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Review

The science and application of ecological monitoring

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ABSTRACT

We provide a broad overview of the underlying philosophy of ecological monitoring. We argue that the major characteristics of effective monitoring programs typically include: (1) Good questions. (2) A conceptual model of an ecosystem or population. (3) Strong partnerships between scientists, policy-makers and managers. (4) Frequent use of data collected.

We classify monitoring programs into three categories – (1) Passive monitoring, which is devoid of specified questions or underlying study design and has limited rationale other than curiosity. (2) Mandated monitoring where environmental data are gathered as a stipulated requirement of government legislation or a political directive. The focus is usually to identify trends. (3) Question-driven monitoring, which is guided by a conceptual model and by a rigorous design that will typically result in a priori predictions that can be tested.

There are advantages and disadvantages of mandated monitoring programs, which are typically large-scaled, and generally smaller-scaled, question-driven monitoring programs. For example, while question-driven monitoring programs can provide insights into the ecological processes giving rise to emergent environmental patterns, spatial generalization from them is difficult because results may not extrapolate well to other regions, states or to a national level. Conversely, while mandated monitoring can be useful for producing coarse level summaries of temporal changes in a target population or resource condition they may not identify the mechanism influencing a change in an ecosystem or an entity. A key remaining challenge is to develop much improved mandated monitoring programs through more widespread adoption of the features of successful question-driven monitoring programs in efforts to enhance biodiversity conservation and environmental management.

Contents

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1. Introduction

Countless scientific articles, books, management plans and other documents have been written about the need to do long-term ecological monitoring (e.g. Franklin et al., 1999; Goldsmith, 1991; Krebs et al., 2008; Likens, 1989, 1992; Lovett et al., 2007; Spellerberg, 1994; Strayer et al., 1986; Thompson et al., 1998). Indeed, as part of writing this review, a search of the ecological literature published between 1985 and mid-2009 produced more than 5500 articles with the term 'monitoring' in the title or abstract. Within this very large literature are some distinct biases in subject material. First, much has been written about specific methods of monitoring a particular entity, but we believe that these will often be relevant only to that entity (e.g. a species or group of species) or to a given place; they may not be readily transferable to other entities or landscapes. A second bias in the literature is toward generic lists of entities that are advocated as "mandatory" to monitor and generic frameworks to guide the measurement of these entities. However, we believe that the transferability of these approaches to other ecosystems can be problematic. Third, much of the monitoring literature focuses on statistical methods. While these approaches are valuable, they may not be relevant to specific questions or problems that any given particular monitoring program aims to address. Fourth, much of the monitoring literature focuses on "indicators" and claims that entity X or species Y is an "indicator". Often these claims are unsubstantiated. Where they are substantiated, the generality of the indicator function can be limited – either spatially, taxonomically or both, and this approach may not be helpful for those proposing to establish new monitoring programs.

In this paper, we do not revisit these already well-covered themes and advocate, for example, particular field techniques, statistical methods, or target entities for long-term ecological monitoring. We have not undertaken a meta-analysis or systematic review of world-wide, monitoring programs, nor do we provide summary statistics on different kinds of monitoring programs or the range of entities targeted in monitoring programs. Rather, our focus is on the underlying philosophy of monitoring for ecological knowledge. First, we provide a definition of long-term monitoring. We then classify long-term monitoring into three broad categories – (1) curiosity-driven or passive monitoring, (2) mandated monitoring, and (3) question-driven monitoring. We then discuss the key characteristics of each category and present a short treatise on the kinds of ecological values that can be derived from data gathered in long-term, ecological monitoring programs. Our assessment of the vast literature on monitoring suggests that monitoring programs are often ineffective or fail completely and we present a series of reasons for these problems. As a counter to that section, we then present a description of the key characteristics of effective ecological monitoring programs. The concluding section of this paper focuses on two topics: (1) some important impediments to be overcome in improving monitoring programs – particularly given current attributes of the culture of science and society and (2) the challenges of integrating data from different kinds of monitoring programs that are undertaken at different spatial scales and with different approaches.

Our aim in writing a set of general philosophical perspectives on long-term monitoring is to foster a renewed interest in, and an improvement of, ecological monitoring. We consider that it is now increasingly critical to undertake high-quality, question-driven, statistically-designed monitoring, given the rapid increase in the effects of climate change (Lawler, 2009; Heller and Zavaleta, 2009), other human-accelerated environmental changes (Likens, 1991), and the need to reverse current, widespread environmental degradation (Millennium Ecosystem Assessment, 2005). We believe that given the increasing seriousness of environmental problems throughout the world, there never has been a more important time to establish effective and interacting monitoring programs.

2. A definition of long-term monitoring

For the purposes of this review, we use a practical, operational definition of long-term monitoring efforts that is:

> *Repeated field-based empirical measurements are collected continuously and then analyzed for at least 10 years.*

Some in the scientific community view monitoring as a management activity unrelated to scientific research (e.g. Hellawell, 1991). Conversely, we believe that long-term monitoring is both science and research (Nichols and Williams, 2006; Yoccoz et al., 2001). Good science and hence good monitoring starts with good questions. Good questions are developed by: (1) Using critical thinking. (2) Building robust conceptual models of how ecosystems work (e.g. Bormann and Likens, 1967). (3) Testing "true" policy questions (Walters, 1986) of management relevance (Russell-Smith et al., 2003). (4) Promoting open dialog between scientists and managers (Lawton, 2007; Likens, 1989; Likens et al., 2009). And, (5) Critically evaluating study manipulations, both designed and opportunistic.

We acknowledge there are many nuances to discussions about what constitutes "long-term" monitoring. Strayer et al. (1986) note that some workers consider long-term studies to be those that continue beyond the generation time of dominant organisms in an ecosystem or sufficiently long to quantify the key processes, which structure the ecosystem under investigation. This definition would mean that studies of bacterial assemblages with very rapid generation times would be long-term investigations if they were to persist for a year or even a month. Conversely, a 300-year study of stands of Giant Sequoia (*Sequoiadendron giganteum*) in western North America in which the dominant trees may live for over 1000 years would not qualify as a long-term study. These considerations are important because they emphasize the variable lifespan of different organisms, but they are not feasible to use for many ecosystem analyses.

2.1. What is not long-term monitoring

We do not consider long-term monitoring to be haphazard revisits to a site after a prolonged absence (e.g. Currie and Parry, 1999; Smith et al., 2007) or simply measuring something in the environment. Although simulation models can make projections for thousands of years, we also do not consider simulation modeling per se to constitute long-term monitoring.

3. Three broad kinds of monitoring

We believe there are three broad types of long-term monitoring within the general definition we have proposed above. These are curiosity-driven or passive monitoring, mandated monitoring and question-driven monitoring. We further discuss these kinds of monitoring in the remainder of this section.

3.1. Curiosity-driven or passive monitoring

This is monitoring devoid of specified questions or underlying study design and with little or no purpose other than curiosity. It may be done out of inquisitiveness, but has limited usefulness in addressing environmental problems or in discovering how the world works because it is not hypothesis-driven and because it lacks management interventions or different experimental treatments which facilitate scientific understanding about such things as ecosystem responses to natural or human disturbance.

3.2. Mandated monitoring

This is monitoring where environmental data are gathered as a stipulated requirement of government legislation or a political directive such as monitoring of weather or river flow. Rigid quality assurance protocols are usually strictly mandated in this type of monitoring. Mandated monitoring does not attempt to identify or understand the mechanism influencing a change in an ecosystem or an entity. Rather, the focus is usually to identify trends (e.g. whether environmental conditions are getting "better" or "worse"). Data from mandated monitoring programs is often used in state of environment reports (e.g. The Heinz Center, 2008), although this is not always the case (e.g. in Australia; State of Environment 2006).

3.3. Question-driven monitoring

This is monitoring guided by a conceptual model and by a rigorous study design. The use of a conceptual model will typically result in a priori predictions that then can be tested as part of the monitoring program. Often such learning is informed by strongly contrasting management interventions (Carpenter et al., 1995). In statistical parlance, such studies might be termed "longitudinal studies with interventions" (e.g. Lindenmayer et al., 2008). In many respects, these methods are akin to formal experiments and natural experiments, such as wind storms, and hence we see that the distinction between monitoring and research is blurred. Thus, such approaches may lead to robust predictive capacity and enable an investigator to pose new questions – an advantageous part of the Adaptive Monitoring framework (sensu Lindenmayer and Likens, 2009), in which a monitoring program can evolve as key questions change. Predictive capacity can be of immense value for ecologists, resource managers and decision-makers, in contrast to simply extending trend lines such as in many mandated monitoring programs.

Obviously, there can be overlap between these broad categories of monitoring. For example, a rigorous statistical framework can characterize both mandated and question-driven monitoring. Mandated monitoring is often coarse-scale, leading to assessments of resource condition, but providing limited understanding of ecological mechanisms. Question-driven monitoring is often the converse. It is finer scaled and often process-based, but it is very difficult to make valid spatial extrapolations to larger scales (e.g. regions or continents). As we discuss below, we believe these differences are often overlooked in an effort to develop an all-encompassing, "one-size-fits-all" framework for monitoring programs.

4. Some ecological values and uses of datasets from long-term monitoring

All organisms, including humans, depend upon the functioning of ecosystems for their well being and survival. High-quality ecological information collected over long periods provides critical insights into changes in these ecosystem services. Without this information, we would have no knowledge about the changing status of the life-support system of the planet. Therefore, data from long-term monitoring programs are fundamentally valuable for many purposes, including:

- Documenting and providing baselines against which change or extremes can be evaluated (e.g. Keeling et al., 1995, 1996).
- Evaluating ecological responses to natural or experimental disturbance (Schindler et al., 1985).
- Detecting and evaluating changes in ecosystem structure and function (Krebs et al., 2001; Danell et al., 2006).
- Identifying ecological surprises (e.g. Zhan et al., 2006).
- Guiding evidence-based environmental legislation (e.g. laws to control air and water pollutants) (Likens, 1992).
- Generating new and important questions about ecological dynamics (Persson et al., 2009).
- Providing empirical data for testing ecological theory (Shrader-Frechette and McCoy, 1993) and developing models such as computer simulation models (Burgman et al., 1993). And,
- Providing data for mining when exploring new questions (e.g. Stelzer and Likens, 2006; Cole et al., 1994).

5. Poor record of long-term ecological monitoring

Although there have been some highly successful long-term research and monitoring programs (e.g. Goldman, 1981; Lawes Agricultural Trust, 1984; Likens, 1985; Lund, 1978; Schindler et al., 1985), there is a prolonged history of poorly planned and unfocused monitoring programs that are either ineffective or fail completely (see Allen, 1993; Krebs, 1991; Legg and Nagy, 2006; Norton, 1996; Orians, 1986; Stankey et al., 2003). For example, Allen (1993) and Norton (1996) have described how nearly half of the more

Table 1
Reasons why monitoring programs and long-term studies can fail or be ineffective.

Problem	Key reference
Mindless, lacking questions	Lindenmayer and Likens (2009)
Poor experimental design	Bernhardt et al. (2005)
Monitoring too many things poorly rather than fewer things well	Zeide (1994)
Failure to agree on what entities to monitor	Lindenmayer and Likens (2009)
Flawed assumption that all monitoring programs can be the same	Lindenmayer and Likens (2010)
Scientific disengagement from monitoring programs	Franklin et al. (1999)
Poor data management	Caughlan and Oakly (2001)
Loss of integrity of the long-term data record	Strayer et al. (1986)
Lack of funding	Caughlan and Oakly (2001)
Loss of key personnel	Kendeigh (1982)
Unexpected major event	Laurance and Luizão (2007)

than 55 monitoring programs on tussock grasslands in New Zealand were unreported, indicating a failure rate that is extremely high. Similarly, Ward et al. (1986) lament about the "data-rich but information-poor" syndrome in water quality monitoring.

Monitoring programs can be ineffective or fail for many reasons as we summarize in Table 1. These characteristics mean that it can be difficult to determine when it is appropriate for a monitoring program to continue, to cease, or when a program can be modified and made more effective. Well-designed and implemented monitoring programs that do not have these characteristics may still fail for other reasons such as lack of funding, or an unforeseen event like a major human or natural disturbance (although both can sometimes provide research and monitoring opportunities). In the remainder of this section we further discuss four of the key reasons why monitoring programs can be ineffective or fail: (1) lack of questions, (2) poor study design, (3) failure to properly articulate what to monitor, and why it is important to monitor targeted entities, and (4) an inappropriate assumption that there is a single approach to monitoring that is uniformly applicable to all monitoring programs.

5.1. Passive, mindless and lacking questions

Some monitoring programs have been driven by short-term funding or a political directive rather than being underpinned by carefully posed questions and objectives. Roberts (1991) argued that too often monitoring has been: '*...planned backwards on the collect now (data), think-later (of a useful question) principle...*'. A paucity of questions is a serious problem because it often results in monitoring programs being poorly focused and incapable of delivering effective outcomes (Field et al., 2007; Legg and Nagy, 2006; Martin et al., 2007). In other cases this means that it is not possible to diagnose the cause of a change which, in turn, limits predictive capability either through time or spatially to other landscapes or environments.

5.2. Poor study design

A second problem has been that monitoring programs have often been very poorly designed at the beginning of a study (Krebs, 1991). Good design is an inherently statistical process and a critical component of any successful monitoring program. But professional statisticians are often left out of the design phases of monitoring programs. Issues are then overlooked such as: (1) calculations of statistical power to detect trends (Field et al., 2007; Foster, 2001; Reed and Blaustein, 1995; Strayer, 1999), for example levels of replication of different treatments, (2) detectability of a particular individual biotic species or chemical element (Martin et al., 2007; Pellet and Schmidt, 2005; Yoccoz et al., 2001), (3) optimization of field methods and statistical design (e.g. Joseph et al., 2006), (4) the importance of contrasts between treatments (e.g. where there is a human intervention and where there is not) (Krebs, 1991; Lindenmayer and Franklin, 2002; Walters, 1992), and (5) the value of innovative rotating of sampling methods for increasing inference (Welsh et al., 2000).

Martin et al. (2007) support our view that proponents of monitoring programs should spend more time getting their study design right. For example, some of the strongest designs to guide a monitoring program will often be those where there are contrasting management interventions that enable strong inferences to be made about both how and why an ecosystem or other entity, like a population, has changed either spatially, temporally, or spatio-temporally. The challenges of good study design, coupled with the rigor of subsequent statistical analyses of high-quality environmental data, re-emphasize our earlier point that monitoring programs need to be good science (Lindenmayer and Likens, 2009; Nichols and Williams, 2006).

Poor design has numerous knock-on effects that can result in the failure of a monitoring program (Legg and Nagy, 2006). For example, it can lead to the results of work not being written up, or when it is, making it difficult for findings to be published in reputable outlets. Poor design also means that it is difficult to assess the effectiveness of a management intervention (e.g. application of a prescribed burning regime in a forest) (Whelan, 1995) or a major environmental initiative (e.g. national or even continental agro-environmental schemes) (Halkowicz, 2008; Kleijn et al., 2006). For example, it is presently not possible to assess the effectiveness of ~$US15 billion worth of projects on river restoration in the USA because of poor study design and a lack of rigorous monitoring of interventions designed to improve river and stream environments, and in ~90% of projects there was no form of assessment or monitoring of project effectiveness and limited data to determine which activities had been successful and which had not (Bernhardt et al., 2005). Hence, key opportunities for management learning have been lost. In other cases, poorly designed monitoring programs could lead to an incorrect decision being made, such as the down-listing of an endangered species when it should not be (Martin et al., 2007).

5.3. "Snowed by a blizzard of ecological details"

A third issue is that the design of monitoring programs is often prefaced by protracted (and frequently unresolved) arguments about what to monitor. One response has been to monitor a large number of things (the so-called "laundry list"). Some monitoring programs are indeed based on very extensive lists (Zeide, 1994). However, the "laundry-list" approach can have a range of problems. First, it can divert those responsible for establishing a monitoring program from posing well-crafted and tractable questions. Second, resource and time constraints frequently mean that a poorly focused "laundry list" will result in many things being monitored badly. It is simply not possible to monitor a vast number of entities properly (Zeide, 1994). Third, a "laundry list" may make a monitoring program too expensive to be sustained financially beyond the short-term and ultimately lead to its collapse. In cases where the objective of a monitoring program is to assess the impacts of resource management practices (e.g. prescriptions for logging operations), demands to measure a long list of attributes may mean that the costs of a monitoring program are mis-matched with the level of economic return from that management practice (Franklin et al., 1999). Finally, a "laundry-list" approach can create problems with the statistical design of a monitoring program. We believe that "laundry lists" should be regarded only as starting points in planning; as they do not reflect the realities of operating or financing a credible monitoring program.

5.4. Squabbles about what to monitor

An alternative response by some workers to the "laundry-list" approach has been to argue that "indicator species" or "indicator groups" should be the targets of monitoring programs (Andersen and Majer, 2004; Cantarello and Newton, 2008; Dung and Webb, 2008; McLaren et al., 1998; Sparrow et al., 1994; Spellerberg, 1994; Woodward et al., 1999). Many would argue that the group of organisms they study is special and any valid monitoring program cannot proceed without including them. We have found that over 55 major taxonomic groups have been proposed as indicators for monitoring programs, ranging from viruses and fungi and bryophytes to invertebrates and virtually all major vertebrate groups. We found that only very rarely was it explicitly stated: (1) what these species or groups were actually indicative of, particularly at the ecosystem level and (2) the circumstances where these species or groups were or were not appropriate indicators.

We believe that the problems of "laundry lists" and indicator species can be avoided by carefully crafting questions at the onset of a monitoring program, using a well-conceived model to help conceptualize a particular ecosystem and make predictions about ecosystem behaviour and response (see below). These key steps will help identify those entities most appropriate for monitoring.

5.5. Assumption that one size fits all

Many scientific articles make recommendations about generic frameworks for monitoring programs. Recommendations are made about lists of entities to be measured and the way they should be measured. These kinds of recommendations are understandable given a desire to create compatibility of data recording and increased co-ordination and comparison across studies. However, this approach is problematic for a range of reasons and can cause monitoring programs to be either ineffective or fail completely.

We believe it is often not appropriate to measure the same entities (e.g. the same species groups or ecosystem function) in different places, an approach which is frequently mandated in very large-scale monitoring efforts such as the International Biological Program (IBP). Measuring diverse assemblages of frugivorous birds may well be valid in tropical rainforests where this group can be species rich, but it is likely to be of little merit in desert environments where this group may have relatively few representatives. Similarly, the kinds of threatening processes in a tropical savanna and an alpine meadow may be so different that environmental monitoring or biodiversity monitoring programs in them would likely be conducted very differently. Even within the same broad vegetation type (e.g. tropical rainforest), the application of identical monitoring protocols may not be particularly informative because of differences in biota, key ecological processes, or other factors (cf. Martins et al., 2007).

As we have outlined above, the choice of what entities to measure and how they should be measured is best guided not by a generic framework, but rather by well-defined and scientifically tractable questions (cf. Martins et al., 2007).

6. Characteristics of effective monitoring programs

From our extensive assessment of the very large literature on ecological monitoring, we believe that it is possible to identify some key features of effective or successful monitoring programs. We summarize these in Table 2 and discuss several of them in more detail in the remainder of this section. It is important to identify such factors to improve public perspectives of ecological monitoring and provide policy-makers with reasons to continue funding investments in monitoring programs.

6.1. Good questions and evolving questions

Posing good questions lies at the heart of good science and hence is essential to effective monitoring (Nichols and Williams, 2006). This is a far-from-trivial task. Some authors argue that ecologists and resource managers have been poor at problem definition and objective setting (Peters, 1991). Good question-setting must result in quantifiable objectives that offer unambiguous signposts for measuring progress (Lindenmayer et al., 2007). Thus, good questions must be scientifically tractable and test real policy and resource management options (Walters, 1986), requiring a well-developed partnership among scientists, statisticians, resource managers and policy-makers (Gibbons et al., 2008). Key questions

Table 2
Some critical components for maintaining effective monitoring programs (Modified from Likens (2007)).

Plots and study sites should be permanently marked and identified. Detailed descriptions of study areas and field protocols filed in more than one location with sufficient detail provided so that other investigators can find sites, reproduce calculations and methods at some later date
Appropriate and adequate reference and/or control sites established at the beginning of the study
Availability of appropriate field equipment
Long-term security of research sites and field equipment
Reliable access to field sites, including availability of safe and reliable vehicles, such as trucks, boats, snowmobiles
Careful attention to field and laboratory protocols. Methods and procedures standardized to the extent possible, and inter-calibrated with other organizations or individuals doing similar studies. Calibration of analytical results by comparison against standardized samples. Analytical methods or collection procedures should not be changed without testing fully the effect of the new procedure on the long-term record
Match the scale of monitoring to the spatial and temporal dimensions of the question being addressed. Duration of measurements at least as long as the phenomenon being evaluated, or scaled to the frequency of the event or the life history of the organism being studied
Methods or procedures developed for one location or study should not be adopted for another area or study without careful testing and justification
Strict database management and data storage, including the agility to adapt with changes in technology. Dataset storage in at least two separate locations to avoid accidental loss. Long-term storage of samples is highly desired
Stability and competence of staff
Resolution of intellectual property issues at the onset of a project
Significant time in the field by senior and junior scientists working together
Constant updating and reviewing of data sets (including scrutinization for errors)
Use long-term data sets to answer questions
Maintenance of a stream of publications to develop project credibility and outreach
Maintenance of scientific independence and integrity of the project by avoiding conflicts of interests
Partnerships among scientists, policy-makers and staff from resource management agencies to ensure that long-term work passes the test of management relevance
Availability of adequate, sustained and reliable funding
Ongoing development and evolution of questions that can use the information from the monitoring program as a frame or operate parallel to it

often change or evolve during a long-term study or monitoring program requiring nimble responses (Ringold et al., 1996), but without breaching the integrity of the overall monitoring program (Lindenmayer and Likens, 2009).

6.2. The use of a conceptual model

A conceptual model is a diagrammatic representation of how key components and ecological processes of a target ecosystem or population interact and/or influence one another (e.g. Bormann and Likens, 1967). An example of a conceptual model is presented in Fig. 1. A conceptual model of the ecosystem or particular entity to be monitored is one way to help identify and focus on the question/s to be addressed (Woodward et al., 1999).

A conceptual model, developed at the beginning of a study, forces the gathering together of ideas to formulate theory about how a target entity works, and helps to ensure that all the relevant components are captured in the project design. By understanding the input and outputs within a conceptual model framework, it is then possible to understand the mechanisms for change in an ecosystem and what responses might occur as a consequence of management interventions.

A conceptual model needs to be able to guide ongoing research and thinking and becomes a focal point for discussions among partners – scientists, managers and policy-makers about how an ecosystem might be managed and monitored. Conceptual models can fail to guide long-term research and monitoring when they are too detailed, too abstract or vague, unsuitable for answering specific or new questions, or are not pertinent to the research site.

In many cases, there may be two or more competing conceptual models of an ecosystem process or other entity that is targeted for monitoring. The fundamental differences among those models can also be useful for designing monitoring programs as they can highlight the types of data needed to discriminate among those models (Nichols and Williams, 2006).

6.3. Well-developed partnerships

Most successful monitoring programs are built on partnerships between people with different but complementary skills. These include scientists, statisticians, policy-makers and resource managers who may be from government and non-government organizations, universities, research institutions and other organizations. Well-developed partnerships between these groups of people are needed to validate policy-relevant and management-relevant projects, as well as contain the scientific and statistical rigor required that ensure results are robust and conclusions are workable and defensible.

Partnerships are important for other reasons. They can facilitate the flow of information between parties in ways that people from different backgrounds and with different expertise can readily understand. In other cases, particular agencies may not maintain the expertise and capability to do long-term monitoring.

True collaborative partnerships are also essential because policy-makers and resource managers will often not know how to frame questions in ways that can be resolved by well-executed monitoring, or may initially pose too many questions without prioritizing them. They also may have unreasonable expectations about what questions or problems can and cannot be solved by scientific projects and how much effective monitoring can cost. Thus, policy-makers need to understand better the scientific approach and the importance of posing the right questions in the correct way. Conversely, scientists need to articulate better what kinds of questions they can and cannot answer. They also need to understand better the complexity of the policy process (Clark, 2002; Pielke, 2007). Scientists will often not fully comprehend the kinds of key problems faced by policy-makers and resource managers that need to be addressed by long-term monitoring (Russell-Smith et al., 2003). Nor will scientists necessarily be fully aware of the policy options and the range of on-ground, management interventions available for testing and monitoring in a particular ecosystem (Walters, 1986).

Developing partnerships is a challenge because representatives of different groups use different "languages" and jargon, have different work cultures, different reward systems, and different skill sets (Gibbons et al., 2008). Trust and mutual respect is essential, in part because various kinds of knowledge – scientific, policy and political knowledge – together influence decision-making in natural resource management (Pielke, 2007). Hence, for example, good science alone is insufficient as often it will be necessary to translate the results from good science into a form that policy-makers and resource managers can understand and use (King, 2004).

6.4. Strong and dedicated leadership

Strong, dedicated and focused leadership is inimical to almost all effective monitoring programs – a champion with the passion to keep the work going (Lovett et al., 2007; Norton, 1996; Strayer et al., 1986). In many cases, long-term projects and team leaders even become synonymous (Strayer et al., 1986). Effective leadership is pivotal to all of the fundamental characteristics of successful monitoring programs described earlier – setting appropriate questions, identifying new questions, developing a workable conceptual model, resolving what to measure, guiding study design, analyzing data, communicating results to management agencies,

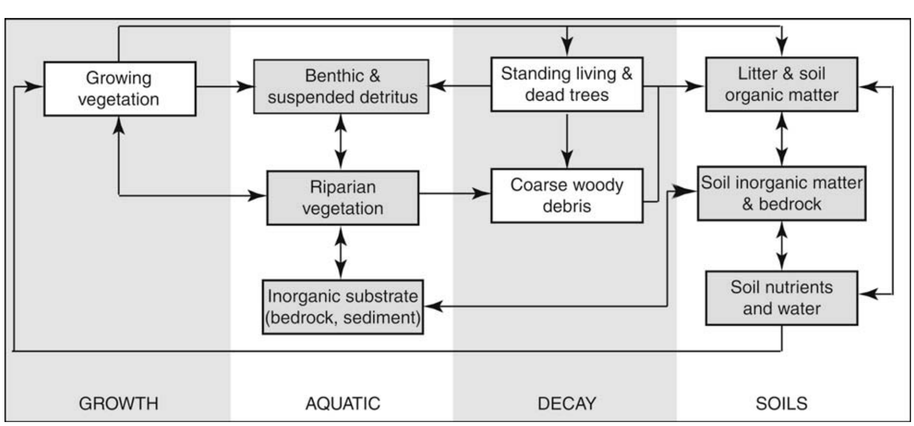

Fig. 1. The conceptual model guiding studies of coarse woody debris at Warra Long-Term Ecological Research site in southern Tasmania. (Redrawn from Grove (2007).)

policy-makers and the public, and establishing and maintaining partnerships. Leadership is also critical to securing funding and ensuring good project management, both of which contribute to effective long-term monitoring programs. Leadership embodies both scientific and management leadership; indeed, partnerships appear to work best when there is a problem, such as an environmental problem, with a shared responsibility to find a solution.

6.5. Ongoing funding

No project can proceed or be maintained without access to funding. Generating the funding to maintain long-term monitoring programs is a truly major challenge and few individuals and organizations have ever managed to do it successfully (Strayer et al., 1986). We suggest that many of the underlying problems appear to be associated with the culture of short-termism that pervades the culture of science and indeed the culture of western societies.

Successful programs where funding has been maintained are characterized by many of the factors discussed above, such as strong leadership, evolving questions that are highly relevant to resource management and society's need to know, and high levels of scientific productivity (i.e. published articles, books and media reports). In some cases, successful ongoing funding is linked with appropriate matching of the size of a monitoring program with the scale of a human activity (e.g. a logging operation) (Franklin et al., 1999; Lindenmayer and Franklin, 2002) or the overall budget for the management of a National Park or nature reserve (Edwards et al., 2003). In some cases (e.g. www.earthwatch.org/FieldReportpdf/Dyer_fieldreport2005.pdf) the passion of an individual is so strong that personal funds have been used for years to support long-term monitoring.

6.6. Frequent use of data

Another key ingredient for maintaining long records of high-quality is the frequent examination and interrogation of these data. Such examinations result in important discoveries and stimulate new research and management questions. They are also the primary way problems such as errors and data artefacts are uncovered.

6.7. Scientific productivity

One criterion often used to gauge success is scientific productivity. We strongly believe that the results of monitoring programs must be published in peer-reviewed literature. This outreach is essential to inform the public, funders and resource managers about valuable findings, and helps to establish the credibility, quality and visibility of a project. This outreach is, in turn, essential to convince funders that investments are appropriate and should be maintained.

A potential problem is that it takes a long time to generate long-term trends and patterns with empirical data. Hence, it can take a long time to generate substantial scientific publications from such work. This delay can be perceived as a lack of productivity and threaten the continuity of a project. As a counter to this problem, we believe there can be considerable value in exploring avenues to generate rapid returns on long-term research and monitoring investments and hence highlight scientific productivity. A long-term monitoring program can be used as a framework around which shorter-term projects can be conducted. For example, retrospective or cross-sectional studies can serve as a prelude to longer-term projects and can provide key initial insights or questions. These other projects, often built around the major research and monitoring program (including student projects), enrich the overall effort.

Working with the news media to generate high-quality and timely reports about long-term data, particularly about trends and extremes discovered, can be another way to enhance outreach from long-term monitoring programs. Such reports can be very effective in informing the public, policy-makers and funders about environmental issues and the research being done (e.g. Likens, 1992).

6.8. Maintenance of data integrity and calibration of field techniques

New sensors, modified or new analytical procedures and real-time data can add significantly to long-term data (Hirsch et al., 2006), but offsets and glitches generated by new methodologies are a common problem in monitoring and must be addressed carefully. In the long-term Hubbard Brook Ecosystem Study in New Hampshire (USA), for example, an analytical chemical method or procedure is not replaced with a new one without first overlapping the two. This overlapping period may be for many months or for more than a year to compare results and avoid offsets in the record due to different methodologies (Buso et al., 2000). Also, many samples are stored for later analysis to help reconcile problems and to enable new questions to be pursued when new technology becomes available (e.g. see Alewell et al., 1999).

7. The methodology of effective monitoring

Based on some of the salient features that should accompany effective monitoring programs, we have previously proposed an "Adaptive Monitoring" framework (Lindenmayer and Likens, 2009). A fundamental part of this framework is that question-setting, study design, data collection, data analysis, and data interpretation are iterative steps. A monitoring program can then evolve and develop in response to new information or new questions. For example, it may be appropriate to alter the frequency of data collection when key entities are changing at rates different than those initially anticipated. An Adaptive Monitoring approach also enables questions to change, new questions to be posed, and new protocols to be embraced when, for example, new technology arises to enhance field or laboratory measurements within the overall monitoring framework.

An important caveat with the Adaptive Monitoring approach is that the adoption of new sampling or analytical methods must

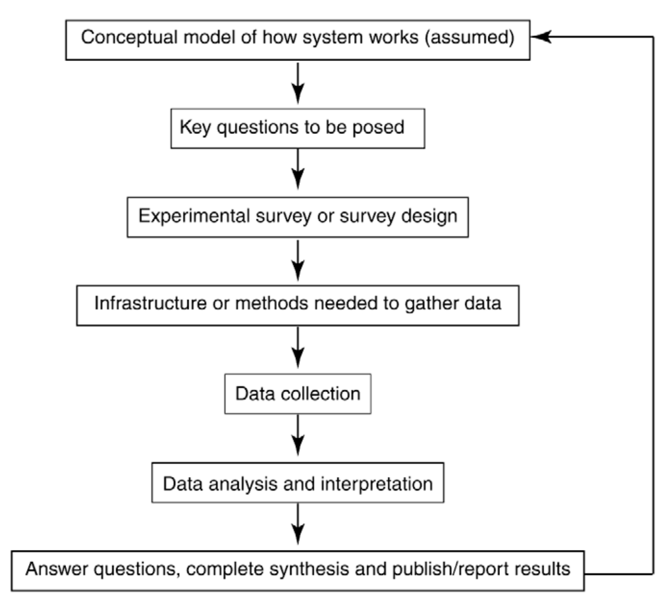

Fig. 2. Flow diagram of the sequence of key steps in a monitoring program.

ensure that the integrity of the long-term data is neither breached nor distorted. Another caveat is that sometimes particular questions cannot be addressed with a given long-term dataset (that it was not originally designed to address) and an entirely new investigation may need to be established.

The core principles of the Adaptive Monitoring framework mean that the approach is relevant to a wide range of circumstances and to all kinds of monitoring – from very simple to very complex programs as well as from mandated monitoring programs usually conducted at a coarse-scale to site- or landscape-level, and curiosity-driven monitoring programs. However, the Adaptive Monitoring framework 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 Adaptive Monitoring framework shares many common elements with the Adaptive Management paradigm (sensu Walters, 1986), which is much discussed but rarely implemented (Lindenmayer et al., 2007; Stankey et al., 2003). That is, (1) the question-setting step will often be best motivated and implemented by testing management interventions, which are relevant to policy options for the management of ecosystems and natural resources (Nichols and Williams, 2006; Walters and Holling, 1990), (2) there is an explicit acknowledgment of ignorance. That is, there are unknown things discovered that the monitoring work specifically did not set out to address (Walters, 1986; Williams and Johnson, 1995), (3) the questions developed for testing are based on a priori predictions from a conceptual model suggesting how an ecosystem might function and what the response of monitored entities might be to competing management interventions in that ecosystem, and (4) there are strong links between the iterative steps in the Adaptive Monitoring framework, which connect question-setting with management actions (e.g. an intervention) and an improved understanding of ecosystem or population responses.

8. Impediments to developing more and better monitoring programs

The two preceding sections of this review contrasted the characteristics of ineffective monitoring programs with the features of effective or successful ones. Our review of the scientific literature suggests that the former are more common than the latter and we believe there are at least four substantial impediments that must be overcome to develop more and better long-term ecological monitoring.

8.1. Structure of organizations

The structure of many organizations is not conducive to instigating and maintaining long-term monitoring programs. Many organizations have high staff turnover and are characterized by a paucity of institutional memory. There is limited or no psyche of long-term studies (O'Neill, 2008) or allied features such as fastidious data and sample curation or long-term data management. In addition, there is usually an emphasis on reducing staff numbers in these organizations during budget crises, leading to a severe drop in morale for those who are retained. Yet, retaining and then ensuring ongoing support for quality staff on the ground over prolonged periods is essential for successful monitoring.

8.2. Intellectual property issues

Successful long-term research and monitoring programs result in the collection of high-quality empirical data and are characterized by high-quality data management. However, an important, but often unresolved issue is intellectual property and data sharing in the wider ecological and resource management communities. Only rarely have reasonable and ethical rules of engagement been developed for data sharing between those who gather long-term field data and others who desire access to those data for modeling, data mining, and other analyses. Without appropriate attention to intellectual property issues at the beginning of a study, the development of better ways of data sharing (e.g. Jones et al., 2006) will be impaired and the full potential of valuable empirical data for enhanced environmental management will not be realized (Bertzky and Stoll-Kleemann, 2009).

Policies regarding public data dissemination should be thought through and clearly stated early in the process of establishing a monitoring program. Likewise, within teams of scientists doing long-term research and monitoring there needs to be a clear, articulated understanding also at the beginning of a monitoring effort about the role of team members and the use and attribution of data collected by individuals in the team (Likens, 2001).

8.3. The academic culture and rewards systems

Deeply ingrained attributes of current scientific culture and associated reward systems create substantial disincentives to undertake long-term ecological monitoring. For example, scientific culture favours new work rather than maintaining ongoing work and does not encourage upcoming scientists to take over pre-existing projects and provide continuity in leadership and focus for long-term projects. We strongly believe that the culture of modern science needs re-examination to tackle this problem and to catalyze greater scientific engagement in long-term research and monitoring programs.

8.4. Funding

Access to funding is an obvious factor influencing the success of monitoring programs. Many aspects of funding are not well suited to the establishment and maintenance of such programs. Monitoring programs are often seen as a luxury and not core for many resource management organizations. They are therefore usually the last initiatives to be funded and the first ones to be cut during budget shortfalls. In addition, budget cycles emphasize short-term projects with rapid achievement of milestones. Funding initiatives of 1–3 years are rarely congruent with the timeframes appropriate for effective monitoring. Thus, there often is a fundamental mismatch between long-term environmental management aspirations and short-term financial realities. We believe funding models based on endowments may be useful to circumvent problems associated with short-term funding problems. An outstanding example is the 175-year research program at Rothamsted in England (Rothamsted Research, 2006).

9. A major challenge – integrating knowledge from different kinds of monitoring

We have shown that there are several kinds of long-term monitoring programs and crudely assigned them into three broad categories: question-driven monitoring, mandated monitoring, and curiosity-driven or passive monitoring. These kinds of monitoring programs are often conducted in different ways and usually at different spatial scales. In this section we argue that fundamentally important challenges remain about how to: (1) better integrate data, approaches and insights from different kinds of monitoring programs into useful environmental management and (2) use knowledge about the advantages and disadvantages of different kinds of monitoring programs to improve monitoring efforts, and in particular, ensure that many features of question-driven monitoring programs are more broadly adopted within mandated monitoring programs.

9.1. Tensions between question-driven and mandated monitoring programs

Question-driven, long-term monitoring programs will often operate at the level of sites, landscapes or regions. When they are based on well-defined and scientifically tested questions (among other features), they can provide important long-term environmental data on emerging environmental problems, as well as insights about the mechanisms or ecological processes giving rise to these emergent patterns. Such programs, in turn, can be highly valuable for informing resource management. However, spatial generalization from question-driven, long-term monitoring programs is difficult because the results from such studies may not extrapolate well or easily to other regions, states or to the national level. That is, it is not straight-forward to produce national perspectives on environmental conditions by integrating across such kinds of different site-level, landscape-level, or region-level studies. Thus, these kinds of detailed programs are usually one-of-a-kind projects that do not produce data at the scale governments may want or need. Nevertheless, they often provide the in-depth perspective vital for developing, understanding and for initiating management protocols.

Mandated monitoring programs often produce coarse level summaries of temporal changes in resource condition (e.g. "status reports") in response to demands from politicians and high-level policy-makers who want some kind of world-, state-, or national-level reflection of environmental performance. For example, there is a large and growing number of regional, state/provincial, national and international organizations producing "State of the Environment" reports (see www.cnie.org for a good, but partial listing of the sources for these reports). The Worldwatch Institute's annual "State of the World" report is a highly visible example (Brown, 2008). Countless United Nations documents on the state of the planet's natural resources and its environment continue to be produced (e.g. Food and Agriculture Organisation of the United Nations, 2007; United Nations Environment Program (UNEP), 1999). The reports and summaries from mandated monitoring programs can be useful information about temporal changes, but only a limited understanding about the site-specific mechanisms that have given rise to those changes. The large spatial scale of this information also may not be particularly useful for guiding targeted on-the-ground management interventions to improve environmental conditions in a given location.

Therefore, there are advantages and disadvantages of questionled monitoring and large-scale mandated monitoring. There is also an inherent tension between state- and national-level mandated monitoring and site- and region-based monitoring, as well as between academic- and organization-based monitoring programs. This tension occurs because these are often quite disparate programs. For example, we note that no data from the USA's 26 Long-Term Ecological Research (LTER) sites costing taxpayers ~$US23 million per year were explicitly included in the USA's, The State of the Nation's Ecosystems report (The Heinz Center, 2008). The tension between mandated monitoring programs and site- and region-based monitoring programs is reminiscent of tensions between top-down and bottom-up approaches in ecological thinking and research approaches. As in the case of taking advantage of the different methods of study in ecology to facilitate progress, there also must be ways to capitalize on synergies between national- and state-based mandated monitoring and question-driven monitoring.

9.2. Learning and cross-fertilization between kinds of monitoring programs

Many authors have argued that ecology is a case-study discipline (e.g. Shrader-Frechette and McCoy, 1993) and it is clear that as outstanding as some particular long-term programs have been, such as those at Rothamsted (England) (Lawes Agricultural Trust, 1984) or the Experimental Lakes Area in Ontario (Canada) (Schindler et al., 1985), they are one-offs that are virtually impossible to replicate elsewhere. However, we believe that these kinds of projects serve as in-depth, reference models often identifying major environmental problems (e.g. atmospheric CO_2 increase at Mauna Loa (Keeling et al., 1995, 1996) and showing what key environmental changes or important ecological processes are occurring in other places. These kinds of long-term research and monitoring programs have led to major discoveries in ecology and environmental management. For example, the findings from the long-term research and monitoring at the Hubbard Brook Experimental Forest in New Hampshire USA clearly suggested that acid rain and its effects were far more extensive throughout North America. They underpinned the passage of the 1990 Clean Air Act Amendments in the USA, primarily because the underlying data were long-term and high-quality. Moreover, the research of the Hubbard Brook Ecosystem Study and the Experimental Lakes Area in Ontario helped to catalyze the commencement of national networks for precipitation chemistry in the USA and Canada. The important lesson then is that leaders of site-based monitoring programs should think about the broader (regional, state, province, or national) implications of their findings, including the implications of site-based work as models for larger-scaled, mandated monitoring programs.

We also believe that the fundamental characteristics of some of the best examples of question-driven monitoring programs (well-defined questions, well-articulated conceptual models, rigorous study designs) are features that should be much more widely embraced as part of efforts to improve mandated monitoring programs. We make this suggestion because we believe question-driven, mandated monitoring programmes are likely to be the most efficient use of resources for addressing most ecological problems. We are aware that there would be many hurdles in implementing such programs (including changing the mindset within many institutions), but it is a much improved standard and should be worked towards and would be a worthy achievement. Thus, for example, the Adaptive Monitoring framework and the iterative steps that comprise the framework (Fig. 2) are just as relevant to mandated monitoring programs as they are to question-driven monitoring programs. We have argued above that any kind of monitoring program will be effective only when it is based on well-defined questions, makes use of a well formulated conceptual model, and is guided by a carefully crafted study design. This formula may sound trite and we have repeated it several times in this review, but we have been shocked at how often these seemingly simple ingredients are missing in toto, or individually, from a very large number of extant monitoring programs.

9.3. Impediments to be overcome to link question-driven monitoring and mandated monitoring more effectively

The challenge of integrating data, approaches and insights from question-driven and mandated monitoring programs is a substantial one and success in meeting this challenge requires overcoming three key impediments. First, attempts to coordinate across programs require a uniform set of protocols to facilitate data compatibility. This is a "one-size-fits-all" approach and we outlined above the suite of problems generic monitoring frameworks can create. In fact, enforcing the measurement of a common string of variables across sites could result in a "race to the bottom". That is, it may lead to a very crude set of common measurements of limited value for environmental management. Many measurements in, for example, Long-leaf Pine ecosystems in southeastern USA, which are strongly fire-dependent, may be irrelevant to the deserts of Antarctica or tropical rainforests of Puerto Rico.

Second, it remains unclear how to combine sensibly the metrics for environmental conditions that have been estimated or calculated in different systems. There is a long, but largely unsuccessful, history of this kind of problem in other topics in ecology. Examples include the difficulties of combining sub-indices for habitat attributes in constructing Habitat Suitability Index models (reviewed by Lindenmayer and Burgman (2005) and Van Horne and Wiens (1991)) and combining landscape indices into meaningful measures of landscape cover (Cale and Hobbs, 1994; McAlpine et al., 2002). It seems to us that combining outcomes from quite different monitoring programs is a similar kind of problem, albeit at large spatial scales and over longer time frames. As an example, poor environmental performance in one place added to a good performance in another could be summed to provide an average overall result, suggesting that the environmental conditions are reasonable. This result would obscure the fact that environmental conditions are degrading in some places (sites or regions). In Australia there are proposals to create a set of National Environment Accounts (Wentworth Group, 2008), similar to those which are used to gauge economic trends (e.g. Gross Domestic Product, employment numbers, budget surpluses and budget deficits). Such accounts would need to be built on high-quality environmental datasets and combine information from a range of sources to facilitate the calculation of credible metrics of environmental condition (Wentworth Group, 2008). There have been recent attempts to develop approaches to measure environmental performance better (Lamb et al., 2009; McDonald et al., 2008; Nielsen et al., 2007). These are promising, however, they are still in their infancy and in many cases currently, are often relatively narrowly focused (e.g. on the amount of area protected).

A third impediment that needs to be overcome is the tension between making long-term data readily accessible to the scientific community and at the same time protecting intellectual property through appropriate attribution.

In summary, we believe that many of the arguments in the scientific and resource management literatures about monitoring frameworks and frustrations about ineffective monitoring programs stem from a failure to recognize the inherent values of, and differences between, large-scale mandated monitoring programs and smaller-scaled question-driven monitoring programs. We believe a major challenge is to combine the datasets, results and outcomes that are conducted at different scales, in different ways and by different groups to produce integrated assessments useful to decision-makers. There may well be methods that have been used to develop broadly-based state/province or national level economic metrics as well as track economic performance in different (often more localized) sectors of economies, which might be usefully applied in solving problems of aggregating datasets from environmental monitoring programs. The development of such approaches could help reflect environmental conditions at local scales as well as highlight overall environmental performance at larger, aggregated scales. However, we readily admit that we do not know how to do this integration for environmental monitoring programs and associated datasets in ways that are scientifically defensible, of value for resource managers, and useful to policy-makers. We know that many readers will find our admission of ignorance to be unsatisfactory and frustrating. However, unless this challenge is resolved, our ability to deal with pressing problems such as rapid climate change and human-accelerated environmental change will be severely limited. Overcoming this challenge should be a primary topic for further published discussions that build on the insights we have summarized in this review.

10. Concluding remarks

We argue that there is a suite of kinds of monitoring programs and that these are often conducted in different ways and at different scales with the most effective ones being those focused on well-crafted questions resulting in a study design, a set of attributes and an implementation approach that will be different in each monitoring program. Thus, there is clearly not a one-size-fits-all approach to monitoring.

Various kinds of long-term ecological monitoring will be fundamental to evidence-based environmental decision-making and, in turn, essential to gauge the effectiveness of management interventions (Field et al., 2007; Krebs, 1991). Long-term monitoring was fundamental to quantifying problems associated with increasing carbon emissions (Keeling et al., 1995) and will be pivotal to gauging the success of attempts to mitigate against, or better adapt to, the effects of rapid climate change (Lovett et al., 2007; Steffen et al., 2009).

While we are fully cognizant of the fact that there is no such thing as a perfect monitoring program, we do believe it is critical to improve on the poor record of ecological monitoring to date. On this basis, we have outlined attributes we believe are pivotal for effective, long-term ecological monitoring programs. For example, we believe that a major challenge is to work out how to ensure that many of the key features of successful question-driven programs are more widely adopted and implemented within mandated programs. The broader adoption of these characteristics will be critical for encouraging governments, private foundations and the general public to increase significantly the levels of funding that are urgently needed for expanding and extending environmental monitoring.

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