Making ecological monitoring successful

Insights and lessons from the Long Term Ecological Research Network
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Authors

The Long Term Ecological Research Network (LTERN) is a group of experts in ecological research, ecological monitoring, field ecology, conservation science and policy, data management, and statistics. LTERN is a facility within the Australian Government–funded Terrestrial Ecosystem Research Network.

Booklet authors were:

Dr Emma Burns—Executive Director, LTERN; Fenner School of Environment and Society, The Australian National University, Australian Capital Territory

Professor David Lindenmayer—Science Director and Plot Leader, LTERN; Fenner School of Environment and Society, The Australian National University, Australian Capital Territory

Mr Philip Tennant—LTERN Statistician; Fenner School of Environment and Society, The Australian National University, Australian Capital Territory

Professor Chris Dickman—Plot Leader, LTERN; School of Biological Sciences, The University of Sydney, New South Wales

Dr Peter Green—Plot Leader, LTERN; Department of Ecology, Environment and Evolution, La Trobe University, Victoria

Mr Ivan Hanigan—Data Manager/Analyst, LTERN; Fenner School of Environment and Society, The Australian National University, Australian Capital Territory

Professor Ary Hoffmann—Plot Leader, LTERN; Bio21 Institute, Departments of Genetics and Zoology, The University of Melbourne, Victoria

Professor David Keith—Plot Leader, LTERN; Australian Wetlands, Rivers and Landscapes Centre, School of Biological, Earth and Environmental Sciences, The University of New South Wales; Ecosystem Management Science Branch, NSW Office of Environment and Heritage, New South Wales

Dr Dan Metcalfe—Plot Leader, LTERN; CSIRO Land & Water Flagship, EcoSciences Precinct—Dutton Park, Queensland

Mrs Kathryn Nolan—LTERN Data Librarian; Fenner School of Environment and Society, The Australian National University, Australian Capital Territory

Dr Jeremy Russell-Smith—Plot Leader, LTERN; Darwin Centre for Bushfire Research, Research Institute for the Environment and Livelihoods, Charles Darwin University, Northern Territory

Associate Professor Glenda Wardle—Plot Leader, LTERN; School of Biological Sciences, The University of Sydney, New South Wales

Professor Alan Welsh—Senior Advisory Statistician, LTERN External Reference Group; Centre for Mathematics and its Applications, The Australian National University, Australian Capital Territory

Dr Richard Williams—Research scientist, LTERN; Research Institute for the Environment and Livelihoods, Charles Darwin University, Northern Territory

Mr Cameron Yates—Research Scientist, LTERN; Darwin Centre for Bushfire Research, Research Institute for the Environment and Livelihoods, Charles Darwin University, Northern Territory
**Executive summary**

Ecological monitoring allows us to track changes in the environment and helps us see how our actions affect the environment. Long-term monitoring is particularly important, yielding valuable insights that are not possible from shorter-term investigations.

We consider successful ecological monitoring to be monitoring that generates knowledge that is useful to others, and can be valuable in adaptive and effective environmental management. Any effective monitoring program requires a number of fundamental considerations, and additional factors should be considered in the design of a long-term monitoring program.

This booklet describes what we consider to be the key characteristics of successful ecological monitoring, including long-term monitoring. In summary, these are as follows:

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Characteristic 5: Maintenance of field infrastructure

Characteristic 6: Reflection and adaptation

Characteristic 7: Project momentum built through co-located projects

Characteristic 8: Communication of the value and importance of long-term monitoring
All these characteristics work together. For example, good project design cannot meet its objectives without long-term funding; data management must be matched by good communication; and good partnerships must be maintained through succession and project planning.

In discussing these characteristics and our recommendations for how they may be achieved, we present a series of stories and quotes. These insights are based on the collective experience of research leaders of the 12 plot networks within the Long Term Ecological Research Network, along with other professionals associated with the network.

These stories highlight just how difficult it is to do long-term ecological research in Australia. They also illustrate the unique value of this kind of research for helping to understand and manage the Australian environment. We hope that this booklet will support the development of more effective and influential long-term ecological projects in Australia.

Checklists of the requirements for achieving the characteristics are available on pages 23 and 50.
Introduction

Ecological monitoring is the process of purposefully collecting information to track and help understand changes in ecosystem structure, ecological processes, and the ecological services that ecosystems provide to nature, including humans (Lindenmayer & Likens 2010). The need for ecological monitoring is well established (e.g. Goldsmith 1991; Lindenmayer et al. 2012a; Lovett et al. 2007). Monitoring allows us to track changes in the environment and to see how human actions—both positive and negative—may play a role in affecting the environment.

We use the term ‘long-term monitoring’ to refer to the persistent and conscientious collection of information over enduring periods of time. In previous publications from the Australian Long Term Ecological Research Network (LTERN) (e.g. Lindenmayer et al. 2012a), we have defined ‘long term’ to mean 10 years or more. It is widely accepted that long-term ecological monitoring yields important insights into changes in ecosystem structure and ecological processes that are not possible from shorter-term investigations (e.g. Daily 1997; Holmes 2011; Holmes & Sherry 2001; Knowlton & Jones 2006; Krebs et al. 2001; Lindenmayer & Likens 2010; Odum 1959; Westoby 1991; Willis et al. 2008). Long-term monitoring is especially important for exploring the complex, multiple, simultaneous, nonlinear interactions that are prevalent in many ecosystems (Estes et al. 2011; Levin 2009; Runyoro et al. 1995), and can be valuable in determining the success (or otherwise) of management interventions such as restoration programs (Kearney et al. 2011).

Although the need for monitoring is clear and accepted, the realities of how it can best be achieved are not as clear, despite much having been written on the subject (e.g. Lindenmayer & Likens 2009; Wintle et al. 2010). In practice, there are usually constraints that prevent an effective and influential monitoring program from being implemented. The most common constraints are a lack of money, time and relevant skill sets.

Long Term Ecological Research Network

LTERN brings together some of Australia’s leading ecologists from eight institutions. Established in 2012 as part of the Terrestrial Ecosystem Research Network and administered by the LTERN Office at the Australian National University, LTERN draws together a range of existing long-term ecological monitoring programs to establish a new coordinated and collaborative approach.

The LTERN plot networks span different Australian ecosystems, systematically record data on different groups of species to examine ecological processes, and have been established for various reasons (see www.tern.org.au/ltern). This research, along with other long-term ecological research in Australia, is showcased in the recent book Biodiversity and environmental change (Lindenmayer et al. et al. 2014a). An associated policy handbook describes the key findings and messages from this research for policy-makers and the general public (Burns & Lindenmayer 2014). This handbook is freely available at www.tern.org.au/ltern.

Details on monitoring protocols employed by plot networks within LTERN are available on request from the LTERN Office (ltern@anu.edu.au). LTERN monitoring protocols are also available as metadata for various data packages via the LTERN Data Discovery Portal at www.ltern.org.au.

‘Natural systems are inherently variable.
Without long-term monitoring, our ability to detect real changes in populations, species and ecological processes is severely compromised.’

Chris Dickman
This booklet

Aims

This booklet aims to collate some practical wisdom learned first-hand by a diverse set of people who have successfully supported long-term monitoring. It is not a prescriptive manual. Although general principles often apply to the development of effective and influential monitoring, each circumstance or management issue needs to be considered, and targeted methodology developed.

By effective, we mean that monitoring achieves its purpose; by influential, we mean that the knowledge generated is used by others (or is available to be used if needed)—ideally to guide policy, management and conservation efforts. There are two key questions associated with long-term monitoring: What are the characteristics of effective monitoring studies? What factors contribute to their being maintained and influential in the long term? In this booklet, we attempt to answer these questions.

The characteristics we discuss are based on the collective experience of research leaders of the 12 plot networks within LTERN, along with other experts associated with the network.

Audiences

This booklet will be of interest to:

- people who are involved in designing, implementing and maintaining ecological monitoring
- decision-makers who are responsible for determining whether ecological monitoring is needed to inform current and future policy directions and management activities.

Structure

The first section of this booklet focuses on characteristics common to all types of monitoring. The second part is devoted to characteristics needed to maintain a monitoring program in the long term.
Section 1
Characteristics of successful monitoring
Characteristic 1—Fit for purpose

To be successful, monitoring needs to meet its predefined purpose and objectives. To do this, the budget, duration, scale and design of the monitoring program must be appropriate and relative to the purpose and objectives. In this sense, no one type of monitoring is better than another, provided that it is well designed and fit for purpose. For example, a monitoring program aimed at detecting changes in species diversity will be very different from one aimed at monitoring population changes, and a statistical design sufficient for one may be completely inadequate for another.

To be fit for purpose, the monitoring design needs to pay careful attention to:

- scientific question(s) of interest
- statistical principles
- a ‘working’ conceptual model(s) that incorporates the key factors thought to influence ecosystem dynamics
- the type of entities that need to be monitored
- the data collection methods that will be effective
- the scale of the required monitoring program.

Ensure that the study is based on sound statistical principles

When planning the monitoring, one important task is to identify what needs to be measured and why. It is important to keep in mind that some things in ecology are measured with substantial amounts of error. Trying to understand a process that is inherently variable to begin with, and then measured with error on top of that, can lead to a poor level of understanding. If there are too many constraints in implementing a scheme that is likely to be successful, it is not worth doing.

An appropriate and sound statistical design is a critical component of any successful ecological monitoring, including long-term studies. Statistical advice should be at the core of most of the key phases of an ecological monitoring program, especially during the initial design and establishment phases. This recommendation is made because sound study design is an inherently statistical process (Thompson 2002).

As ecosystems are dynamic, a monitoring program is of limited use where you are only able to conclude that a change is likely to have occurred, or that there is insufficient evidence to conclude that a change has taken place. Usually, it is more valuable to estimate the size of an effect, understand the uncertainty associated with that estimate, and assess the evidence for what is contributing to the observed changes.

For monitoring to have practical relevance to policy and natural resource management, some of the strongest study designs will 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 in space, in time, or in both. Study designs with contrasting interventions blur the ‘line’ between monitoring, research and experimentation, with the most powerful studies often containing elements of all three.

There are fundamental aspects of study design that are valuable to consider and incorporate. Big or small, a study will benefit from judicious use of stratification, probability sampling, and relevant and reliable measurement over an appropriate timeframe for the objective.
Use a conceptual model

Developing conceptual models of the system you are working in can be helpful in establishing a fit-for-purpose monitoring design, and then communicating the program design to key stakeholders. For example, an initial conceptual model can be built by thinking about, and identifying, important properties and attributes of the system being studied. These can then be worked into the planning for the monitoring program as design variables or, if a manipulative approach is involved, as experimental treatments. The resulting model can then be a focal point for discussions among project partners—scientists, managers and policy-makers—about how the system will be studied and why. If the model is too detailed, too abstract or too vague, it is likely to be unhelpful for program design and communication.

Ultimately, a sound conceptual model should be a balance between the actual complexity of the system and the simplification of it that is necessary to allow you and others to understand how it may change and why.

In many cases, two or more competing conceptual models of an ecosystem process (or other entity) may be targeted for investigation. The fundamental differences between these models can also be useful for designing additional studies because they can highlight the types of data needed to discriminate between the models (Nichols & Williams 2006). To this end, and more generally, conceptual models are invaluable in shaping the experimental design of monitoring. The design will vary for the particular application. For example, the design may correspond to a stratified random survey (non-manipulative) in some circumstances and to a manipulative experiment on other occasions.

Pose appropriate and evolving questions

Fit-for-purpose program design relies on setting clear questions, and developing conceptual models helps with this process. Posing questions and investigating hypotheses lies at the heart of sound science, and is as essential for effective ecological monitoring as it is for all other sciences (Nichols & Williams 2006).

With an emphasis on fit-for-purpose design and the use of a conceptual model, monitoring programs need not be elaborate, complex endeavours. Clear questions and objectives should be foremost in mind when developing monitoring programs, and this will help to clarify the structure of the program and the level of resources that are needed. It is therefore important to have an initial understanding of how long monitoring is likely to be required, and to reassess this periodically. Although this advice sounds obvious, more thought given at the early stages of a project to its likely duration can be very beneficial down the track. The link between a realistic problem that interests you and how you plan to pursue the answer is worth thinking deeply about.

Some authors argue that ecologists and resource managers have been poor at problem definition and objective setting (Peters 1991), and we have repeatedly observed this over our careers. Deliberate question setting must result in quantifiable objectives that offer unambiguous signposts for measuring progress within specified and appropriate timeframes. Thus, questions for monitoring projects must be scientifically tractable, and test real policy and resource management options (Walters 1986). This requires a well-developed partnership among scientists, statisticians, resource managers and policy-makers (Gibbons et al. 2008; Lindenmayer et al. 2012b).
Select appropriate entities to measure

A key part of successful ecological monitoring is the selection of appropriate entities to measure. This is not always a straightforward task, and progress in many monitoring programs is hamstrung by a failure to carefully determine what to measure. For example, programs frequently fail, or become logistically or financially unsustainable because they attempt to measure too many things. More is not always better. A ‘blizzard’ of ecological information gathered without good questions to guide data collection can be a hindrance to important discoveries (e.g. the case of the ozone hole in Antarctica; Shanklin 2010). In addition, such studies often measure many things poorly rather than a few things well (e.g. Lindenmayer & Likens 2010). This can lead to a lack of statistical power to estimate the size of effects because survey resources are heavily focused within sites, rather than being used to incorporate additional independent study locations.

Problems about what to measure can usually be resolved by:

- targeting those entities that are best for answering predefined questions (see above)
- using a model to conceptualise a particular ecosystem, and make predictions about its behaviour and response (see above)
- implementing a pilot study.

Pilot studies are valuable exercises for exploring the various factors (e.g. methods, protocols, alternative designs) that can affect the reliability of a monitoring program. The sensitivity to bias in the methodology, the required duration of measurements and the inherent variation in the attributes of interest in a study can all affect the efficacy of a monitoring program. Pilot studies should be seen as an opportunity to learn about the system of interest so that the formal program can be developed soundly.

Sometimes the system under consideration affords a simple approach. An example of this is the Parks Australia annual monitoring program looking at flatback turtle nesting on Gardangarl (Field Island) in Kakadu National Park. To inform recovery planning, surveys at Gardangarl were initiated in 1994 and continue today. The limited extent of beachline that was used by the animals for nesting and the restricted season in which nesting took place meant that field resources could be concentrated on only a portion of the beach, at a particular time of year, to help understand trends in flatback turtle reproductive effort on the island. This program, which has been implemented by Parks Australia staff, has been effective in directly informing parks management.

‘While analysis of field data is an important step, it is often design aspects that determine how well monitoring objectives can be met.’

Jeremy Russell-Smith

Photo: Toechima plenocarpum, D Metcalfe.

‘Monitoring does not need to be complicated to be effective.’

Philip Tennant

While analysis of field data is an important step, it is often design aspects that determine how well monitoring objectives can be met.

Jeremy Russell-Smith

While analysis of field data is an important step, it is often design aspects that determine how well monitoring objectives can be met.

Jeremy Russell-Smith
Select appropriate data collection procedures

Fundamental to sound study design is the selection of appropriate data collection procedures. It is important that the methods for collecting data are, as much as possible, robust to the variation in skills, equipment, resources and knowledge of the people used to collect the data. For example, in general, designs covering a large area require either a large number of people in the field or a limited number of people over extensive periods of time. Data collected by a large number of people can be sensitive to detection variability due to variation in skills and knowledge (Lindenmayer et al. 2009b). Studies that rely on volunteers or ‘citizen-scientists’ can be especially sensitive to these problems. However, well-trained volunteers make valuable contributions in a variety of ways when they are working on well-structured field studies where field measurement protocols are clear and unambiguous. Even automated sensors pose problems for long-term studies as technologies change and older sensor models become unavailable. Cross-calibration by using new and old sensors in parallel can help. However, we recognise that this is not always possible, as some sensor failures may be unexpected.

In addition, data collected over extensive periods will be sensitive to climate variation during the collection period, and this can affect the detection rates of many species of interest. Technologies such as automated remote cameras can offer innovative ways to study fauna and potentially reduce survey costs. Although such technological advances offer other data collection opportunities, consideration needs to be given to whether these methods complement, replace or are more effective than traditional methods.

Modify the project to suit the scale

In principle, statistically sound monitoring can be designed at large scales, but there will usually be great practical difficulties in doing so. Depending on the objective or question, monitoring programs across large geographic areas can be expected to make greater use of stratification in the design because of the variation in vegetation communities, ecosystems and land use across the landscape. The ability to access survey locations to collect data for the duration of the program is also an essential aspect (especially for longitudinal data). Consideration needs to be given to the consequences of limited access, including how it may affect the breadth of the conclusions that can be drawn from the study results.

Design also needs to ensure that resources are used cost-effectively. Resources will always be limited, but pragmatism should not be about cutting corners but a means of retaining the critical aspects of study design that allow project objectives to be met. A pragmatic approach involves thinking carefully about the distribution of limited survey resources and matching it with the program objectives. If financing or motivation is inadequate, project objectives should be modified accordingly.

‘Basically, it is important to know the data collection process very well so that you are mindful of its limitations.’

Emma Burns

‘I am often asked about uniform methods that could be applied at a continental scale. My response is that it would be unproductive and uninformative to measure the same entities on sites in markedly different ecosystems.’

David Lindenmayer

Photo: Malurus cyaneus (superb fairy wren), C Macgregor.
Characteristic 2—Early use of data to examine its properties and test assumptions

Periodic examination of data can be valuable in understanding the variability in the attributes that have been chosen for measurement. This also increases familiarisation with ‘incoming’ data, and can help identify errors or inefficiencies in data collection or storage. Such examinations can result in important discoveries, and stimulate new research and management questions.

‘Looking at our response data to fires in different years made us realise the importance of post-fire weather. We then adjusted our aims and monitoring design so that our fire management recommendations can be tuned to different weather scenarios.’

David Keith
SECTION 1 — CHARACTERISTICS OF SUCCESSFUL MONITORING

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Characteristic 3—High level of data curation and management

Effective data management is essential in managing risk. Data-related risks include data loss or corruption, technological obsolescence, breaches of privacy or copyright, and unintended errors or misuse due to user misunderstandings about data attributes (see Michener et al. 1997).

Ecological monitoring can generate large amounts of data. These datasets need to be stored so that they can be readily accessed for subsequent analysis and scientific publication. The careful storage and curation of datasets is critical—data from far too many studies are lost (Pullin & Salafasky 2010; Vines et al. 2014).

Data management should involve:
- creating a data management plan
- developing methods to keep data safe
- ensuring that all relevant data are collected, including field protocols
- making data understandable and available to others.

Create a data management plan

Developing a data management plan is a valuable step in the establishment of any new monitoring study. It is important to consider what data will be created, what policies will apply to the data, who will own the data, how the data will be described, where the data will be stored, how integrity of the data will be ensured and who will have access to the data. In the United States and United Kingdom (UK), funding agencies now require data management plans for all funded projects (for a review of UK funders’ policies, see the UK Digital Curation Centre’s data management resources at www.dcc.ac.uk/resources/data-management-plans; for plans in the United States, see https://dmp.cdlib.org/). In Australia, both the Australian Research Council (ARC) and the National Health and Medical Research Council have indicated that they will also implement this model. In February 2014, the ARC announced that researchers are now required to outline how they plan to manage research data arising from ARC-funded research (http://ands.org.au/news/arcandresearchdata.html).

A parallel process to data management is the curation of samples collected in the field (e.g. invertebrate pitfall samples, animal scats, soil samples) that are stored until further data can be collected from them. In some instances, these may wait for years until time, personnel and resources are available to work on them. In such instances, clear labelling, electronic records and regular checks on the integrity of the containers are helpful to ensure their safekeeping.

Data management is especially critical for long-term monitoring as there is likely to be a turnover of staff during the study. Whether data management involves the individuals collecting or collating the data or a lead scientist, clarity on how and where data are stored and managed is vital.

‘Data collected as part of long-term monitoring effort are intended to outlast the individual researchers. While we have custody though, it makes sense to have a ‘data champion’ to ensure the quality and integrity of the data are protected and the process for achieving that is archived.’

Glenda Wardle
Keep data safe

Data management planning helps address issues associated with data security. The need to adequately back up data and have disaster recovery capability is a concern not only for information technology groups but also for researchers.

It is important to ensure that the methods of storage accommodate changes in technology. Formats such as Microsoft Office products (e.g. Access or Excel) are popular and are likely to be accessible for a reasonable length of time, but changes between product versions or the loss of a product may make data unreadable. The ability of a software product to work with input generated by an older version is known as ‘backward compatibility’. An example is the transition from Access 97 to Access 2000; the latter is not backward compatible with earlier versions. A related issue is the inability to access data on a variety of computer operating systems; for example, Access databases are not supported on Linux or Macintosh systems.

Saving a copy of the data in nonproprietary, ‘open’ or portable formats for long-term access can help reduce the risk of losing data to technology obsolescence. In cases where raw data are recorded on paper sheets, copies need to be stored in multiple places to avoid the disastrous consequences of catastrophes such as fire or flooding (Hook et al. 2010; White et al. 2013).

Document the field protocols and other methods that are used

Reproducible research is an idea focused on the provision of sufficiently detailed information about how a study was conducted so that other researchers can reproduce the work that has been done. There are practical advantages to this, but it requires adequate understanding and documentation of the collection, cleaning, exploration and subsequent analysis of data. All of these stages are critical in any effective research project.

Many different people may work on a study, and those conducting measurements at a given point in time may not be the same as those who completed the initial measurements. Documenting field methods employed at the outset of the study is critical to enable a given set of field measurements to be repeated by different people and, at least for some attributes, to limit the amount of observer heterogeneity in those measurements. We suggest that field protocols should not be changed until new methods have been carefully calibrated against the original methods, to ensure that the consistency of the longitudinal data is maintained. We also recommend that methods or protocols developed for one location or study should not be adopted for another area or study without careful consideration of their appropriateness.

The Hubbard Brook study in the north-eastern United States (Buso et al. 2000) and the long-term study on cycles of animal populations in Canada (Krebs 2012) are good examples of monitoring projects that have carefully documented their field protocols.
Make data understandable to others

The reproducibility of data analyses, and reuse of data, are becoming more topical among scientists and their funding bodies (King 1995; Peng 2011; see also http://www.tandfonline.com/doi/abs/10.1080/1047840X.2012.692215#.VCCRaP, http://pps.sagepub.com/content/7/6/615.full). In this context, ‘reproducibility’ refers to the ability to (easily) reproduce all published results from a dataset. This can be needed by the original author, to verify results, or others interested in the technical details of a method. Reproducibility is also useful when undertaking a replication study—that is, obtaining a new dataset from a new location and comparing the results with the first study, to support the inferences made by the original researchers about their results.

Scientists are keen to increase the rigour of their own (and their peers’) published works. Research funders and journals are moving towards the requirement to lodge publications and data in public repositories, with the aim of increasing the transparency of research that has already been undertaken, assist synthesis and reduce duplication.

The increasing emphasis on ‘reuse’ of data is primarily focused on asking new questions using data already collected by others. Data reuse can potentially be useful, but is not without its challenges (Box 1).

‘Data should be managed so it can be preserved and made available for re-use … even by yourself!’
Kathryn Nolan

‘Both “big” and “small” data will play important roles in the future of ecology and scientists need to be free to choose the arena in which they will conduct their own research.’
John Porter
There is a growing emphasis on large-scale questions and monitoring, and an increasing number of claims about the virtues of ‘big data’ to answer such questions (Aronova et al. 2010; Hampton et al. 2013; Kelling et al. 2009). Big data advocates suggest that the approach answers difficult environmental questions through sharing data and drawing together disparate datasets for novel interrogation. Big data is likely to be used to try and answer questions that we may not be able to pose using individual, well-managed (i.e. traditional) datasets. We agree that some important discoveries can be made through amalgamating large datasets from different ecosystems (e.g. global declines of bees and frogs; Garibaldi et al. 2011; Hof et al. 2011). Indeed, this is the basis of well-informed meta-analysis and other kinds of integrative approaches (e.g. Felton et al. 2010). However, the heterogeneity and unreliability of big data currently demand caution, along with a new and evolving suite of techniques.

Despite the potential advantages of big data, there are still very important fundamental components of ecology that inherently entail understanding local patterns and processes, and employing hard-won, field-based understanding to interpret the results of data analyses after interaction with, or systematic observation of, the system in question. That is, reliable knowledge obtained through appropriate data analysis is inherently linked to purpose-built design and familiarity with the system. Therefore, applications to sensibly draw on disparate datasets for novel interrogation are likely to be limited. It is irresponsible to analyse combined datasets without careful consideration of the design (e.g. site selection) of the individual component studies.

We argue that a careful balance between big data and traditional site-based long-term ecological research and monitoring is critical. It is important that an overemphasis on big data does not create a marked disincentive to continue to gather field data and undertake fit-for-purpose, question-driven ecological science. An uncritical focus on big data overlooks the fact that assembling large quantities of data may not correspond to useful knowledge, ecological or otherwise. For example, there are well-documented cases where either a blizzard of data obscured a key signal (Shanklin 2010) or adding poor-quality data to other poor-quality data led to highly misleading results (Wheelan 2013). That is, amalgamating datasets that have limitations in their original design will not ‘fix’ the situation, and careful thought is needed to determine whether any reliable conclusions can be drawn from the larger integrated dataset.

Importantly, in many areas we already have sufficient information to meet our environmental challenges; what we lack is decisive and appropriate action—a case well argued in Fischer et al. (2012a).

Efforts to conduct ‘big science’ should most often be accompanied by big investments to enable appropriately scaled and designed studies to be implemented over long periods of time. This will facilitate sensible and useful interpretation of data. Over time, it will lead to reliable knowledge and an improved understanding of important ecological phenomena.

Data publishing and reuse is not a bad thing—and will more than likely be a very good thing—if due care is taken with how those data are used. However, although it is alluring to think that we can avoid substantial investment in ecological research by drawing together data from the past, this approach may add up to mean very little. As John Tukey, an American statistician, once said, ‘The combination of some data and an aching desire for an answer does not ensure that a reasonable answer can be extracted from a given body of data’. In the above quote, ‘reasonable answer’ refers to an answer that will be useful for the application you are trying to address. A considered balance is what is needed, because it would also be erroneous to conclude that comparative results from published data would not be a useful adjunct to many analyses.

Consider data publishing options

Publishing data raises further issues.¹ It is not always obvious what is meant by ‘the data’ or even what is meant by ‘publishing’. In general, it is possible to identify the key ‘milestone’ datasets or coded/scripted workflows from the different stages of the data life cycle: (a) raw data, (b) tidy data, (c) graphs and tables supporting a paper, and (d) computer code that is used to get (b) and (c) from (a). In some cases, it is not possible to publish the dataset itself. Reasons can vary: the data may be too big (for example, with climate models) or too sensitive (for example, containing location details for threatened species or being associated with protected intellectual property).

For data to be reused in the future, metadata and documentation need to be carefully prepared to allow future users (including the original collector) to find and understand the data (Michener et al. 1997). Metadata refers to information about data (see the Australian National Statistical Service for examples). Metadata should be associated with the data and adhere to a standard schema. A number of metadata schemas are available to choose from. For example, the Dublin Core is a general international standard for metadata, while domain-specific schemas include the Ecological Metadata Language for ecology, and the Data Documentation Initiative for social science. Good metadata requires sufficient detail to describe the collection process and to record decisions that were made during the design phase about the use of different sampling methods. Time and effort may be saved by considering metadata requirements at the commencement of a study, rather than trying to recall all the details later. If metadata adheres to a standard schema, it can be used in catalogues to enable fast searching and retrieval, or in machine-to-machine data queries that assist data access and use.

Sufficient documentation of data will encourage appropriate use of the data by enabling an assessment of whether it is fit for purpose. It will also help reduce the risk of misinterpretation.

Consider data portals and experiments in eResearch collaboration tools

Currently, there is interest and activity in the development of data portals (and associated repositories), and how they can provide access to data from ecological monitoring networks. Ecological data portals have to be able to cope with multiple types of data and to present these data in a way that serves the needs of researchers, governments and the general public.

LTERN is investing in a data portal to centralise data storage and backup, and increase the accessibility of LTERN data. The LTERN data portal uses an open-source software system developed by the Knowledge Network for Biocomplexity (https://knb.ecoinformatics.org) that has been deployed in long-term ecological and agricultural sites across the world. The data are accessible using a searchable web interface (see www.ltern.org.au). Access is controlled via a user authentication system. Data packages are created and uploaded using a stand-alone desktop application that can be downloaded online. Data descriptions will be automatically made available via the TERN Data Discovery Portal and Research Data Australia to reach a broad audience of scientists, governments and the general public.

¹ TERN provides information about data publishing and the different options; see for example http://tern.org.au/Data-publishing-pg26249.html
Characteristic 4—Communication of lessons learned and outcomes generated

One criterion often used to gauge success in ecology is scientific output; this is especially true in academia. We strongly suggest that the results of ecological monitoring must be published in scientific peer-reviewed literature. Firstly, the publication process will help to ensure the quality of the work being undertaken. Secondly, publication is essential to inform the public, funders and resource managers about the scientific credibility and quality of the monitoring. Journal publications will particularly increase the visibility of a project within the scientific community. This, in turn, is essential to convince funders that investments are appropriate and should be maintained.

However, we fully acknowledge that communicating the value of monitoring outcomes must go beyond the publication of scientific articles, to effectively reach the public and non-academic audiences. Indeed, semi-popular articles and books, other kinds of communication products (such as this one), and exposure through the media or community groups will often be critical for building a constituency to support the continuation of an ecological monitoring study.
Checklist of the characteristics of successful monitoring

**Characteristic 1—Fit for purpose**

Based on its purpose and objectives, the monitoring design has chosen:

- sound statistical principles
- an accurate and useful conceptual model
- relevant and answerable questions
- relevant and measurable entities to monitor
- sound data collection methods
- an appropriate scale of operations.

**Characteristic 2—Early use of data to examine its properties and test assumptions**

- Historical and early-collected data are examined to understand normal variability, to aid in identifying new trends or errors.

**Characteristic 3—High level of data curation and management**

- A comprehensive data management plan has been developed.
- Data are kept secure, and issues of future compatibility have been considered.
- Data are understandable to others.
- Field protocols, other methodology and metadata have been documented.
- Data publishing tools and data portals have been used to best advantage.

**Characteristic 4—Communication of lessons learned and outcomes generated**

The results of ecological monitoring are:

- published in peer-reviewed journals and presented to the scientific community in conferences
- communicated to the public and government through the media, public information publications and websites, and presentations.
Section 2
Characteristics of effective and influential long-term monitoring
The features discussed in Section 1 are critical to the successful design and execution of ecological monitoring. In addition to these, other critical factors will enable a monitoring project to be sustainable, effective and influential over the long term. In this section, we discuss these characteristics and provide examples of their use in Australia.

**Characteristic 1—Continuous funding**

Access to continuous funding is a key characteristic of effective and influential long-term monitoring. Generating the funding to maintain long-term studies is a truly major challenge, and few individuals and organisations have ever managed to do it successfully (Strayer et al. 1986). We suggest that many of the underlying problems in securing long-term funding are associated with the emphasis in western science on ‘innovation’. This obsession with ‘new’ can undermine real advances that take time, consistency and persistence (Lindenmayer & Likens 2010; Lindenmayer & Likens 2011b). This reinforces the need for scientists to be strong advocates for long-term ecological monitoring (see Characteristic 8).

Couching long-term environmental monitoring in the context of a single program is one way to help sustain monitoring over the long term, as shown by the US LTER Network, which recently celebrated its 30th year of existence, with government support. It is easier to sustain support for a single integrated program than for many individual monitoring programs, but this approach is not without risk.

In setting out to design a monitoring initiative to be ‘long term’, it is important to design something that is sustainable and affordable from the beginning. Basically, the more expensive and elaborate the project, the less likely it is to be funded continuously. It is also important to ‘future proof’ the design by not aligning the project too tightly with ‘fads’ of the day that can be driven by non-science sectors. For example, within policy circles, shifts in focus can occur quickly. Under one environment minister, an emphasis may be landscape-scale conservation and reservation; then a parliamentary cabinet reshuffle or change in government may result in a minister focused on connectivity and carbon, followed by another change and an emphasis on single species, and so on. These shifts can create opportunities for leverage but can also distract from the fundamental needs of ecological monitoring research. (see Characteristic 6 for further discussion of this issue). This indicates that some kinds of monitoring programs might be best supported under more independent kinds of approaches, such as endowment funding. However, some jurisdictions, including in Australia, do not have a strong culture of such funding models.

‘To keep it long term, we all know within LTERN that data collection must come first.’

Glenda Wardle

‘The work in one of the years of monitoring in the Three Parks Savanna Fire-Effects Plot Network was self-funded. No one else was interested in funding the work at that time. So we only did trees and shrubs, because that was all we could afford and that was what we were most interested in. Another year, we were only able to maintain the work through linkages with a Parks Australia exercise for staff training in fire management.’

Cameron Yates
Box 2  A never-ending challenge—Desert Ecology Plot Network

The first field-based components of the Desert Ecology Plot Network were established in 1990 using a lot of borrowed resources and a volunteer labour force that comprised students, backpackers and travellers from many parts of the world. The first ‘real’ funding, from the Australian Research Council (ARC), came the following year. Although very welcome, the ARC funds did not quite cover the cost of hiring a 4WD vehicle, which is needed for work in a remote area; the shortfall was made up by the chief investigators completing consultancy projects that allowed purchase of one, and then a second, dedicated field vehicle. Continuing consultancy funds were then needed to keep the vehicles in running order and to purchase replacements as old vehicles wore out.

Every 2–3 years, a fresh application has had to be made to the ARC for a project that was sufficiently different from the previous one to be considered ‘nationally significant’ and ‘cutting edge’, but that would still allow the early-established plots to be monitored. ARC funding, and more recently funding through LTERN, has allowed dedicated personnel to be employed, but applications for smaller sums have still been needed to allow student projects to start up and proceed. And continuing consultancy projects have to be undertaken to make up the shortfall in funding from all these sources. On occasion, funds have been so scarce that the only options were part-time work and scaling back the scope of data collection.

This kind of work needs persistence and dedication: Dickman (2013) termed it ‘long-haul’ research.
Characteristic 2—Dedication and determination at multiple levels

Constant vigilance and dedication are needed to maintain a long-term project in a research culture that is driven by short-term funding. The best way to ensure that this occurs is to create a team environment on the project. This will help maintain energy levels, and keep the project fresh and enjoyable. But there is no getting away from the fact that strong and dedicated leadership is also essential.

Support strong leadership

Essential to almost all effective long-term ecological studies is strong, dedicated and focused leadership—that is, a key individual or individuals 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). This is indeed the case for monitoring programs within LTERN (see the LTERN brochure at www.tern.org.au/ltern).

Effective leadership is pivotal to all of the fundamental characteristics of successful long-term studies described here—setting appropriate questions, identifying new questions, developing a workable conceptual model, resolving what to measure, guiding study design, analysing data, establishing and maintaining partnerships, and communicating results to management agencies, policy-makers and the public. Leadership is also critical to securing funding and ensuring good project management, both of which contribute to effective long-term studies.

Although strong leadership is critical to the success of long-term studies, it also can be its weakness, as many projects collapse once the champion has retired or died. Hence, as outlined under Characteristic 3, succession planning will often be critical to whether a long-term study persists or dies along with its instigator.

Box 3 Long-term vision—Desert Ecology Plot Network

A crucial insight about how we have managed the challenge of maintaining the Desert Ecology Plot Network is that it has occurred through shared leadership. Chris Dickman began the Simpson Desert work in 1990, and Glenda Wardle from the University of Sydney joined the efforts in 1998. It was serendipitous that two ecologists shared the same vision for long-term work and also for how to develop a world-class team to achieve it.

Sharing the leadership roles has been one of the key strategies in keeping the effort going for so long. Having two chief investigators has also helped to diversify the types of questions we pursue, the students we can supervise and the funding we can obtain. While the Australian Research Council has been supportive throughout, we also encourage our students to seek their own small grants to supplement their work and build their career profile. Funding from LTERN is now critical to our expanded research and training program, which could not be pursued effectively without the extra field personnel that LTERN supports.

Chris Dickman and Glenda Wardle
Ensure good administrative support

Long-term projects are almost always funded through multiple short-term projects with overlapping funding periods, and varied and sometimes extensive reporting requirements. To effectively meet the demands of this type of resourcing model, administrative support from skilled and dedicated personnel is highly desirable. The same can be said for data curation and management.

Foster dedicated and skilled field staff

One of the more challenging aspects of long-term ecological monitoring projects is attracting and retaining skilled and dedicated field staff. Individuals with a requisite knowledge of species, and a willingness to spend prolonged and frequent periods in the field can be hard to find. Across LTERN, there have been different approaches to this problem (Boxes 4–7).

‘Many long-term studies have been running for decades without admin support, but I don’t doubt that they would be better with it.’

Dan Metcalfe

Box 4  Permanent field-based staff—Booderee National Park Plot Network

Our experience has been that a job is done best when it’s someone’s sole responsibility. To this end, we have tried very hard to ensure that one person is responsible for data collection and the myriad other roles associated with maintaining a particular long-term study. This lesson was learned from Professor Gene Likens, who established the now classic Hubbard Brook study of watersheds in north-eastern North America. Gene Likens made it clear to me that high-quality field staff were critical to the success of long-term research and monitoring. However, we are acutely aware that having all knowledge of datasets reside with just one person is inherently risky. As a result, we use a ‘cross-training model’ in which others in our team understand the databases and the information they contain.

David Lindenmayer
Since 1991, the Desert Ecology Plot Network has been exceptionally fortunate in being able to employ a series of thoughtful, highly skilled, hardworking and dedicated people who have contributed greatly to the scope and success of the overall program. Almost all these people had visited the sites before signing on as project staff members, providing them with an opportunity to see firsthand what the job would entail and giving us a chance to get to know them. These people have been integral members of the research teams for at least three years (indeed, Aaron Greenville has notched up more than a decade on the program, and Bobby Tamayo almost two decades) and have developed enormous corporate knowledge. Both Bobby and Aaron began as research assistants, but, as their responsibilities and expertise grew, their roles evolved into operations manager and data management champion, respectively.

More than 40 Honours, Masters and PhD students have completed projects based on fieldwork in the Simpson Desert, and most of these people also volunteered on initial field trips. The training of so many researchers has been a highlight and part of the success of the Desert Ecology Plot Network. The contribution of this skilled cadre of graduates to our understanding of desert ecology has been immense.

The largest component of the workforce associated with the Desert Ecology Plot Network has been the volunteer component: more than 1000 people have volunteered their time and effort in the field and often, also, in the laboratory. Although volunteers were hard to find in the early years of the program, we are fortunate now to have waiting lists of enthusiastic people who wish to visit the ‘big red playground’ of central Australia. Because of the remoteness of the Simpson Desert, the often harsh climatic conditions that prevail and the physical nature of the work, we try to ensure that prospective volunteers know exactly what to expect before signing on, are reasonably fit, and ideally have some experience of working remotely. Recommendations about new people from previous volunteers are always sought, and experienced people who wish to come back are also most welcome. The volunteer program has worked remarkably well over 24 years, with only a handful of people expressing no interest in returning.

Remote field work requires our team, as well as ourselves, to be flexible in the hours that we work and often to be available over public holidays. We conduct three-week-long field trips, and these have to be scheduled around family, teaching semesters and other academic commitments.

Chris Dickman and Glenda Wardle
Box 6 Institutional security but rotating staff—Tropical Rainforest Plot Network

The CSIRO Rainforest Plots (now known in LTERN as the Tropical Rainforest Plot Network) were set up with core funding, but, as priorities changed, lead scientists moved on and internal funding declined, the plots were maintained by a small group of dedicated technical staff. Newly appointed scientists, CSIRO funding, and external grants from TERN and others have lately ensured continuation of the plot network. But their continued existence is really due to those key permanent staff with the vision and commitment to enthuse volunteers to help out during the lean years. These have included other scientific staff from CSIRO and state agencies, student interns, Earthwatch volunteers and visiting scientists. The permanent staff have ensured that methods have been strictly adhered to; data have been entered, checked and archived; and the network is still delivering unique data more than 40 years after its initial establishment.

Dan Metcalfe

Box 7 Devotion and determination—Connell Rainforest Plot Network

Bob Black is a marine biologist who recently retired from the University of Western Australia, where he studied the population dynamics of sessile intertidal organisms.

Rocky intertidal areas and rainforests are both dominated by sessile organisms whose population dynamics can be described by tracking marked individuals, and Bob has always enjoyed taking short breaks from his marine research to work with Joe Connell in the Connell Rainforest Plots. Bob’s association with Joe goes back several decades to when Bob was a postdoctoral fellow with Joe at the University of California at Santa Barbara. Bob’s contribution to the plots dates at least as far back as 1976, and yet he has never had his name on a publication arising from the rainforest work. Instead, he has been content in his role as ‘a friend of the plots’.

One consequence of his long involvement with the Connell Rainforest Plots is that he’s now one of just two people who know the ins and outs of monitoring them. In fact, in 2006 he re-censused both plots single-handedly when I couldn’t get away from teaching and hadn’t been successful in getting funds to work on the plots. This was a monumental effort—Bob took some sabbatical time, drove his own vehicle across from Western Australia, and spent several months alone in the field in Queensland measuring and counting seedlings, saplings and large trees, all without external funding. Essentially, Bob single-handedly ensured that the plots were monitored at a critical stage when no one else was in a position to do so. Forward planning can take us only so far. When all those carefully laid plans fall through despite the best of intentions, it sometimes takes an extraordinary act of dedication like this to maintain the schedule of censuses.

Peter Green
Characteristic 3—Project management and succession planning

Sustainable and effective long-term monitoring requires careful planning and project management. Critical considerations are:

- determining what to do if there is a major disturbance (e.g. a fire or cyclone) that damages some or all of the plots or sites in a study
- identifying new research questions and potential future sources of financial support or, conversely, contingencies in the case of problems such as the cessation of funding (Boxes 8 and 9).

A loss of funding may involve planning in advance to determine whether it is appropriate to either ‘mothball’ a project and recommence it if a new funding source becomes available, or terminate the project and ensure that remaining work is completed and written up (if possible). And again, if possible, publish the data in a large, multiproject repository so that the data can persist beyond the project.

Box 8  
Flexibility is vital—Desert Ecology Plot Network

Although the success of any long-term monitoring program comes about in part from its use of the same core methods, it needs to be flexible enough to accommodate new questions and directions to test ideas as they are generated, and also to cope with unexpected events. Thus, we have weathered environmental changes—from floods to fires and invasions of feral animals—that may have wreaked havoc on a less-organised field program. Our survey units are deliberately modular (1-hectare grids) and flexible enough to take advantage of these ‘manipulations’. Designing the units in this way has helped us to gain a deep understanding of how biota change over time and across multiple scales of space in response to major environmental events.

A long-term monitoring program also needs to be able to adapt to inevitable turnover in personnel, changes in the tenure and ownership of the land on which the monitoring is conducted, and shifting demands from employers.

With respect to land ownership, we started out on four pastoral lease properties, and there have been several changes of owners over the years. The most notable was the purchase of two properties by Bush Heritage Australia for conservation. This brought another major change, as the properties were destocked, and land management changed to support the persistence of native flora and fauna. The lesson here is that, no matter what the ownership situation, strong personal relationships and good communication are crucial for consistency of access and for understanding the value of continuing the enterprise.

With respect to our employers, visits to the Desert Ecology Plot Network sites in the early years involved signing a car-booking form, and ensuring that teaching and other university commitments had been met in advance. Now a visit entails multiple sign-offs before leaving that take an order of magnitude more time and effort to complete. Of course, the increased emphasis on safety, welfare and efficient protocols is a welcome development. On the other hand, the persistent belief by university administrators that the internet is accessible at our sites in the Simpson Desert (when it is not) seems to be more resistant to change, and represents one of the subtle but never-ending challenges for our field teams!

Chris Dickman and Glenda Wardle
Box 9  One thing led to another—Alpine Plot Network Tundra Experiment

I’m an ecological geneticist interested in how populations and species are adapting to climate change. My group focuses mostly on invertebrates, but we also have a growing interest in plant adaptation. My interests in the alpine area started when I was based at La Trobe University and interacted with members of the Research Centre for Applied Alpine Ecology, including Warwick Papst, Henrik Wahren and Dick Williams. I was a principle investigator on the original Australian Research Council Linkage application that led to the establishment of the ITEX (International Tundra Experiment) plots in 2003, and I led the rebid from the University of Melbourne for this grant.

The plots were set up following an international protocol so that our data could be integrated into a larger database to look for consistent floral and faunal responses to warming. They were the first set of ITEX plots set up in the Southern Hemisphere, and were also the first plots to include burned sites, allowing monitoring of recovery from fire and its interaction with warming. We also established sites along elevation gradients to investigate local adaptation in plant populations, as well as patterns of gene flow facilitating or acting against adaptation. This work led to a number of novel findings, including that plant species showed idiosyncratic responses of flowering time to temperature and different patterns of phenological compensation. However, they also showed that warming responses were consistent with patterns seen elsewhere in the world, including increases in shrub growth rate. In the elevation transects, we found good evidence for local genetic adaptation in grasses that was enhanced by patterns of gene flow linked to elevation, and also strong plastic responses in other species enhancing local adaptation.

Under the LTERN initiative, we have incorporated these ITEX plots and elevation plots into a larger network of plots in the alpine and subalpine areas of Victoria. This network also includes some of the longest established plots in Australia—set up in 1945 to investigate the impact of grazing on alpine biodiversity (Box 11). Our team has been able to integrate the results from the ITEX plots with these long-term plots to demonstrate that long-term changes in vegetation match those in the manipulated ITEX plots. We have also used the different datasets to show that recovery from fire can be rapid, but that climate change is likely to increase shrub growth and potentially fire severity. The extended plot network should allow new questions to be answered that will assist in long-term management of threats to the unique biodiversity of the alpine region. They include questions about the impact of invasive species, and the susceptibility of different plant and insect groups to disturbance.

Ary Hoffmann

‘Succession is an issue looming large for many of us within LTERN as we fast approach retirement age.’

Peter Green

Thinking ahead should also entail succession planning (Boxes 10 and 11). This is critical because the majority of long-term projects cease when the people who established them retire or die (Lindenmayer & Likens 2010). An effective succession plan enables a smooth transition with minimal disruption to field operations. The issue of succession planning is not unique to long-term research; it is addressed in other fields such as business or farming. Essentially, in any field, it is important to start the process early, communicate widely to those affected and document your strategy well. A well-thought out and detailed plan is the best way to avoid problems, and to prevent a crisis if a ‘handover’ is not possible as a result of unplanned circumstances, such as sudden death.
Box 10 Succession is not always a simple process—Connell Rainforest Plot Network

Ecology is a relatively young discipline, and so there are few decades-long monitoring programs that have outlived the working lives of their originators and have been passed on to the next generation of researchers. Consequently, there are next to no case studies from which to draw general lessons and construct a ‘user’s guide’ to handing on the research torch for long-term study plots. What follows are some thoughts on how to achieve a workable transition from plot ‘originator’ to plot ‘successor’. These are informed by my own experience of inheriting the responsibility for monitoring the Connell Plots, and by discussions with colleagues over many years. I’m not claiming the transition was seamless—we muddled through—but what follows are some ‘lessons’ that are largely the benefit of hindsight and that should apply more broadly.

Ensure that the successor knows the methodology of actually performing the field work, and managing and maintaining the database.

This is a basic, obvious requirement. In the case of the Connell Plots, I became intimately familiar with both the field methodology and database procedures through a long period of overlap with Joe Connell (the original leader)—I was a postdoctoral fellow with him for several years, through several major recensuses of the plots. This kind of close association also gave us an opportunity to pass on all those procedural idiosyncrasies that often don’t make it into archived metadata descriptions.

Choose a successor who is well placed to inherit the responsibility for maintaining the research.

It makes good sense that the best chance for a project to continue for many years beyond the transition period is to hand it on to someone with a permanent position, or good prospects for securing such a position. In the academic arena, postgraduate students or postdoctoral fellows on fixed-term contracts are probably not best placed to ensure the long-term stability of a project. Who knows where they will end up, and if they can be effective successors? In an ideal world, ensuring several more decades of effective monitoring is best done by handing on the project to a relatively young research academic on a tenure-track path, rather than to someone whose academic future is less certain.

Publish co-authored papers to increase the chances of future grant success.

The chances of future grant success will be increased by the successor having co-authorship on publications arising from the long-term research, because it should give the successor credibility in the eyes of the grant reviewers. Ideally, this might happen as part of the succession plan, but at the very least papers should be published soon after handover to get some ‘runs on the board’.

Ensure that the successor has freedom to make their own key decisions.

The successor should be mindful of, but not weighed down by, the way in which the research has been run in the past. This is not a comment about research methodology—it goes without saying that, in long-term research, the core monitoring methodologies should be maintained ad infinitum unless there is an excellent reason to change them. Rather, this is more a comment about managing the strategic decisions that enable the research to continue. For example, one of the core values of LTERN is to make the historical data from long-term research available to other researchers, who may have no history of working on the plots. This is similar to the data access policy of the National Science Foundation in the United States, which funded the Connell Plots through most of the 1990s. These policies have caused some robust discussion among colleagues with past and current connection to the Connell Plots. The call for open access to data hard won over several decades was anathema for some, but agreeing to some level of future data sharing was a condition of gaining access to LTERN funding to continue the work. In these kinds of situations, the successor needs to be able to make strategic funding decisions that affect the future of the research, but are not necessarily consistent with past practices and attitudes.

Peter Green
Scientific research in the Australian Alps has a long and rich tradition. It began with the botanical expeditions of Baron Ferdinand von Mueller in the 1850s and continues to this day. Detailed ecological research commenced in the 1940s with the work of Maisie Carr and John Turner on Victoria's Bogong High Plains, and Alec Costin and colleagues in the Snowy Mountains of New South Wales. Much of what we know about the alps is based on discoveries made by these pioneers of Australian ecology.

Maisie Carr and John Turner were botanists from the University of Melbourne. In partnership with the State Electricity Commission and the Soil Conservation Board, they established long-term monitoring plots at Rocky Valley and Pretty Valley on the Bogong High Plains in the mid-1940s. These plots have been maintained to the present day and are now an integral component of the Alpine Plot Network within LTERN. Their value as reference areas is inestimable. They have allowed us to ask and answer questions about long-term ecosystem dynamics, basic ecological processes, fire, and land-use impacts, such as those of livestock grazing on alpine ecosystems. Importantly, they have also influenced the research of generations of alpine ecologists.

The plots were monitored each year between 1945 and 1958. They were remeasured in 1966, when Maisie returned to Melbourne briefly from University College Dublin. The Land Conservation Council's 1977 investigation into the alpine region was the impetus for a concerted effort to find, map and remeasure the plots in the late 1970s. This would not have happened without Warwick Papst and colleagues at the Soil Conservation Authority.

The Land Conservation Council–inspired effort led to a new wave of research in the 1980s, including my own PhD. My supervisor, the late Dr David H Ashton, was part of the first wave, having first visited the plots as a graduate student in 1949. Dave’s research on the ecology of mountain ash was being supervised by John Turner. I remember sitting with Dave in a lovely, comfy patch of snowgrass at the top of the Rocky Valley Plot as we were trying to nut out experiments to test some of Maisie’s ideas. ‘I remember this being nice, springy Poa back in 1949’, he said with fondness. Hmm, I thought, not only do these plots provide data, they are also chock-a-block with memories.

I have been very fortunate to supervise a number of postgraduate students who have worked on the Bogong High Plains. The first was Henrik Wahren, who was funded through a scholarship provided by Denis Carr, Maisie’s husband. Denis provided the scholarship to Monash University on the occasion of Maisie’s passing. Denis also provided all the original data, hard copy of course and enough to fill a large trunk! Henrik’s PhD examined all of the data from all the plots over all years of collection. From this, we were able to put together the definitive story of long-term vegetation change in grasslands, heathlands, wetlands and snowpatch herbfields. Maisie’s plots have been the feature exhibit on Day 1 of the Alpine Ecology Course, which has run more or less annually since 1987.

Henrik duly left to do postdoctoral studies in the Alaskan tundra, where he came across the International Tundra Experiment (ITEX). He brought the protocol back to Australia in 2002, and we received Australian Research Council funding to establish an ITEX outpost on the Bogong High Plains in 2003. Over the course of this experiment, Henrik and I have supervised other PhD students, including Frith Jarrad (climate change, and plant phenology and growth), Andrea White (climate change and sphagnum bogs) and James Camac (future trajectories of vegetation change). James, in turn, co-supervised Honours students such as Imogen Fraser, who worked on fuel dynamics. Data from Maisie’s plots were fundamental to interpreting the results of all these studies. And when you think about it, Turner, Ashton, Williams, Wahren, Camac and Fraser represents an impressive, intergenerational succession of alpine ecologists over seven decades.

Sadly, Maisie died in 1988, John Turner in 1991 and Dave Ashton in 2006. Upon Dave’s passing, a diverse clan of alpine ecologists and their mates drank a hearty toast to them all. And where else but at the lovely springy patch of snowgrass at Rocky Valley, which was still there, as it was in 1949. Long may their memory live.

Dick Williams

Notes:
Characteristic 4—Development of enduring partnerships

Many successful long-term monitoring studies are built on partnerships between people with different but complementary skills (Lindenmayer et al. 2011; Russell-Smith et al. 2003). These include scientists, statisticians, policy-makers and resource managers, who may be from government and nongovernment organisations, universities, research institutions and other organisations (Gibbons et al. 2008; Lindenmayer et al. 2012b). Well-developed partnerships between these groups of people are needed to validate policy-relevant and management-relevant projects (Russell-Smith et al. 2003), as well as to provide the scientific and statistical rigour required to ensure that results are robust, and conclusions are workable and defensible (Lindenmayer et al. 2011).

Developing cross-disciplinary partnerships recognises that different groups of people have different reward systems and different demands, which will often operate on different time scales (Gibbons et al. 2008). Mutual appreciation of these differences is critical; otherwise partnerships will fail (Lindenmayer et al. 2012b).
Box 12  A partnership to guide on-ground management—Booderee National Park

Booderee National Park is located in the Jervis Bay Territory, 200 kilometres south of Sydney on the south coast of New South Wales, south-eastern Australia. The area is an iconic reserve managed jointly by Parks Australia and the Wreck Bay Aboriginal Community. Booderee National Park supports an array of nationally endangered species, including the eastern bristlebird (*Dasyornis brachypterus*) (Lindenmayer et al. 2009a). The reserve has one of the highest human visitation rates of any national park in Australia: around 450 000 visitors annually (Director of National Parks 2012).

Like almost all natural areas, Booderee National Park faces a suite of major management and conservation challenges. An important one is the impact of fire on biodiversity. In an attempt to address some of these management challenges, a partnership has been forged between park managers and research staff at the Australian National University. A key part of this partnership was the establishment in 2002 of a new program to monitor vertebrate biota. This work is now part of the Booderee National Park Plot Network within LTERN.

The monitoring entailed the establishment of 110 permanent sites, each of 2 hectares, on which populations of small mammals, arboreal marsupials, birds, reptiles, amphibians and plants have been measured annually to date (i.e. 2002–12) (Lindenmayer et al. 2013). The monitoring has been used to inform the management of Booderee National Park. This relationship and its benefits were portrayed beautifully in a recent book, *Booderee National Park: the jewel of Jervis Bay* (Lindenmayer et al. 2014b).

Fire is the predominant form of disturbance in Booderee National Park. However, at the time the monitoring program began in 2002, the impacts of fire (including prescribed burning) on biodiversity in the park were poorly known. In 2003, a major wildfire burned around half of the park. Data gathered from the 110 monitoring sites indicated that the bird assemblage had fully recovered within 3–4 years of the fire (Lindenmayer et al. 2008). This short-term pattern of recovery included a rapid post-fire recovery of the eastern bristlebird (Lindenmayer et al. 2009a). One of the key factors influencing the recovery of both the overall bird assemblage and the eastern bristlebird was the patchiness of the fire, with faster and more complete recovery (to pre-fire conditions) documented for the sites supporting more unburned areas. However, a longer-term analysis revealed a highly significant effect of fire history: bird species richness has decreased by about 9.1 per cent per site per fire over a 30-year period.

The empirical results of the monitoring program have been used to improve the park’s fire management program. Uniform prescribed burning of entire compartments of native vegetation has been replaced by a mosaic of burned and unburned areas. In addition, burning in the park is now typically directed away from areas that have had many fires in the past 40+ years (Lindenmayer et al. 2013).

David Lindenmayer
Characteristic 5—Maintenance of field infrastructure

A key feature of longitudinal and time-series studies is that a given set of plots, sites or other measurement units is visited on a repeated basis over a prolonged period. The quality of the data gathered from repeated site visits is often contingent on ensuring that precisely the same points are surveyed in each sampling event. This makes it important to permanently mark field sites, and carefully record and document their location. Technology such as global positioning systems (GPS) has obvious advantages in this regard, although geo-referenced locations need to be appropriately entered into databases for long-term storage. Clearly marked plots or sites also can increase the efficiency of field work, and reduce the chance of the plots or sites being destroyed in the event of a change in land use (e.g. logging or clearing).

It is also important that other infrastructure is maintained, or adapted as needed, to ensure the accurate repetition of studies (Box 13).

Box 13 Unexpected field events—Booderee National Park

All long-term studies produce ecological surprises—indeed, they are more likely to occur the longer a study runs (Lindenmayer et al. 2010). Some ecological surprises require considerable work to reset the trajectory of field work programs. Work at Booderee National Park is a useful illustration of this. A key part of the infrastructure in that study has been the establishment of hard plastic drift fences, which were set up as part of the pitfall trapping program at all 110 long-term monitoring sites in the reserve. However, these drift fences were heavily trampled by black wallabies! This necessitated the fences being replaced every 1–2 years—a financial and logistical impost that was impossible to sustain. New protocols were required, and drift fences and pitfall traps were dispensed with and replaced by artificial substrates—layers of tin, tiles and wooden sleepers, which provided shelter sites for frogs and reptiles. However, an extended calibration study was required when the infrastructure was changed to ensure that differences in the effectiveness of different field methods could be determined and taken into account, as part of maintaining the integrity of the long-term data record.

David Lindenmayer
Characteristic 6—Reflection and adaptation

There is no such thing as a perfect study. Questions will often change or evolve during a long-term monitoring study, and therefore require prompt and thoughtful revision (Ringold et al. 1996). However, this needs to be achieved without breaching the integrity of the overall research program, which includes the value of the systematic, standardised data collected to date. Lindenmayer & Likens (2009) have recommended the use of an adaptive monitoring approach to evolve questions in long-term studies; they then demonstrated how this can be applied to solve ‘real-world’ problems in the management of natural resources (Lindenmayer et al. 2011).

All projects can be improved, sometimes in ways that cannot be seen by those who established them. For a start, it must be anticipated that long-term studies will yield novel observations that may warrant refinements to the current design, or even the undertaking of complementary research activities (Boxes 14–16).

Developing and maintaining a sound study design is an ongoing process, which is invariably linked with expert statistical analysis of the data gathered. The analysis and interpretation of results from long-term research studies can be extremely challenging (Thomas & Martin 1996; Welsh et al. 2000). For example, separating long-term population declines from annual or cyclical fluctuations in population size is a nontrivial task (Krebs 1991; Martin et al. 2007; Thomas & Martin 1996). This is particularly true for some rare species for which it may be difficult to determine if they are declining (Martin et al. 2007; Taylor & Gerrodette 1993), or for populations of species that can exhibit rapid short-term fluctuations in population size after disturbances such as fire or logging (Bradstock et al. 2012; Brawn et al. 2001; Whelan 1995).

Statistical and ecological reviews are one important way to improve the quality (and sometimes increase the breadth and scope) of a long-term study. Although this can seem confronting, it is important to recognise that more is often learned from what went wrong than from what went right (Redford & Taber 2000). Reviews can also help you deal with unexpected events and outcomes that may force you to reconsider how to proceed.

It is also important to reflect on when monitoring should cease. This can be a difficult question to answer and, more often than not, it is not posed because funding opportunities cease or the project stalls when the lead researcher retires. Nevertheless, knowing when to stop is important. The most obvious advice is to stop when the program’s key questions have been answered—collecting further data may well be interesting, but there will be a diminished return on investment. This is when posing new questions in other systems will become more attractive and beneficial. Another reason to stop is because you have been unable to answer the scientific questions within the anticipated period. This may occur for a variety of reasons, including those associated with sampling and measurement error.

‘Long-term data provide an ever more valuable baseline to test and refine ideas about environmental change and the processes that drive it.’

Chris Dickman
One of the most interesting and rewarding aspects of our long-term studies is how we have managed to evolve them to address new questions, which were not even thought of when the studies were initiated. When I initiated our upland heath swamp plot network in late 1982, it was to satisfy curiosity about high levels of fine-scale plant diversity and striking spatial patterns in vegetation. It never occurred to me that the patterns were a dynamic mosaic responding to fire regimes. But when this hypothesis soon emerged, we shaped the study and repeat sampling to address important questions about the management of fire regimes to maintain diversity.

Thirty years on, the plot data (in combination with remote sensing and bioclimatic modelling) are producing important insights into the impacts of climate change on these hydrologically sensitive ecosystems. In the near future, the plots will provide important reference sites to monitor the effects of longwall coal mining and coal seam gas extraction. Our other long-term plot networks in restored grassy woodlands and spinifex mallee also have evolved in exciting ways. The value of these investments is increasing over time.

David Keith

Over time, we have found that the program, which was originally designed to primarily address biodiversity conservation issues, has provided some substantial serendipitous benefits. For example, one of the key elements of the original plot sampling design was to understand the effects of savanna fire regimes on vegetation structural and associated habitat components (e.g. tree and shrub-layer density and size-class distributions). While plot observations have indeed yielded significant insights into these effects (Prior et al. 2009; Russell-Smith et al. 2010; Russell-Smith et al. 2012), related plot-based observations concerning the effects of fire regimes on biomass and carbon storage (Murphy et al. 2010; Murphy et al. 2014) have also helped to inform the development of a national methodology to address abatement of greenhouse gas emissions associated with savanna fires (Department of Climate Change and Energy Efficiency 2012). Long-term monitoring plot observations are likely to have substantial value for documenting the effects of climate change in the decades ahead.

Jeremy Russell-Smith
Box 16  Taking the long view—Tropical Rainforest Plot Network

To maintain long-term research, you need to take the time to reflect and adapt. For example, an unpublished file note in the rainforest permanent plot archives from the early 1980s states:

_The main question confronting forest ecologists working in management research has changed from ‘What kind of disturbance will promote wood growth on desirable species?’ to ‘What are the floristic and structural consequences of a given type of disturbance?’_

This was farsighted, as the first plots were established in 1971 by the Forest and Timber Bureau of the Commonwealth Department of National Development to effectively provide control plots to understand the results of manipulative experimental plots in adjacent production forest areas. Declaration of the Wet Tropics of Queensland as a World Heritage Area in 1988 stopped all logging activity. But that didn’t mean that the research needed to stop—it just needed to evolve. More than 40 years later, we are still monitoring the same plots, often the same trees, but the disturbance events envisaged (logging) have been replaced by cyclones, disease, drought and flood, giving us an unparalleled before-and-after viewpoint from which to assess consequences of, and responses to, disturbance events (e.g. Metcalfe & Bradford 2008).

Dan Metcalfe
SECTION 2 — CHARACTERISTICS OF EFFECTIVE AND INFLUENTIAL LONG-TERM MONITORING
Characteristic 7—Project momentum built through co-located projects

A long-term ecological study can be used as a framework around which shorter-term projects can be conducted. These other projects can not only enrich the overall research and/or monitoring effort but also highlight added value to funders investing in the long-term research. There are numerous examples from around the world of long-term studies acting as platforms for additional collaborative, multidisciplinary studies, and these additional investigations have helped account for the long-term patterns that have been identified (Lindenmayer et al. 2012a). Within LTERN, most of the plot networks have taken this approach (Boxes 17–19).

Box 17 Co-location of studies—Victorian Tall Eucalypt Forest Plot Network

Many long-term studies benefit from the co-location of different studies. This can lead to greater insights than could be obtained from a single investigation in isolation. The work in the montane ash forests of the Central Highlands of Victoria is a useful illustration of this key point. The long-term ecological research and monitoring program initially focused on the temporal dynamics and habitat requirements of arboreal marsupials. However, over time, other researchers joined the project and gathered data on other groups, such as invertebrates and plants, and more recently carbon cycles of the forest. New insights from these co-located projects have provided vital information on the disturbance dynamics of the forest ecosystems, and generated a more holistic understanding of the similarities and differences in how the forest responds to natural and human disturbance regimes.

David Lindenmayer
**Box 18  Monitoring across countries—Alpine Plot Network**

The Alpine Plot Network includes plots that were established under the ITEX (International Tundra Experiment) program. This program involves monitoring of sites in the tundra and alpine areas of 12 countries, although it focuses mostly on Northern Hemisphere sites. Data collected from the Australian plots have been used in combination with datasets from other ITEX sites to test the likely impacts of warming on tundra vegetation. The combined datasets have demonstrated that the growth of shrubby species is enhanced under warming, that early flowering is a characteristic response of many plant groups, and that there is little change in plant diversity over time under warming, as some species decline in abundance but others increase. By monitoring changes in control areas over time at ITEX sites, it has been possible to compare changes seen in the warmed plots with those occurring in the surrounding area over several decades. Already, the Australian ITEX plots are showing a decrease in grass cover. This has also been documented through other long-term sites within the Alpine Plot Network in LTERN, and at some other overseas sites.

Ary Hoffman

**Box 19  Additional studies—Tropical Rainforest Plot Network**

The CSIRO rainforest plot network was established to document natural processes in a context of commercial logging. Over the past 40 years, it has become a focus for a number of ancillary studies that have used the detailed contextual knowledge obtained from the plots. Pollen traps, and flowering and fruiting behaviour have informed understanding of how plant and animal life-cycle patterns change across the landscape. Students have worked on (or near) the plots on seedling recruitment dynamics, woody debris decomposition rates, and long-term impacts of climate on recruitment and growth, as indicated by tree-ring data. Data from weather stations established in (or near) plots have been used to improve climate models and underpin physiological studies. Growth and mortality data have contributed to international collaborative analyses of carbon dynamics and of carbon storage in terrestrial vegetation. A TERN-supported 25-hectare rainforest supersite2 has now been established next to one of the original plots. It is the first Australian plot in the style of the Smithsonian Tropical Research Institute’s pan-tropical plot network and ushers in a new chapter in documenting the dynamics of Australian tropical forest systems.

Dan Metcalfe

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2 The Australian Supersite Network is another facility within the Terrestrial Ecosystem Research Network (see www.tern.org.au/Australian-SuperSite-Network-pg17873.html).
Characteristic 8—Communication of the value and importance of long-term monitoring

Many current trends in ecology and environmental management disadvantage long-term, field-based empirical work (Lindenmayer & Likens 2011b). To counter this, we need to make sure that this type of research is well communicated, and we need those who appreciate its obvious values to be vocal.

Build an influential body of knowledge

For long-term monitoring to be influential, it needs to be much more than science. Previously, we discussed what makes monitoring successful, and we defined successful monitoring as achieving the stated need and purpose. One important aspect of success that should not be overlooked is building a body of knowledge to influence natural resource management and biodiversity conservation practice. This should be part of the ‘need and purpose’ of monitoring programs. Frustratingly, this is not always the case, especially for monitoring-related research conducted currently within universities.

Be mindful of the ‘publish or perish’ culture

Science careers are built and maintained on publication records, and an ability to secure limited and fiercely contested funding (Bickford et al. 2012). Arguably, this ‘publish or perish’ culture can lead to a lack of communication with society, and indeed superficial scientific outputs, conformity and scientific stagnation (Fischer et al. 2012b; Gendron 2008; Lawrence 2006, as cited in Shanley & López 2009). This, in turn, can lead ultimately to a lack of responsiveness to emerging social needs and a lack of relevance to decision-making.

In addition, generating scientific publications from ecological monitoring can be difficult at early stages. It can take substantial time to detect trends and patterns in empirical data, meaning a long time before publication is possible. This delay can be perceived as a lack of productivity and threaten the continuity of a project. To counter this problem, a long-term ecological study can be used as a framework around which shorter-term projects can be conducted and the associated results communicated to demonstrate scientific productivity. For example, retrospective or cross-sectional studies can serve as a prelude to longer-term projects, and can provide key initial insights or questions. Indeed, an advantage of site-based research is that it can benefit from both long-term monitoring (to identify long-term patterns) and a sequence of short-term experiments and monitoring focused on elucidating the specific processes responsible for those patterns.

‘Knowing how to engage effectively with stakeholders so that management practices or policies change if they need to is one of the great challenges for researchers and management agencies.’

Colin Yates

‘To not account for real-world impact as a measure of success is a peculiarly academic view of the world. For ‘applied’ scientists, research outputs (i.e. publications) are only half way along the continuum of input–activity–output–outcome–impact; therefore impact MUST be a measure of success.’

Dan Metcalfe
Use meta-analysis where appropriate

Data mining approaches that look for patterns in multiple, combined datasets can be popular and may generate publications quicker than long-term research (but see Box 1, Big data—how effective and how relevant?). Quantitative reviews like meta-analysis which combine the results of existing, independent studies can be useful where the experimental design of the component studies is understood. However, without ongoing support for long-term ecological studies, systematic reviews such as meta-analyses will have fewer cases to review and analyse, important ecological discoveries may be overlooked, and evidence-based environmental policy and management (e.g. Evidence 2011; Sutherland et al. 2004) will become harder to achieve (Lindenmayer & Likens 2011a).

Support education for the next generation

Another concerning trend is less field experience and a resulting lack of field identification skills in undergraduate students and junior technical staff. Field-based training is more expensive and difficult to conduct than computer-based learning; as a result, universities and agencies are decreasing field time for students and trainees. This will lead to a shortage of trained people who are ready or willing to participate in ecological research or, more alarmingly, able to train those who need this knowledge in the future (Greene 2005).

These trends in education and research make the already difficult task of conducting long-term studies even more difficult. It is therefore important that long-term monitoring and empirical research have strong advocates—people who frequently and convincingly argue the case for the value of, and need for, long-term research. LTERN is helping this happen.

‘Standing in the Connell Rainforest Plot changed my life and how I think. It was a life experience, not just a research learning experience.’

David Keith
Successful large-scale long-term monitoring

As part of this section, it is worth noting that there are many examples of effective and influential large-scale and long-term monitoring in Australia. Many organisations record data in a systematic manner over time to obtain information on a variety of social, economic and environmental conditions. The Australian Bureau of Statistics, the Bureau of Meteorology and Geoscience Australia are three such organisations. The Australian Bureau of Statistics conducts household sample surveys that obtain information on participation in the labour force (Box 20), use of health services and energy consumption; and business sample surveys that collect data on characteristics such as income and number of employees across a range of industries and geographic regions. The Bureau of Meteorology records data on rainfall and temperature at its weather stations, and volume of stream flow in selected catchments. Geoscience Australia monitors seismic, infrasound, hydro-acoustic and geomagnetic information across the Australasian region.

Although the subject matter that these three agencies deal with differs from the ecological application that is the focus of this booklet, the fundamental goal can be considered the same—to reliably measure attributes over time so that decision-makers can be better informed. Programs from the three agencies have features in common with ecological monitoring applications that help the programs meet their objectives. These include having a clear understanding of:

- why monitoring is needed
- the group or geographic region you wish to generalise your results to
- what needs to be measured (and how), to meet the project goals
- a method for selecting the subset of entities (individuals or sites) to be measured if a complete census is not practical
- what statistic(s) or function(s) of the data will be used to draw conclusions from the results of the survey or data collection program.

For example, the Australian Bureau of Statistics programs are structured surveys with a purpose, and have all these features clearly identified, from identification of a target population through to data analysis. Implementation of a well-considered formal survey provides confidence that reliable information will be obtained from the program for a specific objective.
Box 20 Australian Labour Force Survey

The Australian Bureau of Statistics household Labour Force Survey provides information for monitoring the participation of women and men in the labour force. Collected since 1960, this information (broken down by age, education and other social characteristics) is used to help design and evaluate government policy. Estimates of the number of employed (full-time, part-time) and unemployed, the unemployment rate and the labour force participation rate are key statistics that have been collected monthly since February 1978.

The Labour Force Survey uses cluster sampling, in which a staged process is used to obtain information about the population of interest. A sampling frame (i.e. list of statistical units) forms the survey population, from which a stratified sample of more than 30,000 households is randomly selected to survey. Here, the geographic region is the cluster, and within that unit information on all household members (>15 years of age) is obtained from a responsible adult within the household. A household participates in the monthly survey for eight months, and one-eighth of the sample is replaced each month.

Changes to the Labour Force Survey methodology can be initiated for a variety of reasons, including regular reviews that draw on information captured in the five-yearly population census. Estimation methods have been modified and revised, the questionnaire has been redesigned, and sampling fractions used across the states and territories have waxed and waned. In April 2001, a substantially redesigned survey questionnaire was implemented to incorporate contemporary labour market content, modified technical definitions and reworded survey questions, to improve data quality. Consultation with data users about the proposed changes confirmed the value of making the revisions, while adhering to the important constraint of maintaining comparability of the longitudinal data.

In conjunction with the redesign of the questionnaire, the Australian Bureau of Statistics undertook a statistical impact study to evaluate whether the changes would disrupt the continuity of the core labour force series. For its programs more generally, where changes to the survey affect the ability to compare data over the years, these impacts are documented in the Australian Bureau of Statistics publications.
Checklist of the characteristics of effective and influential long-term monitoring

**Characteristic 1—Continuous funding**
- The project is designed to be sustainable and affordable.

**Characteristic 2—Dedication and determination at multiple levels**
- The project has strong and focused leadership.
- The project has good administrative support.
- The project has dedicated and skilled field staff; field staff can include project staff, undergraduate and postgraduate students, postdoctoral researchers, and volunteers.

**Characteristic 3—Project management and succession planning**
- Plans have been made for various contingencies, including major environmental disturbance or loss of funding.
- Plans have been made for continuation of the project and leadership over time.

**Characteristic 4—Development of enduring partnerships**
- Effective cross-disciplinary partnerships have been established; partnerships can involve scientists, statisticians, policy-makers and resource managers, who may be from government and nongovernment organisations, universities, research institutions and other organisations.

**Characteristic 5—Maintenance of field infrastructure**
- Field sites have been permanently marked and documented.
- Other infrastructure is maintained, or adapted as needed, to enable the accurate repetition of studies.

**Characteristic 6—Reflection and adaptation**
- Study results are used to refine and develop new questions and studies.
Checklist of the characteristics of effective and influential long-term monitoring (continued)

Characteristic 7—Project momentum built through co-located projects
- The long-term ecological study is used as a framework for complementary shorter-term projects.

Characteristic 8—Communication of the value and importance of long-term monitoring
- The results of monitoring have been so well communicated that they can inform and improve policy and management.
- Advocates of long-term monitoring are heard in government, scientific organisations and the community.
- The research is being used to create-high impact publications; meta-analysis is used where required to elicit better understanding.
- There is good support for field-based training.
Conclusion

In this booklet, we have discussed what we consider to be the key characteristics of all monitoring, and how to sustain a program in the long term. The interconnectedness of these characteristics is summarised in Figure 1. At the core of this figure are the principles discussed in Section 1. From this core, the other characteristics in Section 2 can be added. But if the core is not sound—no matter what additions are made—the program will have limited success.

‘There are no free lunches with long-term monitoring. Soundly designed, informative studies that contribute to management related ecosystem questions require effort and resources.’

David Lindenmayer

Figure 1  A visual reflection of the characteristics discussed in this booklet. At the core are the characteristics from Section 1. From this, a desirable balance of additional activities can be added to produce sufficient momentum to achieve an effective and influential long-term ecological monitoring program.
Monitoring the environment effectively is difficult. From continually grappling with this difficult topic, we have learned some things along the way. We have tried to capture these lessons and insights in this booklet.

In summary, at the core of all monitoring should be a fit-for-purpose design. From this, we believe that successful long-term monitoring relies on an appropriate mix of science, data management, communication and resources. In essence, clear ecological and statistical thinking is required to pose tangible questions of management relevance that can be pursued with available resources. Fit for purpose is critical in addressing key questions of management concern. A useful example is the large-scale monitoring associated with the Australian Government’s Environmental Stewardship Program, in which private land managers are paid to undertake conservation actions on their properties. Here the monitoring is explicitly designed to quantify changes in vegetation condition and populations of key groups of biota in response to the management interventions required by the program (Lindenmayer et al. 2012b).

We also suggest that intelligent and creative thinking is needed to deliver clever ways of securely storing and efficiently managing field data obtained from long-term studies. A strong component of social and communication skills is required to maintain enduring relationships with a variety of people and groups, both within and outside the immediate study team.

Finding a balance among the aspects shown in Figure 1 will lead to sufficient momentum to achieve a sustainable long-term program. However, no amount of clear scientific thinking, clever data management and effective interpersonal skills will be enough to maintain long-term monitoring plans without financial support to sustain the programs. In Australia, a lack of recurrent funding and stable policy settings remains a formidable barrier to achieving successful long-term ecological monitoring.
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