and consultation, scientists might implement long-term research and monitoring programs that answer questions with limited value for informing specific management actions. Moreover, although they are the goal, not all answers will be helpful to managers. Professional statistical advice is essential to ensure that an appropriate experimental design can be developed to answer rigorously the questions conjointly conceived by scientists, policymakers and resource managers.

There are now well-developed collaborative approaches to assist people to work successfully in teams [32,33] and to help set appropriate questions for improved natural resource management [34,35]. Monitoring programs developed through such collaborative partnerships can sometimes lead to the discovery of important environmental problems and, hence, can be useful to natural resource managers and policymakers. There are numerous examples of this, including the discovery of acid rain in North America [36], long-term changes in atmospheric carbon dioxide related to climate change [37] and the response of lake systems to interventions designed to reduce eutrophication [38].

An example of adaptive monitoring

Here we give brief examples of how adaptive monitoring might work in practice. Preceding and following a management intervention (in this case the construction of a wastewater treatment plant to lower phosphorus loading to a lake in North America in an attempt to reduce eutrophication), long-term monitoring of phytoplankton diversity and productivity and water chemistry was established. After a decade, it became apparent that, because of the changing climate, it also would be important to monitor changes in thermal stratification and duration of ice cover for the lake to evaluate the rate of recovery from eutrophication. To adapt the monitoring scheme, several issues needed to be considered and resolved. For example: (i) how do these new parameters fit into the conceptual model for this environmental problem? (ii) What new question(s) should be posed and new measurements made to address the problem? For example, a possible new question might be: is there an effect of increasing temperature on water circulation patterns and algal productivity in the lake? (iii) What statistically based experimental design would be needed to answer this question? (iv) How can the integrity of the long-term nature of the data record not be violated given that new questions have been posed and new or additional monitoring protocols will be required? For example, this requirement means that careful steps need to be taken to ensure that new field methods are calibrated against previously used field methods [39].

The example outlined briefly above describes an adaptive monitoring approach to water treatment problems in a lake system. However, the paradigm is readily applicable to many other kinds of situation where management objectives and goals can be broad and complex. For example, the February 2009 fires in southeastern Australia have burned extensive areas of forest used for wood production and protected areas that have been studied as part of a 25 year integrated ecosystem and population monitoring program [40]. These forests are part of a complex system for which there are many issues and multiple management objectives. New questions have now been carefully developed in close consultation with the managers and policymakers for these forests about post-fire ecological recovery on land under different tenures, particularly officials from the Victorian Department of Sustainability and Environment, Parks Victoria and Melbourne Water. The adaptive monitoring framework has been used to guide the process of collaborative question setting, experimental design and the establishment of new phases of on-ground monitoring (http://fennerschool-research.anu.edu.au/cle/vchstudy/longtermmon.php).

These two examples indicate that the adaptive monitoring paradigm does not lead to a set of highly specific prescriptions that can be applied uncritically to any given monitoring program. Rather, its specific application will be context dependent and will vary in response to the particular problem to be resolved, the questions being posed and the composition and ecological processes of particular ecosystems. Our approach also emphasizes that adaptive monitoring is not mindless data collection, but instead pivots on the legitimate scientific practice of posing rigorous questions and carefully designing and implementing appropriate studies to answer them.

The proposed new paradigm of adaptive monitoring shares some common elements with the adaptive management paradigm (*sensu* [21]), which is much discussed but rarely implemented [19,41]. That is, (i) the question-setting step will often be best motivated and implemented by testing management interventions that are relevant to true policy options for the management of ecosystems and natural resources [21,42]; (ii) the approach helps generate data useful for discriminating among competing hypotheses about how a managed system responds to particular management actions; and (iii) the questions developed for testing are based on *a priori* predictions about how a conceptual model suggests an ecosystem will function and what the response of monitored entities will be to competing management interventions in that ecosystem. In addition, the process of evolving questions in the adaptive monitoring framework is akin to the 'double-loop' learning process in adaptive management [21].

Conclusions

We strongly believe that the adaptive monitoring paradigm has the potential to significantly improve the poor record of high-quality, long-term ecological research and monitoring worldwide. It should increase the credibility of monitoring programs within the scientific community by demonstrating the pivotal roles of the traditional scientific method of posing and then answering questions. It should elicit greater engagement by resource managers by ensuring that the questions posed pass the test of management relevance. It also should encourage and provide confidence to policymakers and funders in their attempts to be responsible in the use of public funds. Finally, the adaptive monitoring paradigm will assist scientists and resource managers in moving beyond protracted debates about how to monitor and what to monitor, debates that have greatly impeded progress in ecological research over the past few decades.

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