The Big Ecological Questions Inhibiting Effective Environmental Management in Australia

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Abstract The need to improve environmental management in Australia is urgent because human health, wellbeing and social stability all depend ultimately on maintenance of life-supporting ecological processes. Ecological science can inform this effort, but when issues are socially and economically complex the inclination is to wait for science to provide answers before acting. Increasingly, managers and policy-makers will be called on to use the present state of scientific knowledge to supply reasonable inferences for action based on imperfect knowledge. Hence, one challenge is to use existing ecological knowledge more effectively; a second is to tackle the critical unanswered ecological questions. This paper identifies areas of environmental management that are profoundly hindered by an inability of science to answer basic questions, in contrast to those areas where knowledge is not the major barrier to policy development and management. Of the 22 big questions identified, more than half are directly related to climate change. Several of the questions concern our limited understanding of the dynamics of marine systems. There is enough information already available to develop effective policy and management to address several significant ecological issues. We urge ecologists to make better use of existing knowledge in dialogue with policy-makers and land managers. Because the challenges are enormous, ecologists will increasingly be engaging a wide range of other disciplines to help identify pathways towards a sustainable future.

INTRODUCTION

Many commentators and reports have recently pointed to the worrying status and trends of Australia's natural resources. The first comprehensive assessment of landscape health and biodiversity at a continental scale confirms these patterns (National Land and Water Resources Audit 2000a, b; 2001; 2002a, b). The Audit provided a basis for the 2006 State of Environment Report, an independent national stocktake (Beeton *et al*. 2006). In commentary on the Report, Cork *et al*. (2006) noted that "despite large investments and some promising responses, biodiversity in Australia continues to decline". Ward & Butler (2006) stated that "we may still be facing the decline of important assets and features of ocean and coastal ecosystems". Harris (2006) wrote that "many indicators show that aquatic ecosystems and biodiversity are degraded across large areas of the continent". The challenge is urgent because of the fundamental dependence of human society on the environmental resource base. Human health, wellbeing and social stability all depend ultimately on maintenance of life-supporting ecological processes. As the challenge is enormous, ecologists must work with a wide range of other disciplines to help develop pathways towards a sustainable future.

These challenges are not confined to Australia: human populations are having substantial impacts world-wide on ecosystems at all scales, posing unprecedented threats to future human wellbeing and raising serious concerns about humanity's collective capacity to maintain development (UN Development Program 2007; UN Environment Programme 2007). Hence, the questions posed will increasingly require a multi-disciplinary approach to environmental management, from adaptive management and institutional analysis through to the dynamics of socio-economic and biophysical systems. Many ecologists are motivated to contribute to resolution of such questions (e.g. Saunders *et al*. 1993; Lindenmayer 2007). Although ecological insights may not readily find their way into policy, science remains a significant contributor to improved environmental management. While the search continues for more effective policy development and governance in natural resource management (e.g. Botterill & Fisher 2003; Campbell & Schofield 2006; Hussey & Dovers 2007), it is vital that ecology provides the most objective advice possible on priorities for improved knowledge. The present paper attempts to do this.

Our inquiry was stimulated by the example of Sutherland *et al*. (2006) who identified 100 ecological questions of importance in the United Kingdom. As with those authors, we begin from the assumption that it is the scientific community's responsibility to advise as objectively as possible on where uncertainty is greatest, and where knowledge is sufficient to act. This paper brings together the experience of 20 scientists to identfiy firstly those areas that are hindered by a current inability of science to answer basic questions, and secondly those fields of environmental management in Australia where knowledge is not a major barrier to improved policy and management.

METHODS

The 20 co-authors represent many areas of ecology in relation to Australia's environmental management needs. Among ourselves, we canvassed opinion on knowledge needed to mitigate each threatening process it, adapt to its consequences, and act in policy and management terms. We gradually converged on priority questions representing fundamental barriers to realisation of improved environmental policy and management. By implication, these debates identified areas of knowledge where we concluded that research was of lower priority. However, the purpose of this paper is to focus on questions requiring fresh research, and so we mention only in passing those fields where knowledge seems to be adequate for policy and management application. Our inquiry took us in a different direction from Sutherland *et al*. (2006); rather than allowing for a proliferation of questions, we honed our questions down to a bare minimum.

We scanned previous summaries of the highest level of threatening processes affecting Australia (Burgman & Lindenmayer 1998; Morton *et al*. 2002; Beeton *et al*. 2006; Fischer *et al*. 2007; Lindenmayer 2007; Raven & Yeates 2007) and grouped them under two broad headings – global issues, and issues of particular significance in Australia. Our objective, then, was to ask which processes are too poorly understood to be effectively acted upon. The only purpose of the groupings is to provide a framework for action.

Global issues are as follows.

A Integrating ecosystem management with human social systems.
B Climate change.
C Ocean acidification
D Coastal inundation

These global issues play out in a particular Australian context. The first integrative challenge of environmental management needs to be addressed one of the most highly urbanised nations in the world. The issue of climate change is peculiarly important for because Australia is already the driest continent with a highly variable climate. Finally, ocean acidification and coastal inundation provide especially big challenges given that Australians live predominantly in coastal settlements.

Issues requiring a particularly Australian focus are as follows.

E Alteration, degradation and replacement of natural habitats.
F Invasive species.
G Altered fire regimes.
H Water extraction.
I Urban development and industrial pollution.

RESULTS

A. Integrating ecosystem management with human social systems

It is counterproductive to view social and ecological systems separately when their intimate links demand integration. Under this paradigm, research itself should be intimately connected with policy, management, on-ground implementation and human livelihoods. Participatory research, co-production of knowledge (including Indigenous knowledge), and adaptive management are central to this way of thinking (Head *et al*. 2005; Campbell & Schofield 2006; Fischer *et al*. 2007; Reynolds *et al*. 2007; Williams 2007). Scientists will doubtless continue developing approaches in which both research and management are oriented around 'learning by doing'. Progress towards sustainability may be compromised by lack of ecological input, but in many situations the constraint is actually the lack of knowledge linking ecology to resource economics, governance, institutional design, policy and management, highlighting the need to integrate the humanities with ecology. Ecologists will play a particular role in such integration by advising on the maintenance of resilience (Abel *et al*. 2003; Walker & Salt 2006; Fischer *et al*. 2007). These considerations lead to the following questions.

1. What integrated strategies and tools will help support adaptive management of socio-ecological systems undergoing rapid change?
2. How much change in different ecosystems can be tolerated in the cycling of carbon, nutrients, water, and in biodiversity, if socio-ecological resilience is to be maintained and ecosystem services are to continue being delivered, and at what point should management aim to effect transitions to new states if maintenance proves impracticable?
3. How can natural ecosystems be valued, such that financial incentives encourage their maintenance and the external environmental costs of primary production are incorporated into the prices of goods?

A second element here concerns the over-arching issue of connections between environment and human populations, for example through analyses of ecological footprint (Foran & Poldy 2002), assessment of impact as a product of population, affluence and technology (Chertow 2001; Steffen *et al*. 2004), and analysis of connections between ecosystem functioning, environmental quality and human health (McMichael 2008). Movements in human populations as a result of climate change may further influence these challenges in Australia (section B). One broad question requires further ecological input.

4. How does knowledge of the relationships among human population size, economic systems, technology, institutions, ecological footprint and environmental change need to be expressed to help society define sustainability goals?

Finally, integration of environmental management with socio-economic frameworks demands effective measurement of environmental state, trend and performance, to provide feedback to policy-makers about management action and environmental response. As yet environmental monitoring rarely matches this need (Field *et al*. 2007); we note, in contrast, that society can assume effective economic monitoring.

5. How can data sets be rigorously gathered, analysed and reported to establish environmental trend, critical thresholds, and feedbacks to management?

B. Climate change

This process will act in synergy with other factors to produce numerous direct and indirect effects (Hughes 2003; Natural Resource Management Ministerial Council 2004; Westoby & Burgman 2006; Poloczanska *et al*. 2007; Dunlop & Brown 2008).

- Ocean acidification.
- Coastal inundation.
- Range shifts of species, range fragmentation or shrinkage, extinctions, and changes in the structure of ecosystems.
- Decoupling of established interactions between species through altered timing of life-cycles.
- Potentially greater vulnerability to biological invasions.
- Additional alteration to fire regimes.
- Impacts on production systems, including shifts in geographical location.
- Movements, health, wellbeing and livelihoods of people.
- Changes in linkages between ecological and socio-economic systems.

If management is to respond effectively to the impact of climate change on ecosystem function, the distribution of species and community composition, then long-standing gaps in knowledge of the drivers of ecosystems and the distribution of Australian species need filling (Hughes 2003). Assuming development of meaningful environmental monitoring (question 5), three questions seem compelling.

6. How can the global circulation models that are used to predict climate change be down-scaled to match ecological responses at the landscape level in Australia?
7. How can non-linear responses to climate and substrate, and biotic interactions, be incorporated into improved analysis of ecosystems and distribution of species?
8. How can management attempt to withstand unwanted effects in ecosystems undergoing change in composition, and at what point should it attempt to provide options for ecosystems to adjust to new states?

With invasive species, climate change reinforces the need for research emphasis to shift from responding to invaders towards early anticipation and suppression of threats (Department of Agriculture, Fisheries and Forestry 2008). Efforts should encompass enhanced integration of risk diagnosis, control systems, policy and research. The question has particular relevance to human health.

9. How can we devise and implement an Australian early detection system for potential invaders (including new weeds, pests, pathogens, and diseases as well as genetically modified organisms and native species), and a response system based on prediction of likely entry, establishment, spread and impact?

Ecological responses to fire regimes in Australia are relatively well known (section G). However, insufficient work has been done on dynamic vegetation models that would allow analysis of the following question (Cary *et al*. 2003).

10. What alterations in fire regimes are likely with climate change, and what interventions would be practicable for the maintenance of biodiversity and ecosystem function?

Ecologists are well aware that episodic events are exceedingly important in affecting the structure and functioning of Australian ecosystems (Westoby 1980; Stafford Smith &

Morton 1990; Orians & Milewski 2007; Stafford Smith & McAllister 2008); with care, these well-understood relationships should allow retrospective analyses to be used to project future interactions with climate change. Such interactions in marine systems, however, deserve more research attention. Changes in ocean circulation have the potential to modify the supply of nutrients into surface waters and thence marine primary production; and coastal ecosystems are dramatically affected by extreme events such as cyclones. Shifts in the frequency and intensity of such events could radically modify marine ecosystems and their associated ecosystem services.

11. How will alterations in extreme events interact with changes in ocean circulation and production to modify marine ecosystems and biodiversity under climate change, and how might management respond?

The relationships between production systems, land capability and climate are reasonably well understood because Australia's success as an agricultural nation has depended upon such knowledge (Henzell 2007) – although with substantial external costs still emerging (question 3). Climate change will force major changes in the distributions and types of resource use, with substantial yet poorly analysed consequences for environmental management. In particular, questions remain about the implications of climate change for current developments in 'ecosystem-based' fisheries management, which may be heavily reliant on assumptions of ecosystem stability.

12. What environmental impacts on production and resource-use systems are likely from shifts induced by climate change, where will they occur, and how could their location and extent be managed to satisfy both environmental and production objectives?

C. Ocean acidification

The world's oceans will experience increasing acidification in future because addition of relatively small amounts of CO_2 to the atmosphere causes substantial changes to carbonate concentrations in seawater (Raven *et al*. 2005). As a result, the physiology of marine organisms can be affected through acidosis (Raven *et al*. 2005), but how these impacts will affect ecological systems and fisheries is unknown. A further effect may be reduction in carbonate ion concentrations, directly influencing calcifying organisms such as corals in tropical seas (Hoegh-Guldberg 2005; Hoegh-Guldberg *et al*. 2007), and the many invertebrates and phytoplankton of temperate southern waters. Given that 40% of Australia's coastline is lined by coral reefs, this is potentially serious for marine biodiversity as well as for fishing and tourism. Changes to primary producers could also have flow-on impacts on ecological organisation; for example, changes to Southern Ocean productivity may have implications for the biological carbon pump which could in turn lead to a reduction in oceanic uptake of CO_2.

13. How and where will acidification interact with other climatic changes (e.g. increasing ocean temperatures) to change ecological function in marine ecosystems, and how might management counter the effects?

14. Will buffering from existing coastal 'carbonate' structures and coral reefs diminish as a result of rising acidity, what would be the implications for biodiversity and for physical protection, and how might management counter the effects?

D. Coastal inundation

Sea-level rise is accelerating and Australia and its neighbours will need to adapt rapidly in coming decades (Church & White 2006). Although the various zones of new coastlines can be mapped, uncertainties remain in both the rate and magnitude of future changes in sea level. It may be possible, using current technologies, to assist the migration of coastal forests, wetlands, salt marshes and mangroves under conservative estimates of sea level rise (~0.4-0.6 m rise by 2100). However, the scale and urgency of the problems under more drastic scenarios (>1 m rise by 2100) suggest that added effort is essential.

15. How will coastal ecosystems respond to the direct effects of sea-level rise, to the indirect impacts of reduced reef accretion and changing sediment, nutrient and salinity regimes, and to feedbacks between ecosystems and physical processes?
16. How will key fishery species be affected by changes to nursery grounds as coastal ecosystems undergo re-organisation?
17. How will Australia's coastal aquifers and groundwater resources respond to sea-level rise through effects such as saltwater intrusion, and how can water quality be maintained under these conditions?

Equally significant questions relate to human infrastructure in low-lying coastal areas; this challenge is mentioned in section I.

E. Alteration, degradation and replacement of natural habitats

In relation to harvesting of natural resources from semi-natural ecosystems, management principles to avoid over-exploitation, minimise loss of biodiversity, and maintain primary production are relatively well understood (Jackson *et al.* 2001; Lindenmayer & Franklin 2002; McIntyre *et al*. 2002; Pandolfi *et al.* 2003; Reynolds *et al*. 2007). Ecologists concur that there will be ongoing need for more effective application of these principles, especially with emphasis on interactive effects on other ecological processes (e.g. control of invasive species, by-catch in fisheries). Australia faces challenging problems in setting sustainable harvesting rates because of existing climatic variability, and question 12 notes that such challenges may multiply with climate change. Because barriers to application of these principles rest more in the socio-economic domain than in a lack of ecological knowledge, progress is required in valuing resources (question 3).

Much is already known about degradation and replacement of natural habitats as threatening processes. Ecologists are able to contribute quantitative knowledge on the effects of degradation and destruction of habitats on biodiversity loss, vulnerability to invasion by weeds and pests, soil erosion, salination, water quality, nutrient leakage, and damage to carbon cycles, hydrological cycles, ecosystem resilience, and agricultural and fishing productivity (Jackson *et al.* 2001; Pandolfi *et al.* 2003; Soulé *et al*. 2004; Gleeson

& Dalley 2006). However, processes for reversing or ameliorating such trends are less well developed, and the design of landscape networks for maintenance of biodiversity and ecosystem services requires considerable research (Soulé *et al*. 2004; Lindenmayer and Fischer 2006; Menninger and Palmer 2006).

18. What ecological processes can be manipulated to reverse and restore the loss of biodiversity and ecosystem function in degraded landscapes, and in particular how can connectivity best be preserved and created to prevent further loss?

Intensive agriculture produces large changes in ecological processes. The numerous on-site effects are well known, such as soil erosion and biodiversity loss, and off-site effects have become increasingly obvious, including impacts on water quality through dryland and irrigation salinity, eutrophication, sedimentation, altered flow regimes, agri-chemical run-off, and the decline of biodiversity through landscape-scale effects (Hobbs & Saunders 1992; National Land and Water Resources Audit 2000a). Mitigation and policy are usually technically challenging and always socially and economically complex. Effort is required to develop practices to minimise 'leakiness' of agro-ecosystems, through the adoption of farming systems better adapted to the tolerances of these ecosystems (Lefroy *et al*. 2005; Pannell *et al*. 2006). In regions where safe levels of intensification have been exceeded, methods are required to encourage the adoption of alternative land-use and management systems, including through stewardship payments for environmental services. All of these challenges are playing out in the context of climate change. Our conclusion is that the ecological knowledge required to help develop more effective environmental policy and management is encompassed in questions 1, 2, 3, 9 and 12.

F. Invasive species

Much is also known about the threats posed by invasive species (Burgman & Lindenmayer 1998; Lonsdale 1999; Mack *et al*. 2000; Williams & West 2000). Solutions lie in mitigation through risk analysis, strict quarantine controls, rapid early eradication, chemical and biological control of highly invasive species that get through these safety nets, and maintenance or enhancement of resistance by native communities to invasion (McLeod 2004; Australian Biosecurity Group 2005; D'Antonio & Chambers 2006). Resistance to invasion is usually weakened when disturbance regimes are altered and under conditions of habitat degradation; hence, knowledge from answers to questions 8-11 is relevant. Research into integration of biological control with chemical and manual techniques will remain an ongoing need; providing such control requires resources but is not profoundly limited by knowledge. Current debates (e.g. Stohlgren *et al*. 2003) about the relationship between diversity and invasibility are scientifically significant, but unlikely to lead to rapid increases in ability to manage invasions. For us, question 9 covers the highest-priority need for research that will reduce the impact of invaders on biodiversity.

G. Altered fire regimes

Australia possesses high levels of Indigenous and scientific knowledge of fire behaviour and impacts (Bradstock *et al*. 2002; Cary *et al*. 2003). The outstanding problems with fire management lie in resolving tensions between management for protection of human life and property, and management for other environmental purposes. Climate change will intensify these challenges (question 10). The broad principles of fire management are known but effective on-ground management needs information specific to different ecological communities. Hence, we recognise one critical question.

19. How can the interactive impacts on biodiversity and ecosystem function of altered fire regimes and natural resource use be quantified and incorporated into management?

H. Water use, extraction and management

Water extraction on the driest continent on Earth has led to substantial changes in the structure and function of aquatic ecosystems, with consequent loss of ecosystem services and species from surface waters, groundwater-dependent ecosystems and wetlands (Hussey & Dovers 2007). Accelerating impacts seem likely under conditions of increased variability and decreases in rainfall due to climate change; indeed, it is very likely that some human responses to climate change, such as construction of new dams, will exacerbate existing environmental problems. Continued over-exploitation of groundwater and decreased recharge rates in many areas would diminish the resource. Problems are also likely in coastal environments, where demand will intensify (question 17). Again lack of ecological knowledge is not the primary gap, and the policy-related questions 2-3 encompass the major issues for more effective environmental management (Hussey & Dovers 2007). One ecological question remains.

20. How can we design and implement environmental flows to ensure resilience of rivers, wetlands and estuaries, in light of changing climate, shifting patterns of land use and native vegetation, and changing human demands?

I. Urban development and industrial pollution

Urban development increases water extraction, encourages some invasive species and opens entry pathways to others, creates nutrient enrichment, produces high volumes of wastes and storm-water, and as a form of intensive land use causes loss of biodiversity (Newton 2008). How might Australian cities move toward more energy- and water-efficient design? How can cities contribute to biodiversity conservation within their regions? How can coastal development occur safely? The following question adds to our discussion under climate change and coastal inundation.

21. How can urban and peri-urban intensification be designed to allow both for adaptation to climate change and improved environmental management?

Pollution encompasses global rather than peculiarly Australian problems, but not enough is known locally. For example, understanding of atmospheric pollution, runoff to estuaries, waste flows, and contaminated landfill and groundwater is patchy in extent and application. Because many pollutants such as endocrine disrupters have human health impacts there may be relatively rapid application of knowledge; however, many may also have lesser-known ecological effects. Engineering solutions usually require some ecological input. We conclude that one question deserves particular attention.

22. How can ecological knowledge be incorporated more intimately into industrial life-cycle analysis, recycling and water re-use?

DISCUSSION

Of the 22 questions above, about half are directly related to climate change (seven questions) and the associated processes of ocean acidification and coastal inundation (a further five). Is our emphasis on the impacts of climate change simply due to the fact that it has become such an important public debate during the last few years; in short, is our emphasis on this matter unjustified? We think not. The threats posed by climate change have been identified for over 20 years (Peters & Darling 1985; Williams *et al*. 1994), but support has not been in place for the magnitude of research effort required. Clearly there has been growing scientific and community realisation about the speed of change and the likelihood of synergy between a changing climate and existing environmental problems. This does not necessarily mean that climate change is the most threatening process; rather, it is where ecological science is less able to provide options for dealing with rapid environmental change, due to poor understanding of the processes involved. Consequently, there is a large amount of ground to be made up.

Is our conclusion correct that relatively few big ecological questions are still to be answered about threatening processes such as the alteration, degradation and replacement of natural habitats, invasive species, and altered fire regimes? Of course we recognise that there are some outstanding knowledge gaps in these areas. Nevertheless, we conclude that, in broad terms, sufficient ecological information is available for policy and management to proceed effectively.

If uptake of ecological understanding is not occurring, ecologists need to ask why. Lack of uptake in some areas may be due to failure by ecological science to frame options in the most effective manner, to form sufficiently powerful links with resource economics and natural resource governance, or to develop adequate connections with the policy-making and management communities. In our view it is vital that ecologists debate these challenges with their policy colleagues. Hamel & Prahalad (1989) contend that too many scientists have a "strategy of hope" that their work will be useful for policy-makers. It seems to us that ecologists should continue building capacity to supply reasonable inference from existing knowledge, allowing for adaptive management to refine further application. Whatever conclusion one comes to on these matters, we argue that ecologists must strive even more to make their work relevant to policy and management.

In emphasising 'big' questions we are certainly not implying that the 'small' issues involved in translating current ecological understanding into practical solutions for land-managers are somehow unimportant. Such matters are by no means small. Even when current ecological knowledge finds its way into policy and into on-ground programs, there remains a huge task in providing ecological insight. For example, ecologists know that getting the fire regime right is important, but often are not sure exactly what regime to recommend for a particular patch of vegetation, because of competing management objectives and uncertainty about the responses of individual species. In short, the task of translating present ecological knowledge into practical solutions must proceed in concert with the marshaling of effort on the sorts of big questions that form the focus of this paper.

Humans are changing the biosphere at a global scale and no part of the Earth is escaping this influence. Consequently, ecological questions need to be considered within multidisciplinary frameworks that are aimed at sustainability. A further challenge is to foster understanding of the fundamental dependence of human health, wellbeing and society on the national and global environmental resource base. The challenges are enormous, and ecology must work with a wide range of other disciplines to help develop pathways towards a sustainable future.

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