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Increasing the understanding and use of natural archives of ecosystem services, resilience and thresholds to improve policy, science and practice

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Abstract

Despite the great potential of palaeo-environmental information to strengthen natural resource policy, science and practical outcomes naturally occurring archives of palaeo-environmental and ecosystem service information have not been fully recognised or utilised to inform the development of environmental policy. In this paper, we describe how Australian palaeo-environmental science is improving environmental understanding through local studies and regional syntheses that inform us about past conditions, extreme conditions and altered ecosystem states. Australian innovations in ecosystem services research and palaeo-environmental science contribute in five important contexts: discussions about environmental understanding and management objectives, improving access to information, improved knowledge about the dynamics of ecosystem services, increasing understanding of environmental processes and resource availability, and engaging interdisciplinary approaches to manage ecosystem services. Knowledge of the past is an important starting point for setting present and future resource management objectives, anticipating consequences of trade-offs, sharing risk and evaluating and monitoring the ongoing availability of ecosystem services. Palaeo-environmental information helps reframe discussions about desirable futures and collaborative efforts between scientists, planners, managers and communities. However, further steps are needed to translate the ecosystem services concept into ecosystem services policy and tangible management objectives and actions that are useful, feasible and encompass the range of benefits to people from ecosystems. We argue that increased incorporation of palaeo-environmental information into policy and decision-making is needed for evidence-based adaptive management to enhance sustainability of ecosystem functions and reduce long-term risks.

Keywords

Australia, ecosystem services, environmental history, management, natural resource management, palaeo-environment

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Introduction

Ecosystem services have quickly become the succinct phrase to describe, explain and justify the benefits of natural resources to human well-being. Ecosystem services include provisioning services (e.g. food, water), regulating services (e.g. the role of vegetation and soil systems in regulating climate), cultural services (non-material benefits such as spiritual or cultural heritage) and supporting services (e.g. soil formation and redistribution, water quality and availability for human use; Millennium Ecosystem Assessment (MEA), 2003). Long-term information (≥50 years) is critical for understanding the dynamics and variability of ecological processes (Willis et al., 2007) and is useful for identifying reference conditions, trajectories, thresholds and the availability or degradation of ecosystem services over the longer term (Dearing et al., 2011). Palaeo-environmental science, providing information on the past few hundreds and thousands of years, has made important contributions to improving conservation and ecosystem management (Hope, 1995).

This palaeo-environmental science perspective can also improve understanding of complex socio-environmental interactions that define the value of natural resources. The ecosystem services concept was developed to communicate the reciprocity between human well-being and ecosystem health (MEA, 2003)

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by clarifying the benefits to humans from well-functioning ecosystems and to enable such benefits to be integrated into social, economic and environmental decision-making (Pittock et al., 2012). The maintenance of ecosystem services is a key component of social, economic and environmental sustainability because degradation of these services has been linked to societal change and decline (Beeton and Lynch, 2012; Daily, 1997; Gosling and Williams, 2013). Sound scientific understanding of socio-ecological interactions and histories is thus vitally important to achieve sustainable societies (Chapin, 2009; Daily, 1997; Head, 2008). This requires awareness of the range of benefits to people from ecosystems, their spatial and temporal availability, and changes in demand for those services through time.

Partly because of the ease of quantification and partly because of market failure around common pool resources, the policy development around ecosystem services has tended to focus on the consumptive, provisioning types of services with quick tangible financial benefits and on higher use locations (Cork, 2001; Horwitz and Finlayson, 2011). A palaeo-environmental science perspective can correct this bias by informing about slower processes: the functions and dynamic changes that occur over multi-decadal and centennial or longer timescales. Palaeo-environmental proxies, such as wetland sediments, are particularly informative about the regulating and supporting services on which humans and ecosystems depend and from which consumptive services derive (Wall, 2004).

Australia is recognised for having innovative institutions around ecosystem services (Daily, 1997; Pittock et al., 2012) and a hard-won understanding of managing a megadiverse biota and diverse environment within highly variable and unpredictable climatic and hydrological systems. Management of complex systems, variability and uncertainty are issues being addressed globally; this synthesis of the Australian experience is internationally relevant, given the increasing imperative for climate change adaptation and mitigation.

In this paper, we contribute a narrative of how Australian researchers are creating, and our environmental policy makers and managers are using palaeo-environmental and ecosystem service archives. We describe how palaeo-environmental science is contributing to the following: (1) discussions about environmental understanding and management objectives, (2) collation, creation and access to data on natural resources, (3) understanding of environmental benchmarks, states and transitions, (4) understanding and planning for resource availability and (5) interdisciplinary approaches to managing socio-ecological values and resource allocations. We discuss how these different contexts are crucial to addressing biodiversity and ecosystem service decline and suggest what further actions are needed.

Ecosystem services in Australian natural resource management

Australian science and policy have wrestled, since the early 1990s, with assessment approaches and frameworks to underpin sustainable use and management of biodiversity and natural resources (Pittock et al., 2012; Saunders et al., 1990). In turn, these approaches influenced national and international initiatives, including Australia's commitment as a signatory to the Convention on Biological Diversity, the implementation of an Australian Intergovernmental Agreement on the Environment and a national strategy for biodiversity conservation (1996, updated as a 2010–2030 strategy). As parallel outcomes, the conservation estate has rapidly expanded, along with awareness of the need for off-reserve conservation to maintain natural values. By 2005, the ecosystem services concept was appearing in many legal and policy documents, being introduced into federal law (*Water Act 2007*) and proposed as a national framework that could bring divergent stakeholders together using a practical approach and common language (Australian Government, 2011; Commonwealth of Australia, 2008).

The past decade in Australia has seen ongoing attempts to adapt and apply the ecosystem services concept. This included development of national ecosystem services reviews and policy papers (Cork et al., 2007; Davey, 2005), national workshops (Thackway et al., 2005), factsheets and reports that link market-based instruments to ecosystem services (e.g. Bureau of Rural Sciences, 2008; Coffey and Pearson, 2007), and incorporation of ecosystem services into natural resource planning and management, national indicators, standards and targets for monitoring, reporting and evaluation of natural resources programmes (e.g. National Action Plan for Salinity and Water Quality, Natural Heritage Trust and Caring for our Country). Ecosystem services has been a bridging concept between conservation and economic development, enhancing collaboration between ecologists, economists, managers and policy makers, and advancing development of non-market valuation techniques (Pittock et al., 2012). It is inherent in the global trend to join ecosystem services, risk management, resilience and human well-being in policy development and research.

Currently, ecosystem services are in the process of being explicitly included in Australia's national accounts (Australian Bureau of Statistics, 2010), State of the Environment reporting (Cork, 2011) and implicitly in State of the Forests reporting (SOFR, 2013). Their relevance to agricultural productivity and social-ecological resilience (Sandhu et al., 2012) is also evident through incorporation of ecosystem services into natural resource management planning at national (e.g. the National Water Initiative (Plant et al., 2012)) and regional (catchment) scales (Namoi Catchment Management Authority, 2011).

Ecosystem services information from the palaeo-environmental science – ecosystem services nexus

Ideally, the use of ecosystem services information involves a process of engaging researchers, across the continuum of 'applied' to 'blue sky' research, with managers and policy makers who are seeking information to meet the challenges of protecting, sustaining or enhancing ecosystem function and services. Ecosystem models are most robust when they integrate knowledge of the past, present and future to predict dynamics and limits of tolerance that inform management, such as the potential impacts of changes in climate on species, habitats, ecosystems and ecological functions. The long-term perspective puts into ecological context the potential consequences of human resource use and consumption.

Whereas some ecological experts have used contemporary records and modelled predictions to suggest that fundamental shifts in the drivers of ecosystem change in Australia lie ahead, and that these changes may push some ecosystems beyond a tipping point (Laurance et al., 2011), palaeo-environmental records show that the time-scale of analysis is critical. Coarse-scale models based on contemporary data may not adequately represent topographic or microclimatic buffering in refugia or microrefugia, and since such models are based on the realised niche of taxa neither may encapsulate the potential niche of a taxon and its response to environmental change under altered competitive interactions (Willis and Bhagwat, 2010). Laurance et al. (2011) argued that information about key ecological processes, and especially disturbance and resilience responses, are needed by managers.

More than a century of palaeo-environmental reconstructions in Australia have unearthed the ways that tropical, temperate, semi-arid, Mediterranean, alpine and subantarctic ecosystems have changed, linked and interacted over annual to millennial timescales. Dramatic changes recorded in palaeo-environmental archives indicate that climates, sea-levels, ice sheets, deserts and dryland environments have varied much more over geological time than is captured in instrumental records (e.g. Dodson, 2012).

Such evidence has changed paradigms of the past and scientific assumptions for the future (Birks, 2012) and climate models have been developed and tested against these palaeo-data-sets (e.g. Hill and Hill, 1977; Hill and Peart, 1998). A significant number of Australasian sites with long and high resolution temporal records (Fitzsimmons et al., 2008) have made evident that abrupt and high magnitude events have occurred frequently. New kinds of ecological and environmental explanations were needed for these discoveries, which serendipitously were accompanied by game-changing advances in the technology of radiocarbon dating from decay counting, where 1–5 g of carbon was required previously for measurement, to the capacity now for atom counting (sub-mg) using AMS techniques (Hua et al., 2004).

A new range of chronological tools based on other cosmogenic isotopes (e.g. ^{10}Be and ^{26}Al), along with OSL and TL dating techniques, now contribute to landscape and exposure studies (e.g. Butler et al., 2011). Rapid advances in isotope methods applied to the large quantities of radiocarbon, tritium and ^{137}Cs injected into the atmosphere by nuclear weapons testing provided insights into sediment, nutrient and ecological processes at annual and sub-annual resolution. Organic residues, including ancient DNA, pollen, individual forams, charcoal, tree rings and compound-specific biomarkers from hair, bone, soils, speleothems and sediments, are increasingly accessible, and the refinements and precision in chronology lead to ever finer insights into prior and current ecosystem processes.

In Australia, all these tools have increased the capacity to retrace, model and monitor ecosystem services and drivers of variation at sub-decadal levels and at various spatial scales within the biosphere, cryosphere, atmosphere and hydrosphere. Innovations provided insights into variability in fire regimes (Mooney et al., 2011), droughts and salinity episodes, and the potential for state changes in ecosystems under differing climatic and land management regimes (Dodson and Lu, 2005).

There are now meaningful overlaps between field ecological data, the instrumental record, and palaeo-ecological and proxy data series that form a basis for more reliable quantification of past ecosystem dynamics. These data are converging with the information requirements and spatial and temporal scales of policy makers and land managers into a new framework for evidence-based decision-making and to explore ecosystem functions. The ongoing challenge is to increase engagement between scientists, policy makers, managers and the community to facilitate exchange and incorporation of such information into planning and management of ecosystem services. That challenge is substantial, given that information about the past often appears indigestible to non-specialists; its lack of accessibility and immediacy couple with a strong perception that the past is unhelpful for understanding or planning for the future.

Palaeo-science contributions to ecosystem services implementation

In this section, we present five contexts in which information on long-term records of ecosystem services is being used in Australia to inform environmental decision-making. These contexts include the following: contributing to development of environmental management objectives and actions (section 'Environmental management objectives and actions'); collation of increased data and syntheses that inform understanding of ecosystems and relevant benchmarks, variability and change (sections 'Collation, creation and access to data and research' and 'Environmental benchmarks, states and transitions'); and how improved understanding of ecosystem variability is being incorporated into resource planning and management at a national level and conceptual level (section 'Resource planning and management'), and could improve community understanding and planning for ecosystem service availability (section 'Engaging people about values and allocations').

Environmental management objectives and actions

Palaeo-environmental science has contributed to a paradigm shift in understanding of ecosystem dynamics since the 1990s. The shift has seen the replacement of the equilibrium models of the 1950–1970s with dynamic and non-equilibrium hypotheses (Bowler, 1992). In consequence, the focus has shifted from concern with steady states, biotic constancy, species saturation, optimisation, determinism and competition towards models that emphasise transience, stochasticity, abiotic stress and resilience as the critical factors, with acknowledgement of the importance of opportunism and contingency (Caswell, 1978; Stiling, 1999). Some of this paradigm shift is attributable to the observations of the past and their contribution to enhanced predictive power (Anderson et al., 2006; Costanza et al., 1997).

Long-term historical data also provide support for a precautionary approach to managing natural resources, by suggesting that many ecosystems are more variable and might be approaching threshold levels of degradation that could change how these systems function (MEA, 2005; Rockström et al., 2009). Similar conclusions have been drawn in assessments of Australia's natural resources, processes and biodiversity (Australian State of the Environment Committee, 2011; Dovers, 2000; Morton et al., 2002). Managing these dynamic systems requires long-term records to establish reference conditions and trends, and a greater focus on function and system-level attributes like resilience (the ability to change within limits while maintaining core functions and identity when shocked) and adaptive capacity. This contrasts with the more traditional approach of managing natural resources for stable, optimal states within fixed boundaries.

Yet, there remain fundamental stumbling blocks to knowing more about the past (or future) than is known about the present. The management imperative precludes complete knowledge being acquired before decisions are made, and the declining influence of the precautionary approach parallels a growing confidence in ecological engineering (Costanza, 2012) and a willingness to further manipulate ecosystem function. With proposals such as species translocation, release of genetically modified species and construction of non-analogue ecosystems, we need to be able to predict the outcomes of such actions and prevent or ameliorate perverse outcomes. History reminds us of failed management experiments, such as from the use of exotic taxa in biocontrol, and palaeo-ecology informs us about the changing interactions between faunal assemblages, vegetation communities and fire regimes (Johnson and Isaac, 2009).

Ecological dynamism is an important scientific and management challenge (Cork et al., 2007) for which palaeo-ecological knowledge of species interactions and threshold changes in complex adaptive ecosystems can be better used to inform ecosystem management and policy. Syntheses of palaeo-environmental data have been collated to assist sustainable management (Saunders et al., 1990). However, the declines in key internationally significant Australian assets, such as the World Heritage Kakadu National Park (Woinarski et al., 2012) and the Great Barrier Reef (Brodie and Waterhouse, 2012; Roff et al., 2013), indicate that considerable financial and logistical resource investment and ongoing policy commitments may be insufficient without detailed understanding of long-term dynamics, thresholds, species interactions and ecosystem resilience. If Australians expect sustainment of national asset values and the evidence shows that the management is not able to deliver it, then there is a growing policy legitimacy risk.

Achieving better on-ground resource outcomes requires enhanced cross-sectoral communication to interpret and progress our understanding of such complex systems and how to maintain their resilience and adaptive capacity. It also requires translation of the ecosystem services concept into tangible management objectives and actions that are useful, feasible and incorporate comprehensive, best available scientific knowledge across the range of benefits that humans derive from ecosystems.

In general, scientists are finding the ecosystem services concept increasingly useful in articulating how their research might have direct relevance to policy makers, resource managers and funding bodies (Plant and Ryan, 2013). However, this may not be widespread yet. Of 172 key authors writing on ecosystem services (Costanza and Kubiszewski, 2012), only eight were Australian, and none were palaeo-environmental scientists. Visionary syntheses of long-term environmental evidence authored by Stephen Pyne, Tim Flannery, Ian Low and Bill Gammage have gained traction with the Australian public. To date, that long-term perspective has largely been absent from scientific and policy debates around ecosystem services implementation, which have focused on typologies (Haines-Young and Potschin, 2010; Wallace, 2007), monetary valuation (Bennett, 2005; De Groot et al., 2010) and governance mechanisms (Lockie, 2013; Zammit, 2013). There are many publications that have used information from natural archives, such as tree rings and geomorphological features, to provide proxy evidence of past climate or hydrological conditions that inform management (e.g. Swetnam et al., 1999; Willis et al., 2007; Woodroffe and Murray-Wallace, 2012) yet, the question remains, 'what actionable knowledge comes from ecosystem or environmental history?' We believe detailed regional or local discussions about where ecosystems and their services have come from, and their status and trajectory, are necessary to address ecosystem service and resource sustainability.

Collation, creation and access to data and research

The global-scale contribution of Australian palaeo-ecology to conceive, research and understand changing ecosystems has included understanding of ecosystem origins (e.g. Byrne et al., 2008) and ecosystem functioning and services in disparate environments, such as coral reefs (De'ath et al., 2009; Roff et al., 2013), stop-go ecosystems (Brereton, 1971) and coupled ocean–terrestrial–atmosphere systems (Gergis and Ashcroft, 2012). It has aided understanding of the causes, risks and social consequences of natural disasters, such as tsunamis (Courtney et al., 2012), mega-droughts (McGowan et al., 2012) and of fire-biodiversity management (Lynch et al., 2007; Mooney et al., 2011; Williams et al., 2009). In particular, Australian palaeo-fire research has established that persistent ecosystem changes and fixed ecosystem boundaries have occurred where human actions have increased landscape flammability (McWethy et al., 2013; Mooney et al., 2011), creating an omnipresent risk of such events. At specific sites, palaeo-ecology has disentangled the influences on unusual landscapes such as the cause of grassy balds in the Bunya Mountains of Queensland (Moravek et al., 2013) and the impact of long-term rainforest dynamics on threatened species such as grey-headed fruit bats (Luly et al., 2010).

Synthesis of proxy evidence, including records from many sites across Australia, shows the importance of understanding regional hydrological balances (Harrison, 1993) and fire regimes (Mooney et al., 2011). For example, starting with the 'Salinity, climate change and salinisation' workshop under the International Geosphere–Biosphere Programme's core project on Past Global Changes (PAGES) focus IV at Mildura in 2004 (Gell et al., 2007) and follow-up meetings at Nanjing in 2007 (Fritz and Gell, 2010) and in Chandigarh (Kotlia et al., 2011), natural archives of human, climate and environmental interactions were discovered. They showed the critical role of rivers in the provision of ecosystem services over long periods (Hausmann et al., 2011), and the need for regional records and data syntheses to understand geographically specific processes and drivers.

Most Australian long-term records have been synthesised and improved for hydrologists and climatologists (Gergis and Ashcroft, 2012), fire or biodiversity managers (Atlas of Living Australia (ALA)), and other scientists (e.g. PEP (Hope et al., 2004) and OZ-INTIMATE syntheses (Fitzsimmons et al., 2008; Reeves et al., 2013) both available online). Yet, these syntheses include highly filtered records that exclude data that might be used to identify different issues for managers (Pearson and Searson, 2002; Suding and Hobbs, 2009). Access to original datasets and data catalogues is needed to address this mismatch of expectations. For example, most compilations so far have been records of Australian vegetation, lake levels, circulation systems and fire histories, which show remarkable stability in comparison with the faunal record (Burbidge et al., 2009). Palaeo-records of fauna include surprises that challenge environmental reconstructions, for example, the past presence, during arid conditions similar to present-day, of arboreal taxa in areas that now lack trees (Johnson and Isaac, 2009).

Making palaeo-records like these available is an important issue, and one tool developed recently to improve data availability is the ALA. The Atlas is an extensive collation of material on Australian species (and through ecosystem models to some ecosystem services) from millions of biological specimens and media in museum and herbaria collections, with further enrichment possible by linking palaeo-data to these repositories (Binning et al., 2002). The website (http://www.ala.org.au) and database design allows searching by the public of distributional, taxonomic and ecological data, the importing of prehistoric information and analyses using the biotic and abiotic data and modelled variables. Furthermore, citizen scientists involved in gathering biodiversity and ecological data often gain an understanding of the process of scientific inquiry, the importance of data quality and the use of scientific data. Such tools increase public awareness of the importance and implications of long-term scientific data and the probability of future changes. They are an essential co-requisite to understanding the past and predicting changes and trends in biodiversity and ecosystem services by creating an interface to contemporary, historical and predictive information on Australian biodiversity.

Environmental benchmarks, states and transitions

Knowing about pre-Aboriginal, Aboriginal, early European, and present-day land management and their impacts is important for discussing and choosing appropriate environmental benchmarks. We note that among managers and ecologists alike this is a lively and developing research field (e.g. Gammage, 2011), which includes contested political dimensions.

Water and wetlands provide a spectrum of ecosystem services that support different uses; so their management often results in strong stakeholder conflict. Water availability and quality are key aspects of these services, so getting palaeo-environmental information about boundaries, state shifts, thresholds and non-linear responses then informs management of these services. The following four examples relate to the use of long-term records in the water sector to evaluate the following: (1) the extremeness of recent temperature and drought conditions, (2) altered states in wetland systems, (3) reference conditions to meet international agreements and (4) the need for multi-proxy methods to interpret degraded and highly dynamic environments.

Recent temperature and drought extremes. To improve understanding of regional climate variability over the last 2000 years, the PAGES Regional 2K network was established in 2009 (http://www.pages-igbp.org/workinggroups/2k-network). Neukom and Gergis (2012) reviewed all monthly and annually resolved palaeo-climate records available in the Southern Hemisphere to make a 1000-year-long annual land and ocean temperature reconstruction for the Australasian region. This temperature reconstruction indicates that the post-1950 temperatures were the warmest of the past 1000 years, with anthropogenic forcing implicated by modelling as the dominant cause of recent temperature increases (Gergis and Ashcroft, 2012).

Australian ecosystems are strongly influenced by water availability, so a robust record of rainfall is essential for contextualising events like the recent 12-year drought across southern Australia. Palaeo-climate estimates suggest that this 1998–2009 'Big Dry' drought and associated low stream-flow periods were anomalous in the context of the past two centuries. The recent River Murray stream-flow deficit is estimated to have a return period of 1 in 1500 years (Gallant and Gergis, 2011), while rainfall reconstruction suggests a very high (over 95%) probability that the 1998–2009 decadal rainfall anomaly was the worst experienced since European settlement of Australia (Gergis and Ashcroft, 2012).

These inferences derive from palaeo-climate, documentary and early instrumental data collated in the South-Eastern Australian Recent Climate History (SEARCH) project to improve understanding of climatic variability over past centuries and to assess its impacts on Australian society (http://www.climatehistory.com.au). The project has reconstructed south-eastern rainfall and River Murray stream-flow back to 1783 (Gallant and Gergis, 2011; Gergis and Ashcroft, 2012), recovered early instrumental records dating back to European settlement in 1788 (Gergis et al., 2009) and used historical sources to assess the influence of climatic variability on settlement (Fenby and Gergis, 2012; Gergis et al., 2010). This project also shows the importance of citizen science with Australia's first online database of climate information (dating back to 1788) compiled using a volunteer programme (http://www.ozdocs.climatehistory.com.au).

Altered states and environmental resilience. The exploration of ecosystem histories using palaeo-records can identify the stability of ecosystems, and offer insights into altered states and drivers of change. Reid and Gell (2011) analysed a suite of site studies of billabong wetlands across the Murray–Darling Basin in south-eastern Australia. They developed a typology of four ecological responses to past geomorphological and hydrological changes. The four types vary in the timing and variability of domination by macrophyte versus phytoplankton taxa, in association with local timing of European settlement and geographic location. The patterns reflect how the morphology of the wetland (size and depth), which is a function of the geomorphological and hydrological character of the parent river and reach, can provide resilience against anthropogenic stressors (i.e. sedimentation, water extraction). The wetland types differ in their sensitivity to catchment management impacts, so the typology can be used to identify wetlands at risk of change, wetlands that differ from their historical condition and the consequences of manipulated hydrological regimes. The research reinforces the importance of regional studies to describe the longer-term situation and to test and refine broad-based generalisations. Wetlands and floodplains in the Murray–Darling Basin were identified by Laurance et al. (2011) as being highly vulnerable and at critical tipping points. Resilience and vulnerability vary within an ecosystem type, so scale of analysis and management needs to be taken into account.

Use of reference conditions to meet international agreements. The long-term view is also useful for setting benchmarks, such as those required to meet international environmental agreements. For example, the Convention for the Conservation of Wetlands of International Significance (Ramsar) seeks the wise use of the world's wetlands with a view to ensuring the protection of wetland ecosystems, particularly populations of fish and birds. However, its short temporal perspective in setting baseline conditions (against which signatories choose 'limits of acceptable change') has created problems even in areas where more than a decade of monitoring underpinned the nomination. Some Ramsar-listed wetlands in regions with high climatic variability and substantial change in condition from early settlement have been described in their nomination with 'baseline conditions' that were unrepresentative of the full range of historical condition identified through palaeo-limnology (Mills et al., 2012a). In the absence of evidence for historical change and the amplitude of natural variability, the identification of condition at one point in time poses an unnecessary obstruction to appropriate resource management. The convention will be strengthened when lessons from the past provide a way to inform 'natural' ecological character of dynamic, and sometimes directional, change.

Interpreting degraded and highly dynamic environments. Australian coastal environments are functionally different to those of North America and Europe, although they also have been extensively modified and degraded because of increasing population growth (Dick et al., 2011). The residual ecosystem values of the coastal zone remain under threat from urban sprawl and associated land uses (Saunders et al., 1990). Environmental records are of insufficient duration or accuracy to identify natural ecological thresholds or benchmarks, whereas palaeo-ecology is providing management answers through multi-proxy techniques (Logan et al., 2010; Tibby et al., 2008). For example, Logan and Taffs (2011) were able to identify sub-tropical estuarine reference conditions using a combination of geochemical and biological techniques, while studies in the Coorong, South Australia, show the level of temporal detail possible using natural archives (Dick et al., 2011).

Figure 1 illustrates the use of palaeo-ecology to define baseline conditions in Tuckean Swamp, New South Wales, where multiple stakeholder debate on natural benchmarks was unresolvable and historical records and living memory insufficient to establish pre-Anthropocene or European settlement conditions. In this case, community stakeholder meetings were deadlocked as living memory and historical records were inadequate to clearly identify 'natural' swamp conditions. A combination of sedimentary and biological proxies was used to infer the salinity and pH history of the swamp and enable implementation of effective land management practices. The palaeo-ecological record identified that the swamp was brackish with slightly acidic pH prior to introduction of agriculture within the catchment. Information on benchmark conditions enabled managers to reinstate tidal flows that have assisted neutralisation of the acid soils and increased flushing to reduce nutrient accumulation.

Yet, the dynamism of the estuarine environment has challenged Australian palaeo-ecologists to combine freshwater and marine techniques and to work collaboratively using multi-proxy methodologies as well as with policy makers and managers (Dick et al., 2011; Perrings et al., 2011; Saunders and Taffs, 2009). Greater collaborative effort is needed to improve methodologies, increase data collection, collate regional syntheses and use the breadth of information to guide management objectives and actions, and assess management effectiveness in such environments.

Resource planning and management

Policy makers have included ecosystem services in their thinking, programmes and regulations (e.g. Commonwealth of Australia,

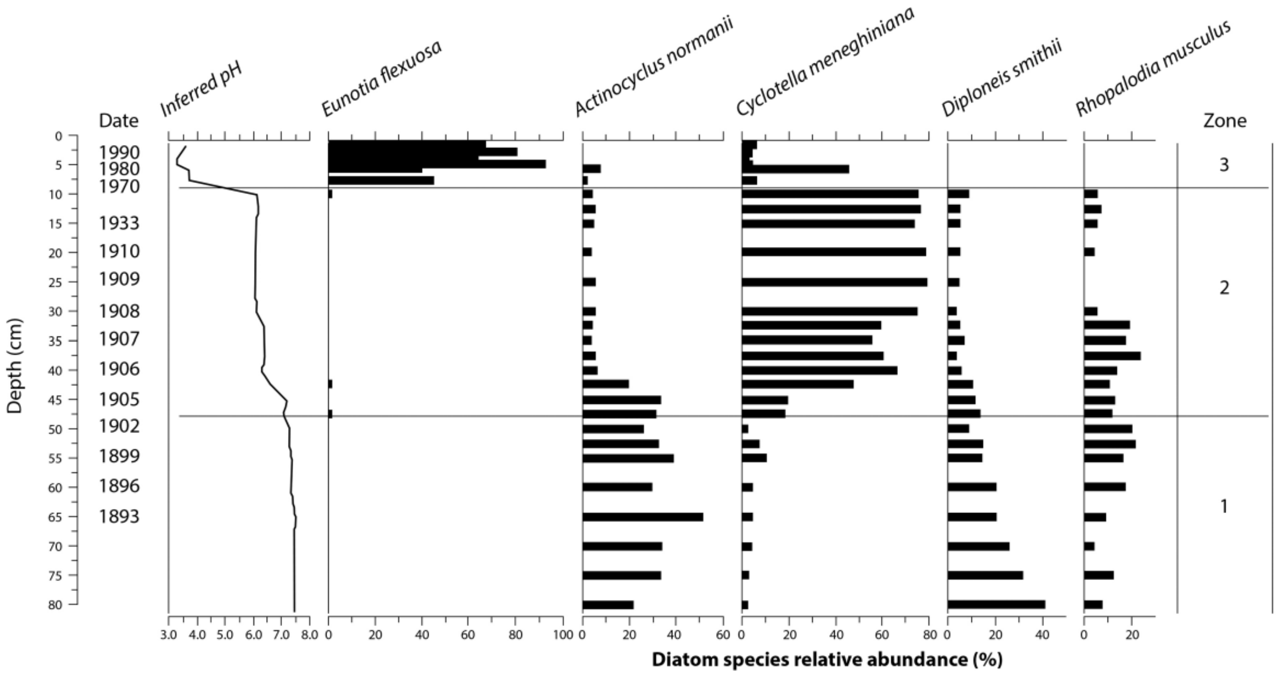

Figure 1. The recent palaeo-ecological record of Tuckean Swamp, New South Wales (adapted from Figure 3 in Taffs et al. (2008)). The palaeo-ecological record identified Zone 1 (pre-1900) had benchmark environmental conditions with brackish swamp and minimal anthropogenic disturbance. Zone 2 (1900–1970) records the change in the diatom community as agriculture intensified and increased the trophic status. Zone 3 (post-1970 to core collection date of 2002) records a dramatic pH change as a result of barrage construction that prevented tidal intrusion into the swamp area and neutralised acid sulphate soil runoff. Information on benchmark conditions enabled managers to reinstate tidal flows that assisted neutralisation of the acid soils and increased flushing to reduce nutrient accumulation.

2012) and invested in research projects to clarify issues. Framing discussions between managers and their communities about desirable futures using knowledge of the past is an important starting point for dialogue about planning and management of ecosystem services (Morley et al., 2012: especially, Figure 3.1 and 3.2). Adoption requires understanding and belief in the processes, capacities and functions that underpin ecosystem services (Potschin and Haines-Young, 2011). Greater collaborative efforts and discussion about ecosystem conditions to sustain resource availability are needed to achieve trans-formative changes in understanding and supporting the resilience and security of ecosystem services. The following two examples describe two planning approaches in the aquatic and terrestrial ecosystem sectors informed by long-term histories of ecosystems and their services.

National water governance. The Australian National Water Commission has begun using an ecosystem services approach for more comprehensive consideration of water benefits in national water allocation planning (Plant et al., 2012; Plant and Prior, 2014). Water planners often struggle to explicitly consider and communicate the links and interdependencies between environmental, social and economic outcomes. There is a well-established tradition of incorporating benefits associated with extractive water uses, but less emphasis on systematically identifying and incorporating the benefits of leaving water in the river or ground (Brauman et al., 2007). The ecosystem services concept provides a language and the tools for water planners and communities around Australia to re-examine their relationship with water resources by engaging in dialogue about water resources (Plant et al., 2012) and learning about the potential outcomes and consequences of trade-offs between ecosystem services (Pittock et al., 2012).

Such engagement is essential because contests over natural resource allocation, such as the provision of environmental flows within the Murray–Darling Basin (Murray–Darling Basin Authority, 2012), remain vexed despite legal underpinning, at least partly on account of the lack of a longer-term view of the degraded state of the ecosystems (Gell, 2010). However, when the relative health, risks and values of the system can be contested, information alone is unlikely to resolve the conflict. Given that water volume translates so directly to income for irrigators, there is reluctance to cede water volumes to the environment. Furthermore, evidence from a metadata set of sediment records shows that the mere provision of water for environmental flows is unlikely to be a panacea for waterway restoration when the quality (e.g. nutrient status, sediment load, salinity) of the environmental flow is compromised or the quantity and timing inappropriate. Indeed, the accelerated sedimentation rates they generate may infill critical wetlands (Gell et al., 2009).

Palaeo-environmental data also have strong potential to inform the quantitative stages of the water allocation planning process: for example, describing the water resource, setting objectives, informing trade-offs and subsequent measuring and monitoring of ecosystem services. Regional syntheses of the most culturally relevant time-frames (e.g. Fitzsimmons et al., 2008) have contributed new archives of processes, water quantity and quality at a site-scale. Recent efforts have focused on producing syntheses relevant to national (e.g. Murray–Darling Basin syntheses by Mills et al., 2012a, 2012b) and international (e.g. Ramsar) natural resource managers and policy makers.

Vegetation assets, states and transitions. Baselines and evidence of ecosystem dynamics have made conservation and environmental management both better informed and more difficult. Arguments about whether places should be managed for pre-European or other baseline conditions are fraught. An example from vegetation management is the Vegetation Assets, States and Transitions (VAST) framework (Thackway and Lesslie, 2008), an assessment, communication and reporting tool that assists with analysing trade-offs between ecosystem services by enabling stakeholders to engage in broader dialogue on multiple ecosystem services at national, regional and local scales (Yapp et al., 2010).

Encompassing information about the structure, composition and function of vegetation-related ecosystems, the VAST framework accounts for the effects of land management practices on vegetation condition and the delivery of ecosystem services over time. The framework describes and accounts for anthropogenic modification of vegetation through its representation as a series of condition states, from a baseline condition to total removal. Four of the major changes in the state of Australia's vegetation and, as a corollary, the changes to ecosystem services and biodiversity are shown in Table 1 and Figure 2. They represent a generalised series of states for a vegetation type widespread in south-eastern Australia, grassy gum and box woodlands: (1) during the late Quaternary (AA1 before human arrival), (2) before European settlement of Australia (an assumed reference state used by many people; A1, A2), (3) after changes wrought by early settlers' management of vegetation (B1, B2), (4) under current land management (C1) and future states assuming two scenarios of changes in land management (D1, D2). The transitions between the various states (B, C and D) are the result of land managers manipulating key attributes of vegetation structure, species composition and regenerative capacity/functioning.

These functional changes and land use intensity changes drive the modification of ecosystem services and can be described from the palaeo-record, for example, from tree wood and ring studies and herbivore middens. Ecosystem function is linked to changes in the status and condition of vegetation via its structure, composition, regenerative capacity and functioning (Figure 3). By making explicit the links between land management practice and vegetation condition states, the framework provides a mechanism for discussing the socio-ecological consequences of land management practices on vegetation condition and resilience (Yapp et al., 2010) as well as values-based management objectives.

These ideas have evolved into large programme-scale policy investment information tools such as Reef Rescue (Hajkowicz, 2009). Reference condition assessments are also recognised in national policies and programmes, including the National Wilderness Inventory, the National Forest Policy Strategy, the Native Vegetation Management Framework, the National Monitoring and Evaluation Framework, and for listing of nationally threatened ecological communities and in numerous state and territory vegetation programmes (Thackway and Lesslie, 2008).

Engaging people about values and allocations

While there has been considerable progress in understanding ecosystem services across different stakeholder groups and levels of government, broad community acceptance and uptake of the concept have been slow (Pittock et al., 2012). Yet, practical engagement and participation (Maynard et al., 2011) – using deeper understanding of the way ecosystem services change and deliberate choices about livelihoods, ecosystems and futures – may help manage policy risk, for example, under climate change in coastal communities (Morley et al., 2012). Discussing palaeo-environmental data provides an opportunity to explore values, management scenarios and ecosystem service risk (likelihood and consequences), and to enhance people's appreciation of local places, complexity, relative scarcity, threats and opportunities, and their cultural backgrounds (Braat and De Groot, 2012). Australia's palaeo-environmental community is increasingly engaging with the public through science personalities such as Professors Tim Flannery, Mike Archer, Will Steffen and Chris Turney.

There is a growing expectation among communities that government and industry will cope with natural disasters and that they will meet wider legal liability tests such as ensuring community and ecosystem resilience. This will drive an increasing demand for relevant palaeo-information such as spatially explicit, quantified risk statements and assessments of threats to ecosystem services. The following example of implementing the ecosystem services approach identifies where further development is needed.

Implementing ecosystem services in regional planning. In South East Queensland, a regional natural resource management agency (23,000 km^2) coordinated over 190 experts and stakeholders from government, universities, non-governmental organisations, business and industry to map 32 ecosystem types, 19 ecosystem functions and 28 ecosystem services that influence 15 constituents of human well-being. The collaboration used the language of ecosystem services to create a common understanding that allowed all stakeholders to engage through ownership, transparency and social learning (Maynard et al., 2010).

The experience provided insight into the types of information needed for local decision-making and the reality of data availability and analysis (Maynard et al., 2011). The decision-making context (i.e. rapid population growth and concern about the capacity of the region to maintain ecosystem services) determined which ecosystem services information was relevant and that multidisciplinary inputs and vast amounts of information on local environments, societies and economies were ideally required. However, not all the information was available in an accessible, reliable form, but a lack of resources and time prevented collection of new information or development of complex ecological models for the region. Expert and local knowledge was essential, therefore, to fill areas of limited data availability, but this improved acceptance of the final product. Data were primarily qualitative with priority setting based on scoring of relative values of ecosystem services to the SEQ community's well-being (Maynard et al., 2011). Ecosystem services and the framework developed with the stakeholders have now been incorporated into state and local government policy and planning documents, and in State of the Region reporting.

An historical perspective on ecological functions (such as disturbance regulation that contributes to support ecosystem services) could not be incorporated but would be of benefit in further iterations of the approach (Maynard et al., 2010). First, the SEQ approach focused on immediate values for ecosystem services rather than information about past and future services and values. Planning without an historical perspective puts pressure on intergenerational equity and may increase the community's susceptibility to the hazards and risks of crossing ecosystem service thresholds. A palaeo-ecological component would help contextualise regional processes and ecosystem service characteristics, and may help with expert and community discussion about the adequacy of current management and information time horizons. A shift is needed away from the monetary ecosystem services valuation controversies, such as those focussed on discounting (Spash, 2008), towards embedding ecosystem services thinking in participatory planning processes based on longer-term records and long-term futures (Maynard et al., 2011).

The second area for improving integrated environmental and socio-economic management at the regional level is the incorporation of more comprehensive disturbance regulation information. Information about the types, frequency and intensity of past environmental events such as floods, fires and tsunamis is important for sustaining many ecosystem services and can be informed by palaeo-environmental science. It also requires effective measurement, monitoring and evaluation of environmental state, trend and performance to provide feedback to policy makers about management effectiveness (Morton et al., 2009). Monitoring is rarely sufficient to meet this need, but evaluation of past approaches using historical and pre-historical data can

Table 1. Pathways of vegetated landscapes through time in Australia, fragmented and modified to deliver vegetation-related ecosystem services (Thackway and Lesslie, 2008) shown in Figure 2.

Before human arrival	Reference state (assumed)	Early settlers, management of plant community types and condition classes	Present land managers managing plant community types and condition classes and replaced vegetation cover classes	Future land managers managing plant community types and condition classes and replaced vegetation cover classes
Plant communities and species changing in distribution, composition and abundance (AA1)	Past plant community – ecological stable state (A1)	The ecological function of plant community (i.e. Aboriginal stable state) was unmodified and needed to be cleared and modified for grazing and cropping (B1)	Depending on the need/aspirations of sequential land managers and successive societal needs, native vegetated landscapes were kept intact (unmodified), modified, transformed, removed and replaced to produce different ecosystem responses by changing structure, composition and ecological function. This in turn changed the mix of ecosystem services, for example, native and improved pastures, crops and plantations for food and fibre production or removed vegetation altogether, for example, cities and infrastructure. Some areas were converted to minimal use, for example, forest reserves, nature conservation reserves and Indigenous protected areas (C1)	Future societal groups maintain and improve native vegetation cover and/or plant communities to produce different services, for example, pastures, crops and plantations for food and fibre production. Areas will be converted from more intensive production to minimal use, for example, forest reserves to nature conservation reserves and grazing land to Indigenous protected areas (D1)
	Past plant community – Aboriginal stable state (A2)	The ecological function of plant community (i.e. Aboriginal stable state) was already modified and fit for grazing with sheep/cattle because it had been modified by Indigenous peoples to produce a managed and productive landscape for grazing and hunting and gathering (B2)		Future societal groups remove and replace native vegetation cover and/or plant communities to produce different services, for example, biodiverse pastures, mono-culture crops and plantations for food and fibre production or remove vegetation altogether, for example, cities and infrastructure (D2)
	Human manipulation of vegetation to produce ecosystem services increasing as demands changed, markets and productivity demands grew, and scientific and technological opportunities increased.			

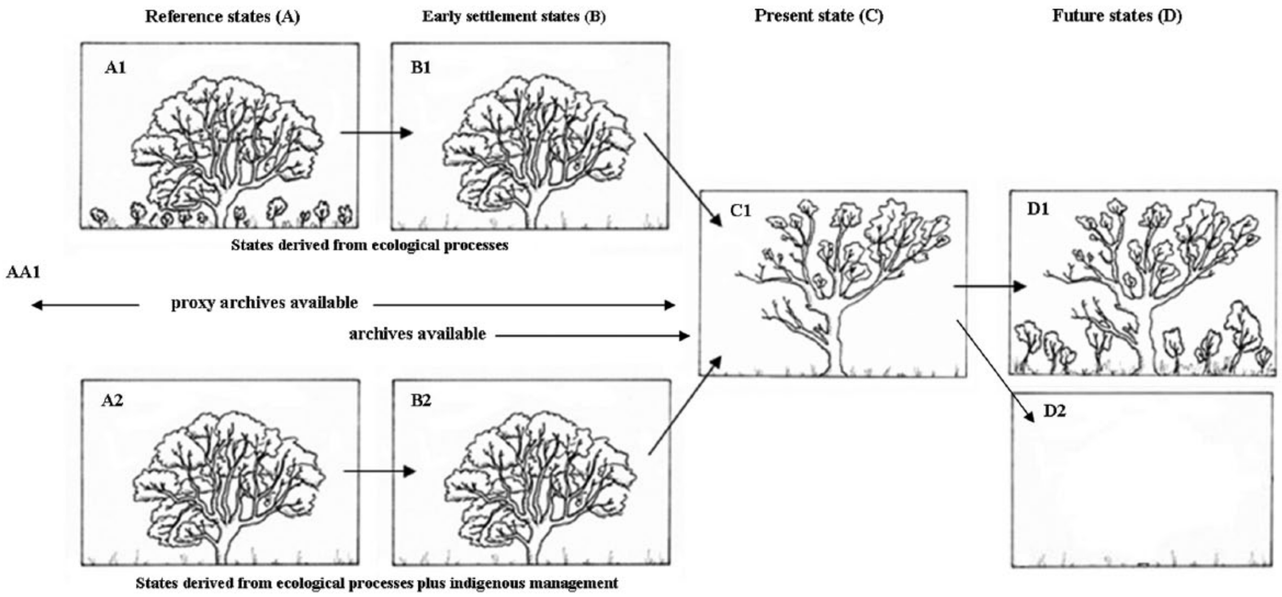

Figure 2. Pathways for vegetated landscapes over time (AA to D) where original natural vegetation was derived either from ecological processes or ecological processes plus Indigenous management practices. Further explanation is provided in Table 1.

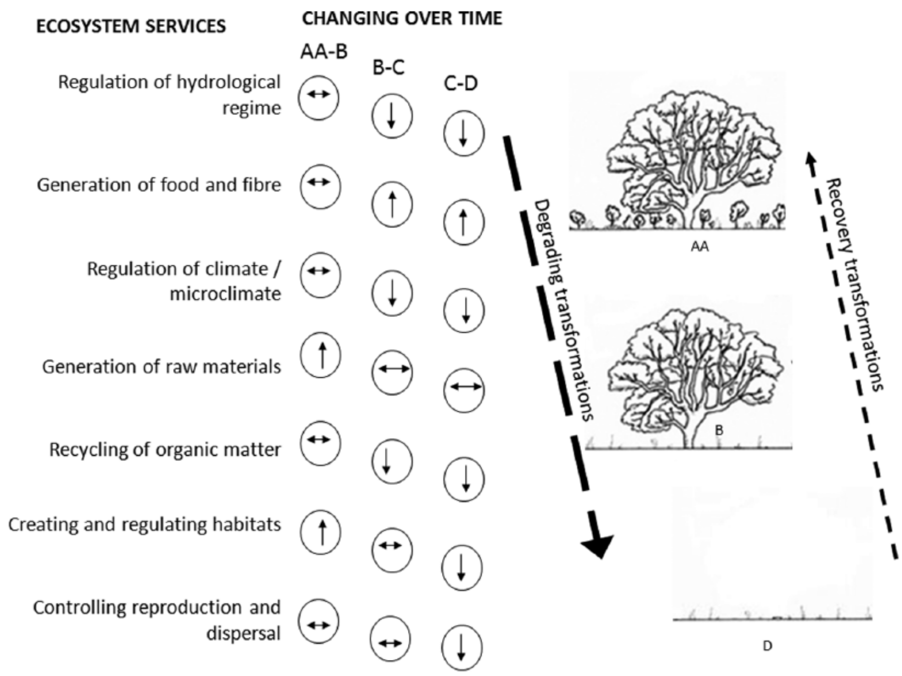

Figure 3. Ecosystem service changes caused by changing environments, ecological functions and landscapes (AA to D) over time. Further explanation is provided in Table 1.

be informative. Coastal wetlands were highlighted as important during expert mapping for their disturbance regulation value, and vegetation for its potential flood control value (Petter et al., 2012). Consideration of how these ecosystem functions and services may vary under climate change will add to the efficacy of hazard and risk assessment.

Conclusion

Highlighting five different resource management contexts, we have shown how information on long-term records of ecosystem services could be and, in several cases, is being used in Australia to inform environmental decision-making. Natural archives of past changes in ecosystems and ecosystem services are available in most environments and should be used to a greater extent to strengthen natural resource policy, science and practical outcomes. Australia is a recognised innovator around ecosystem services (Daily, 1997; Maynard et al., 2011; Pittock et al., 2012), incorporating the concept into policy and planning at national to local scales and in implementing international agreements. Yet, better incorporation and understanding of knowledge of long-term processes and dynamics are needed to achieve more sustainable socio-ecological systems and natural resource management. Australian palaeo-environmental science is contributing to improved environmental understanding through local studies and regional syntheses that inform about past conditions, extreme conditions and altered ecosystem states. Rethinking how the past informs the present and future involves awareness of long-term dynamics, state shifts, thresholds and non-linear responses, and incorporation of such understanding into planning and management tools.

Achieving better on-ground environmental outcomes requires managers and communities to use comprehensive, best available scientific knowledge in a re-evaluation of their relationship with ecosystem resources. Framing discussions between managers and communities about desirable futures guided by knowledge of the past is an important starting point for dialogue about planning for sustainable ecosystems and services (Morley et al., 2012; Setten et al., 2012). It will also help determine how much palaeo-science can contribute to managing ecosystems. A palaeo-environmental perspective on resource variability and the processes, capacities and functions that underpin ecosystem services can inform the setting of resource management objectives, inform about potential consequences of trade-offs and guide strategies for evaluation and monitoring of ecosystem services. However, current management needs to value this contribution and to appreciate the uncertainty associated with evaluations of antecedent conditions, rates and trajectories of change recorded in natural archives. An important next step is to translate knowledge of long-term ecosystem services dynamics into tangible management objectives and actions that are practical (useful), practicable (feasible) and incorporate stakeholder values.

It remains a critical conclusion that decision-making about future ecosystem services requires a process that accommodates the range of benefits that people obtain from ecosystems and assessment of their spatio-temporal availability. Non-consumptive benefits have been less emphasised in planning and economic valuation (Brauman et al., 2007). Anthropogenic climate change is showing, through increasing frequency of natural disasters and failed water planning and agricultural production, the dependency of provisioning services on regulating and supporting services. Ecosystem services, when used in its broadest sense, offers a means of re-engaging with less tangible but nevertheless critical services when assessing trade-offs and their consequences (Daily, 1997; Plant and Prior, 2014). It enables greater consideration of the continuum in which nature co-exists with human impact and intervention, and the capacity to protect and restore natural capital on economic and socio-cultural grounds, including the prevention of future costs of failing to do so (Beeton and Lynch, 2012; Potschin and Haines-Young, 2011).

Furthermore, greater communication and engagement are necessary to evaluate ecosystem service availability, resilience and value to communities. Communication and collaborative efforts are necessary across communities of scientists, planners, managers and citizens. Scientists from a diversity of fields are now often using the ecosystem services concept to articulate the relevance of their research to policy makers, resource managers and funding bodies (Plant and Ryan, 2013). Through networks (e.g. http://www.tern.org.au/) and other resources (e.g. ALA), relevant data are starting to be made publicly available, and this should continue.

There also needs to be transformational change in our understanding of the structures and functions that create ecosystem services and of their resilience and security (likelihood and consequences of hazards). Decision-making about the kinds of services provided by an ecosystem, how much of the service is needed, and the threats to the services will be most effective when grounded in broad-scale, long-term knowledge of ecosystem structures, processes and functions, and limits to their supply. Such decision-making should also encompass resource planning commitments through mechanisms including the Convention on Biological Diversity and Ecologically Sustainable Development principles like intergenerational equity.

The conclusion that the need for greater collaborative effort is recognised by scientists and managers to improve methodologies, increase data collection, collate regional syntheses and use the breadth of information available to guide management (Dick et al., 2011) is encouraging. Inter-disciplinary collaboration is necessary to develop metrics and monitoring of human impacts on ecosystems, of management effectiveness, projections of ecosystem trends and futures, and the translation of futures scenarios into meaningful indicators of socio-economic and human well-being because information alone does not engender policy implementation (Daily, 1997). Increased communication with managers and communities, using engagement tools such as narrative histories represented in various vegetation states and futures scenarios, will help raise awareness of ecosystem changes and natural disaster risks.

Communities will vary in their valuing of particular ecosystem services depending on their socio-cultural and economic attributes, but also their level of ecological and palaeo-ecological understanding. Increased engagement through citizen science, participatory planning processes, collation of expert knowledge, and interpretation of regional ecological and risk syntheses will enhance such understanding, along with ownership, transparency and social learning in relation to local resource governance (Maynard et al., 2010, 2011). A palaeo-environmental perspective is a necessary contribution to such processes as it strengthens the outcomes by contextualising regional processes and ecosystem service characteristics, assists with analysing ecosystem services and trade-offs, and contributes to expert and community discussion about the adequacy of management and information time horizons and objectives. Palaeo-environmental understanding is indispensable for development of evidence-based adaptive management policies and strategies to guide conscious choices about desirable, sustainable socio-ecological landscapes.

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