Austral Ecology

Contemplating the future: Acting now on long-term monitoring to answer 2050's questions

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Abstract

In 2050, which aspects of ecosystem change will we regret not having measured? Long-term monitoring plays a crucial part in managing Australia's natural environment because time is a key factor underpinning changes in ecosystems. It is critical to start measuring key attributes of ecosystems – and the human and natural process affecting them – now, so that we can track the trajectory of change over time. This will facilitate informed choices about how to manage ecological changes (including interventions where they are required), and promote better understanding by 2050 of how particular ecosystems have been shaped over time. There will be considerable value in building on existing long-term monitoring programs because this can add significantly to the temporal-depth of information.

The economic and social processes driving change in ecosystems are not identical in all ecosystems, so much of what is monitored (and the means by which it is monitored) will most likely target specific ecosystems or groups of ecosystems. To best understand the effects of ecosystem-specific threats and drivers, monitoring also will need to address the economic and social factors underpinning ecosystem-specific change. Therefore, robust assessments of the state of Australia's environment will be best achieved by reporting on the ecological performance of a representative sample of ecosystems over time.

Political, policy and financial support to implement appropriate ecosystem-specific monitoring is a perennial problem. We suggest that the value of ecological monitoring will be demonstrable, when plot-based monitoring data make a unique and crucial contribution to Australia's ability to produce environmental accounts, environmental reports (e.g. the State of the Environment, State of the Forests), and to fulfilling reporting obligations under international agreements such as the Convention on Biological Diversity. This paper suggests what must be done to meet Australia's ecological information needs in 2050.

Keywords: Ecosystem-specific monitoring, networks of monitoring sites, biodiversity conservation, environmental management, adaptive monitoring, adaptive management, Australian continent, environmental accounting.

Introduction

The planet is changing rapidly as a result of increasing human population; land, ocean and climate transformations (IPCC & Editors 2013); and biodiversity loss (Butchart *et al.* 2010; Barnosky *et al.* 2012). The current rate of change is greater than at any previous period known to science (Rockström *et al.* 2009; Hooper *et al.* 2012). Many predictions are being made about the conditions likely to characterise the planet in the future (e.g. http://hsctoolkit.bis.gov.uk/The-tools.html; KPMG International and The Mowat Centre (2013)). Some authors refer to 2050 as being a “crunch-time” for humanity in terms of dealing with the multiple demands of a large and resource-intensive human population and rapidly dwindling natural resources (Turner 2008; Holloway 2012; Fulton 2013). But these predicted trends need to be rigorously examined so that they can be validated, adapted or dismissed (Andersen *et al.* 2014). That is, in addition to making predictions about change based on models of unknown accuracy, we also need to measure **directly** what is changing, how it is changing, and why it is changing. This process will help to track current trajectories of change relative to previous predictions, and inform future predictions. It also will improve society’s capacity to adapt, innovate and avoid the occurrence of predicted worst-case scenarios.

Uncertainty about the present and future state of the environment contributes substantially to the ultimate costs of addressing environmental change (Pindyck 2007; Dietz & Fankhauser 2010). It is difficult to formulate cost-effective policies to address changes that are poorly understood either with respect to magnitude of change or driving mechanisms. A relatively small amount of money spent on long-term monitoring can help to better define problems and their solutions, thereby reducing the chance of expensive mishaps. Thus, recognition of change, and understanding the causes of change, require long-term investment in data collection. Indeed, many questions in ecology and environmental science cannot be addressed without long-term monitoring and research (Likens 1989; Muller *et al.* 2011; Lindenmayer *et al.* 2012).

In recent years in Australia, there has been growing recognition of the need to conduct environmental monitoring, with some progress made through the establishment of the *Environmental Accounting Function* within the Bureau of Meteorology under the *National Plan for Environmental Information* (BOM 2014). This led to significant products such as the Biodiversity Profiling report (Zerger *et al.* 2013). This initiative, however, was curtailed in 2014, making it apparent that the basic case for environmental accounting needs to be reinvigorated. A new dialogue needs to emerge which emphasises the importance of implementing appropriately stratified ecosystem-specific site-based monitoring which can detect change and explain the drivers of that change (Burns *et al.* 2014). Importantly, this approach is distinctly different from approaches to reporting on ecosystem changes which rely heavily on a large body of inventory data (Hampton *et al.* 2013). In Australia, many of these data are now accessible through the Atlas of Living Australia or the Australian Ecological Knowledge and Observation System. Data housed within these important repositories are drawn from a variety of sources ranging from standardised surveys undertaken by government agencies to opportunistic sightings recorded by amateur naturalists. While these repositories constitute impressive inventories in themselves, care should be taken when using these data for scientific monitoring and explaining ecological phenomena and predicting their trajectories into the future. This is because common features of such databases, such as unquantified spatial bias, the use of non-standardised sampling methods, lack of taxonomic rigour and a lack of spatial accuracy in data collection, can limit the utility of the information they contain.

Fit-for-purpose long-term ecological monitoring and research are essential if we are to answer key questions about environmental changes, particularly gradual change happening in small iterations (i.e. chronic change) rather than abrupt (acute) change resulting from a sudden alteration in conditions. However, there is a very patchy and disjunct history of long-term environmental research and monitoring in Australia (Youngentob *et al.* 2013). For example, because of a paucity of credible long-term ecological monitoring, it has been virtually impossible to tell how effective actions associated with billions of dollars of annual expenditure have been on environmental management outcomes in Australia (Hajkowicz 2009; Pannell & Roberts 2010). In addition, environmental reporting initiatives like the five-yearly State of the Environment reports (produced by the Commonwealth Department of the Environment), and the State of the Forests Reports (produced by the Australian Bureau of Agricultural and Resource Economics and Sciences) are largely disconnected from any long-term ecological monitoring programs or from other major programs designed to improve environmental outcomes (Lindenmayer & Gibbons 2012). Instead, they are reliant on 'multiple lines of evidence', none of which is appropriately designed to provide adequate information on the condition of the environment relative to its natural fluctuations and ecosystem drivers.

In light of the problems outlined above, coupled with the suggested risks of an impending "environmental crunch", a key overarching question is:

> *What should we begin measuring now that can help society better understand and manage natural resources by 2050 (and beyond) and, in turn, guide human societies through a likely transition to a less bountiful world?*

We argue that to improve natural resource management by 2050, we **must:** **(1)** begin measuring key components of ecosystems systematically and purposefully **now**, **(2)** establish the necessary infrastructure on-ground to facilitate ecological monitoring, and **(3)** further develop information management architecture to archive, analyse and re-use the data at appropriate scales. This should inform the public about the status of the environment and help decision makers implement more sustainable environmental management. We outline the features that would characterise a successful nation-wide monitoring initiative capable of serving the public interest towards 2050. We also summarise some of the general principles that should guide efforts to collect meaningful ecological measurements from terrestrial ecosystems. We do not make specific recommendations regarding the ecosystems and parameters to be monitored, but rather focus on general recommendations.

Characteristics of effective ecosystem monitoring by 2050

Prior to embarking on any credible set of ecological monitoring programs, it is essential to properly define an ecosystem (Keith *et al.* 2013). This is to ensure that all stakeholders are working with common concepts and units for monitoring and reporting. An ecosystem is identified by four key elements: a biotic complex; an abiotic complex; the processes and interactions that link them and drive ecosystem change; and the distributional area they occupy (Keith *et al.* 2013). These elements are implicit in the System for Environmental-Economic Accounting (SEEA) (United Nations 2012) and also the recent IUCN process for identifying by 2025 a global Red List of Ecosystems (Keith *et al.* 2013). Such ecosystem-specific elements mean that the majority of entities to target for long-term monitoring will vary among ecosystems according to differences in ecosystem processes (including threatening processes and the interventions designed to mitigate them), differences in biota, and other factors. Thus, suitable entities for long-term measurement in, for example, a desert ecosystem may well be markedly different to those in a temperate woodland. This is highlighted in a special edition of *Austral Ecology* (Nicholson *et al.* 2015) which contains a series of assessments of ecosystems in the southern hemisphere employing the IUCN Red List of Ecosystems criteria. It follows that continental reporting of the environment will be done best by detailed and focussed monitoring and subsequent reporting on environmental performance **within** an ensemble of targeted ecosystems over time.

In the remainder of this section, we outline key elements that should underpin the development of robustly designed and implemented (and consequently long lasting) ecological monitoring programs within targeted ecosystems.

1. **Complete an audit** of existing monitoring programs and long-term ecological research to determine what work has been completed where and by whom (e.g. Youngentob *et al.* 2013). This is critical for taking ecological, financial, and policy advantage of pre-existing long-term work with an already documented time series of information. Building greater time depth increases the potential for increased inference (Lindenmayer *et al.* 2012). This is because time can be a key variable influencing the effects of particular processes and the effectiveness of particular interventions such as ecological restoration (Benayas *et al.* 2009) and invasive species control (Buckley 2008). It is also cost-effective to build on previous research investments, depending on the research question at hand. However, there will be a need to establish new long-term monitoring to document changes within a more representative array of ecosystems, in populations of additional species or communities, or in response to additional ecological processes and management interventions (including responses to emerging environmental issues (Sutherland *et al.* 2012)). For example, some widespread and ecologically important Australian ecosystems, such as those dominated by Mitchell grass (319 000 km^2 across Queensland, Northern Territory, Western Australia and New South Wales (Orr & Holmes 1984)), are currently highly deficient in robust monitoring efforts, especially with respect to biodiversity responses to pastoralism (White *et al.* 2014).
2. **Target** environmental monitoring within a subset of key ecosystems across the Australian continent. Choosing a subset of ecosystems to robustly monitor should be guided by an appropriate stratification that leads to a range of variation in biota,

physical environments, and ecosystem processes being monitored nationwide. Priority ecosystems for selection also should be those suggested by standardised processes, such as evidence-based risk assessments, which could highlight those ecosystems which are most subject to threatening processes and activities, and therefore likely to benefit most from systematic experimentation and monitoring.

3. **Develop** standardised, evidence-based conceptual models using accepted eco-evidence frameworks (e.g. Webb *et al.* 2011; Norris *et al.* 2012) which reflect collective understanding of ecosystem functionality (e.g. see White *et al.* 2013). Systematic synthesis of evidence will greatly improve the transparency and defensibility of decisions. A more ‘evidence-based’ approach to environmental management also will lead to improved environmental outcomes.
4. **Identify and document** the key environmental drivers in each ecosystem that require targeted monitoring. These include a range of threatening processes (which increasingly interact) such as habitat loss and fragmentation, invasive species and exotic pathogens, hunting or other kinds of harvesting, pollution, climate variability and climate change, and human population growth (Table 1; and see Evans *et al.* (2011)). We need to document and compare the relative frequency and severity of drivers of change that act as chronic pressures, such as salinity, with those that act as acute pressures such as cyclones and severe bushfires. We also need to understand the scale at which they have impacts. In an Australian context, there are already well developed maps and spatial prioritisations of where particular kinds of threatening processes predominate and these can provide a valuable basis to help target monitoring (Evans *et al.* 2011). Similarly, given that rapid climate change is likely to be a major driver and threat to ecosystems and biota *per se* in Australian ecosystems (Steffen *et al.* 2009), maps of where such impacts are likely to have greatest effect

(Burrows *et al.* 2014) will be important for guiding where to monitor as well as what to monitor (and also how to monitor those targeted entities). A powerful way to quantify the effects of a particular ecosystem threat is to ensure that monitoring is conducted, wherever possible, not only where those threats manifest, but also where they are absent or limited.

5. **Identify** the important kinds of management interventions in each ecosystem which are needed or currently implemented to mitigate the impacts of threatening processes. These interventions need to be evaluated over time to gauge the effectiveness of prescriptions such as reservation, maintaining or enhancing ecosystem connectivity, rehabilitation, fire or grazing control, and invasive species control.
6. **Select** particular entities for monitoring that are likely to respond significantly to important environmental drivers, threatening processes, and management interventions. These entities will be characteristic of particular ecosystems and could include ecosystem spatial extent, structural features, species composition and dominance, populations of species and/or key ecological processes (including threatening processes). The target entities for long-term monitoring will vary among ecosystems in response to among-system differences in key ecosystem processes (including threatening processes and the interventions designed to mitigate them; see Table 1), differences in biota, and other factors. This means that suitable entities for long-term monitoring in, for example, a dry sclerophyll forest ecosystem will most likely be different to those in an ephemeral wetland. Selection of target entities for monitoring should be based on several criteria including: **(a)** suitability for answering pre-defined and evolving key questions about conditions in a particular environment, **(b)** the potential for (and sensitivity to) change over time, and **(c)** feasibility for repeated monitoring. Feasibility for ecological monitoring does not mean a focus only

on entities that are cheap to monitor, which risks directing effort away from entities crucial for answering key questions. If the target entities are elements of biodiversity, they should be a subset of biota and the abiotic component of ecological processes and interactions that influence biodiversity. This is because it is not logistically or financially possible to monitor all biodiversity. Rather than monitoring many things poorly, we should strive to monitor a few things well, as this can increase the power to reliably detect change (Lindenmayer & Likens 2010).

7. **Consider** additional structure in the stratified design of a long-term monitoring program in relation to scale of ecosystem extent, with a particular focus on those parts of an ecosystem thought likely to show responses to change in important drivers (see (Burrows *et al.* 2014). This approach should include stratification of sites across climatic, edaphic, latitudinal, disturbance or other gradients within an ecosystem targeted for monitoring. The use of some form of probability sampling that involves randomisation to guide site selection will also provide greater confidence in generalising results from a subset of chosen survey sites (Welsh 1996).
8. **Balance** monitoring effort strategically between problem-focussed and surveillance-oriented approaches. Problem-focussed monitoring programs aim to improve understanding of identified environmental problems by tracking ecosystem responses under different management scenarios. When designed in a scientifically sound fashion, they are more likely than surveillance monitoring to deliver informative, cost-effective and relevant outcomes, but they may not detect responses to untargeted processes and emerging threats. Surveillance-oriented approaches may detect unexpected trends and problems. By definition, they cannot be shaped to measure particular ecological responses. Consequently, they risk poor returns on investment when no trends are detected, but may occasionally return windfalls in the form of

important discoveries (e.g. long-term, pesticide-derived changes in eggshell thickness in birds (Olsen *et al.* 1993)). An appropriate balance would be a significant weighting towards problem-focussed monitoring, with limited effort directed towards surveillance monitoring. Over-investment in surveillance monitoring at the expense of problem-focussed monitoring is unlikely to deliver progress on the most pressing environmental imperatives (Likens & Lindenmayer 2011).

9. **Recognise** that continental reporting of the environment will often entail reporting on the environmental performance **within** particular, targeted ecosystems over time. This is because, as outlined above, ecosystem properties, characteristics, biota, drivers and threats vary markedly among ecosystems (Evans *et al.* 2011). Although a systematic approach is often required in monitoring, it is likely that those approaches will need to be varied to enable the effect of ecosystem-specific processes, functions and threats to be quantified. For example, even the same individual species may need to be monitored in different ways in different ecosystems (Sutherland 1996; Michael *et al.* 2012), have different habitat requirements in different ecosystems (Morrison *et al.* 2006), and be subject to quite different threats in those ecosystems (Lindenmayer *et al.* 2011). Therefore, many of the appropriate entities (although not all) to monitor to reflect environmental performance will vary among particular ecosystems. For example, what is sensible to monitor in the tropical savannas of northern Australia may be largely irrelevant in the temperate rainforests of south-western Tasmania (Lindenmayer *et al.* 2014). Hence, reporting (nationally and globally) under such an ecosystem-specific approach would be best comprised of reports on temporal trends for ecosystem extent in some ecosystems, the composition of particular communities in other ecosystems, populations of target species (such as threatened species) in others, and the impacts of key ecosystem processes (e.g. altered fire regimes) in yet

others. Although some ecosystems might support all four broad kinds of monitoring (Lindenmayer *et al.* 2014). Accordingly, monitoring work might necessarily be conducted at different spatial scales in different ecosystems, but the common thread will be the collection of high quality longitudinal data within a single information management system (as discussed below). This permits an interpretive synthesis of trends over time. Notably, an ecosystem-specific approach has recently been employed in a major book on Australian ecosystems, which provides a continent-wide overview of selected long-term ecological research in Australia (Lindenmayer *et al.* 2014). Where it is practicable to do so, trends identified from localised longitudinal studies may be scaled-up to the ecosystem as a whole using appropriate spatio-temporal datasets. Such approaches have been undertaken in a wide array of long-term monitoring studies, including broader regional extrapolation of fire effects on biodiversity elements derived from the Three Parks Savanna Fire-Effects plot network in northern Australia (Russell-Smith *et al.* 2014).

10. **Entrench** monitoring by linking the data streams generated from major reporting initiatives such as: State of the Environment and State of the Forests reporting; meeting international obligations under the Convention on Biological Diversity (United Nations 1992); emerging global policy initiatives such as the Ecosystems Red List being undertaken by the IUCN (Rodríguez *et al.* 2011; Keith *et al.* 2013); and environmental accounting (United Nations 2012) (Figure 1; Figure 2). The creation of an integrated set of environmental accounts (e.g. soil, biodiversity, carbon and water accounts) makes explicit the sources of the impacts of the economy on the environment (and *vice versa*). This means it becomes possible to consider the environment in regular economic planning processes (United Nations 2012; Vardon 2012; Vardon *et al.* 2014). It also would enable Australia to address Aichi Target 2 of

the Convention on Biological Diversity, that is: "*By 2020, at the latest, biodiversity values have been integrated into national and local development and poverty reduction strategies and planning processes and are being incorporated into national accounting, as appropriate, and reporting systems*" (UNEP 2010).

Specific design features

There is a fundamental need to undertake and then maintain long-term ecological monitoring of targeted entities within a selection of ecosystems within a design framework that provides confidence in generalising the results to unmonitored areas. Below we make ten additional general recommendations about how best to invest in, and maximise, the value of long-term ecological monitoring.

1. **Ensure** that the same protocols are employed over the duration of any given long-term study. This is important to prevent confounding effects between changes in measurement methods and temporal changes in the target entities of interest. If the protocols have to be changed, then calibrate new methods of measurements with the previous methods – and document the change (including when the changes were made).
2. **Establish** reference plots or sites (wherever appropriate) for investigating the monitoring themes at hand. These should be adequately replicated to allow appropriate interpretation of the trends observed. The use of references plots is essential because a key part of documenting temporal responses to threatening processes involves the quantification of responses not only in places where those processes are active but also where such processes are absent or where they have been mitigated (e.g. through management intervention) (Caughley & Gunn 1996). For example, monitoring to assess the effectiveness of reserves should be done both inside and outside protected areas (Kelaher *et al.* 2014; Rayner *et al.* 2014).

3. **Measure** particular targeted entities directly wherever possible, rather than measuring proxies or surrogates for that entity (see Lindenmayer & Likens 2011). For example, measure the abundance of animal species X rather than the occurrence of a particular tree species which is thought to be an indicator of animal species X. This is because the surrogacy relationship between the target entity and the proxy might not remain consistent over time or in different places (Caro 2010; Zettler *et al.* 2013).
4. **Record** the raw data of a given target entity, such as, for example, the presence or abundance of individual species of reptiles rather than only composite values (e.g. composite metrics like the number of species present). This is because raw values can later be aggregated to give a composite metric, but if only composite measures are gathered they cannot later be dis-aggregated to give raw values.
5. **Understand** that the frequency of temporal measurements taken is important to rigorously document trends. This is related to the variability of the system (Wilson *et al.* 2011) and is especially critical in ecosystems characterised by high temporal variability in conditions, as in many parts of Australia (McMahon *et al.* 1992). While observations taken in two periods a long time apart can be interesting, they may reveal little about trends, especially when there is considerable inter-year variability in the measured parameters (McNamara & Harding 2004; Lindenmayer & Cunningham 2011). The need for an appropriate frequency of monitoring does not specify that it must be regular, or the same frequency across ecosystems. For example, more frequent measurements (within years) may be appropriate in times of large changes compared to relatively static periods, as found in the boom and bust dynamics of desert ecosystems (Dickman *et al.* 2014).

6. **Directly measure** covariables and factors that influence (or are strongly correlated with) measured response variables, such as climatic conditions or the amount of vegetation cover coincident with bird monitoring. This provides a powerful approach to document the relationships between change in a given entity (e.g. animal abundance) and the change in key attributes of the environment (e.g. the spatial extent of vegetation cover; (see Cunningham *et al.* 2014)).
7. **Specify** meaningful trigger points within a given monitoring program to activate key management responses well before major problems manifest, such as catastrophic declines in populations of a threatened species (Martin *et al.* 2009; Lindenmayer *et al.* 2013) or substantial increases in the impacts of an invasive plant or animal. Such trigger points, coupled with the implementation of additional management interventions that attempt to deal with these new and/or developing problems, might demand changes to monitoring protocols, such as altering the frequency of monitoring (Lindenmayer & Likens 2009), although without breaching measurement protocols (if at all possible; see Point #1 above).
8. **Track** details about the history of plots, sites or other units that are the target for measurement in long-term monitoring programs. This will provide context for how things have changed, which is important for diagnosing causes of change now or in 2050. But if asked now, then key aspects of history would include: **(a)** the prior state of the system, such as conditions at the beginning of restoration (Egler 1954); **(b)** the number, types and spatial patterns of biological legacies remaining after previous disturbances (Franklin *et al.* 2000; Banks *et al.* 2011); and **(c)** patterns of site affinity for animals (Gill 1995). In addition to recording site history and initial site conditions, it also can be important to record other information such as the amount and type of invasive plant and animal control, or

the timing, cost, and type of fencing to exclude domestic livestock. Documentation of the history of management intervention is often rare or patchy, even though interventions can have profound effects on biota and/or ecosystem extent and condition. We suggest that documenting management interventions should include records of the amount of money spent so that the cost-effectiveness of interventions can be determined in relation to the biodiversity outcomes that have been derived. Some details about site characteristics and history should be informed by the study site stratification process.

9. **Properly** manage, archive and publish the datasets accumulated to make them discoverable to others (White *et al.* 2013). The efficient organisation of datasets for analysis and synthesis is vital to any future use, but it is all too easy for these databases to become complicated and unwieldy. Unfortunately training in database design is mostly restricted to computer scientists; ecologists often make do with sub-optimal database solutions. Too often, poor design or lack of curation leads to potentially valuable datasets being lost or rendered virtually valueless (Pullin & Salafasky 2010). Management and archiving of datasets must include meta-data that documents the way things have been measured. This will allow others to adopt comparable methods allowing them to build on past datasets and maximise the re-usability of existing datasets. It also will assist data analysis and interpretation and facilitate re-analysis if new methods of data analysis and interpretation become available in the future. Capturing meta-data also should include contextual information on how a given long-term monitoring program started, the rationale for its inception, initial objectives, and underpinning methods like site selection. This information is particularly critical for long-term datasets in which the timespan of data collection should extend beyond the career-spans of

the people responsible for instigating, establishing and implementing monitoring projects. Ideally, in 2050, we should have a readily accessible archive that is founded on, and extends, work that has documented what studies have previously been done, what studies are still current, what was measured, and what is still being measured, and how (see Youngentob *et al.* 2013).

10. **Recognise** that curating critically important environmental datasets comes at a non-trivial cost (Berman & Cerf 2013). These costs must be factored into the budgeting for all major programs, and individual projects, as well as the approvals for infrastructure and development projects (e.g. for the ongoing monitoring associated with mining) (Mudd 2014).

General Discussion

Ecosystem-specific measurements

The selection of response variables for ecological monitoring, whether species-based or ecosystem process-based, will depend on what is most appropriate for detecting and quantifying change in a given ecosystem (Keith *et al.* 2013). In some cases, there will be important synergies from simultaneously linking species, community and ecosystem process monitoring (Likens & Lindenmayer 2012), thereby enabling conclusions to be drawn not only about how processes influence biotic patterns, but also about how particular patterns (e.g. changes in the spatial coverage of vegetation cover) influence other patterns (such as the occurrence of species of birds) (Cunningham *et al.* 2014).

The assessment of important ecological processes in given ecosystems, including threatening processes, can be useful for identifying and quantifying what important priority actions need to be undertaken and where (Table 1). Such management actions would also then be assessed as part of monitoring programs. Identification of priority actions can provide the basis for a continental strategy around what needs to be invested, and where, to achieve what outcomes. This can give politicians, policy makers and the general public a sense of how much funding is required to adequately address environmental problems across the continent – a national, bipartisan, whole-of-government strategy rather than a piecemeal one.

Entrenching long-term monitoring into environmental accounting

Long-term ecological monitoring has consistently been the last task to be funded and the first one cut in constrained budgets. The unreliable support of long-term ecological monitoring contrasts markedly with the long-term and entrenched support of the network of Bureau of Meteorology sites. The state of long-term ecological monitoring also contrasts markedly with the long-term monitoring of the Australian economy which has been achieved and maintained via the processes used to collect information through the System of National Accounts (Obst & Vardon 2014). Lessons from long-term economic monitoring can be applied to biodiversity and ecosystems (Vardon 2012). The production of economic accounts in Australia demands detailed economic monitoring that is undertaken primarily by the Australian Bureau of Statistics (Australian Bureau of Statistics 2013; Australian Bureau of Statistics 2014). Notably, such kinds of accounting revolutionised economic reporting and management in many nations around the world and, for example, assisted with economic reconstruction following the Great Depression and the Second World War (Vardon *et al.* 2014). Mandating environmental accounting has the potential, if done properly, to create the financial, logistical, legislative and governance frameworks that permanently entrench robust programs of long-term ecosystem and biodiversity monitoring and integrate them with existing economic and social data used by governments, business and the general public. However, environmental accounts will only be as good as the data that go into making them. The approach we have outlined here for ecosystem monitoring will ensure the quality of much needed long-term ecological monitoring data. Moreover, enhanced monitoring capability has the potential to save large amounts of money through more effective environmental management. Environmental accounting will be one way of demonstrating this (Wentworth Group of Concerned Scientists 2008; Vardon *et al.* 2014).

Mandating environmental accounts would create an information system that would enhance State of the Environment and State of the Forests reporting and also allow the environment to be better considered in mainstream economic planning and decision-making. It also would enable a framework to measure the effectiveness (including costs) of the use of natural resources. Environmental accounts enable the trade-offs between environment and economy to be clearly seen and would redress the current dominance of economic information in government and decision-making. The long-term plots and sites that would form part of the monitoring and generate the data used to create biodiversity and other environmental accounts would then be acknowledged as critical parts of the nation’s data infrastructure and be maintained alongside social and economic data infrastructure. Ultimately, the data from designed monitoring programs and their use in environmental accounts will enable biodiversity and ecosystems to be recognised as equally important to the functioning of society as roads, power grids, the sewerage system and other built infrastructure.

A further strategy for entrenching environmental monitoring will be to coordinate study design, project implementation and data storage through an organisational entity charged with the responsibility for doing this. The Australian Bureau of Statistics and the Bureau of Meteorology are good examples of such organisations and are widely acknowledged as independent and non-partisan. Notably, there is currently a suite of initiatives within the Australian Bureau of Statistics linked with the development of a set of environmental accounts (e.g. Australian Bureau of Statistics 2014) according to international recognised frameworks (United Nations 2012).

Concluding comments

Long-term monitoring is crucial to the conservation and management of the Australian environment. Yet environmental monitoring is rarely done in this nation, in part because there has generally been very limited support for sustained long-term ecological monitoring programs and co-ordination within and across programs. Serious environmental problems associated with resource use and management are already evident and well-documented. The year 2050 is forecast as a crisis point when the consequences of past practices, in concert with continued population growth, will see the breakdown of critical ecosystem services, resulting in a less predictable and bountiful environment (Turner 2008; Holloway 2012; Fulton 2013).. We must begin measuring key components of ecosystems now and continue that work for many decades to improve ecosystem integrity and ecologically sustainable resource management. We have outlined a series of key attributes that must characterise effective ecological monitoring. These include recognition that the entities being measured and the approaches to monitor them will be ecosystem-specific and relevant to the key ecological processes, threatening processes, and management interventions in particular ecosystems. Strategies crucial to success include the integration of ecosystem-specific monitoring approaches with initiatives like State of the Environment reporting and systems of national environmental accounting, and the development of appropriate information management architecture. A way forward would be for the community of ecological scientists and managers to agree on a set of general principles for long-term ecological monitoring, possibly including recommendations for a new body analogous to the Australian Bureau of Statistics or the Bureau of Meteorology to co-ordinate long-term ecological monitoring in Australia. Indeed, this is one of the key recommendations of the plan for Australian ecosystem science (Andersen *et al*. 2014).

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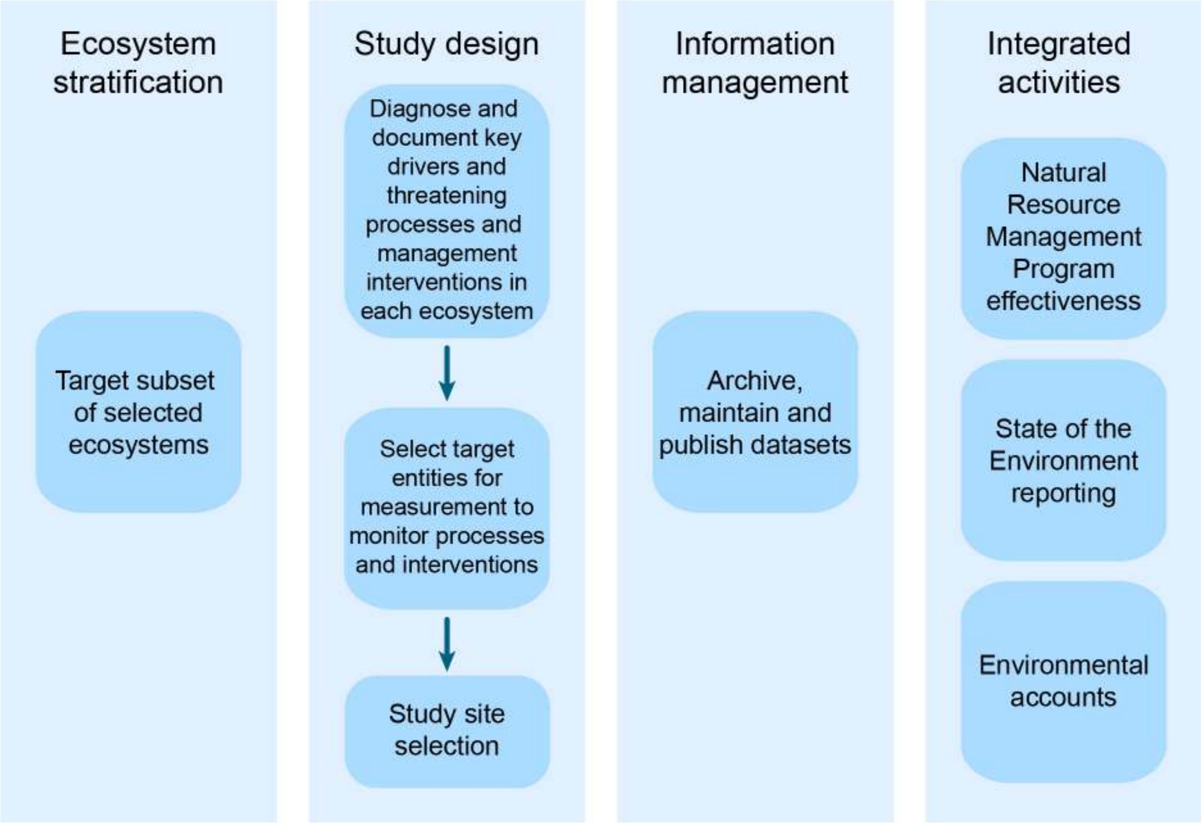
Table 1: Examples of threatening processes in some Australian ecosystems based broadly on the threat classifications of Salafasky *et al.* (2008) and Auld and Keith (2009).

IUCN threat class	**Threatening processes**	**Applicability to terrestrial Australian ecosystems**
Residential and commercial development	Clearing and fragmentation	Ecosystem-specific but relevant to many non-protected areas (and some protected environments)
Agricultural and aquaculture expansion and intensification	Clearing and fragmentation	Ecosystem-specific, mainly woodlands, grasslands and wetlands
	Grazing by domestic livestock	Ecosystem-specific, typically woodlands, grasslands, shrublands, and deserts
	Soil disturbance and degradation. Introduction of pathogens. Erosion and subsidence.	Ecosystem-specific, typically woodlands, grasslands, shrublands, and deserts
Energy production and mining	Exploration and mining for coal, iron ore, bauxite, gold, uranium, oil, gas	Ecosystem-specific, dependent on location of resources
Transportation and service corridors	Fragmentation	Pervasive, but more common on flat terrain

IUCN threat class	Threatening processes	Applicability to terrestrial Australian ecosystems
Consumptive use of “wild” biological resources	Timber harvesting. Loss of habitat.	Ecosystem-specific to forests
	Bio-prospecting	Ecosystem-specific
Human intrusions and disturbance from non-consumptive use	Tourism	Ecosystem-specific, but often relevant to protected areas
Natural system modifications (disturbance regimes)	Altered fire regimes	Pervasive in most ecosystems
	Altered hydrological regimes	Ecosystem-specific, notably wetlands and groundwater-dependent ecosystems
	Salinity	Ecosystem-specific, usually relevant to woodlands and wetlands
	Removal of dingoes	Ecosystem-specific, most evident in deserts, savanna and shrublands
Invasive and other problematic species and genes	Grazing by over-abundant native herbivores	Ecosystem-specific, usually relevant to woodlands, grasslands, shrublands, and deserts

IUCN threat class	**Threatening processes**	**Applicability to terrestrial Australian ecosystems**
	Disease	Ecosystem-specific, e.g. heathlands
	Invasive predators	Pervasive in many ecosystems
	Invasive herbivores	Ecosystem-specific
	Invasive plants	Pervasive in most ecosystems
Pollution	Eutrophication	Ecosystem-specific, usually those associated with urban and agricultural areas
Geological events		Ecosystem-specific, often on steep land
Climate change	Increased frequency and intensity of droughts, storms, heat waves, sea-level rise	Pervasive and ecosystem-specific

Figure 1. Conceptual model highlighting key linkages between monitoring and environmental reporting.



751

Figure 2. The potential links between ecosystem monitoring and environmental accounting and reporting. The sequence of steps underscores the critical importance of appropriate study design and from that high quality field-based monitoring data. These are the fundamental building blocks not only in environmental accounts, but also in predicting future conditions in an ecosystem under different management decisions and interventions. The study design, and quality and availability of data links directly to environmental policy and decision making.