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From myopia to clarity: sharpening the focus of ecosystem management through the lens of palaeoecology

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Maintaining biodiversity and ecosystem services in a changing environment requires a temporal perspective that informs realistic restoration and management targets. Such targets need to be dynamic, adaptive, and responsive to changing boundary conditions. However, the application of long-term data from palaeoecology is often hindered as the management and policy implications are not made explicit, and because data sets are often not accessible or amenable to stakeholders. Focussing on this translation gap, we explore how a palaeoecological perspective can change the focus of biodiversity management and conservation policy. We embed a long-term perspective (decades to millennia) into current adaptive management and policy frameworks, with the aim of encouraging better integration between palaeoecology, conservation management, and mainstreaming viable provision of ecosystem services.

A multiscalar perspective

New approaches to conservation aim to conserve biodiversity, ecological integrity, and evolutionary potential, while simultaneously maintaining sustainable ecosystem services and supporting livelihoods [1–4]. Conservation practices that aim for stasis by preventing disturbance are unrealistic in a dynamic world where changing climate, population, and land use interact with other drivers, such as fire and invasive species, to impact on ecosystem resilience and flux [5–7]. We suggest that conservation goals with aspirations of ecological, environmental, and economic sustainability can only be achieved using a multiscalar perspective that incorporates an understanding of ecosystem dynamics and tipping points over decadal–millennial timescales. Such a perspective is only possible by integrating data from palaeoecology, archaeology, historical ecology, long-term monitoring, and satellite imaging into an understanding of change in the past–present–future continuum (Figure 1) [1,6,8,9].

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Keywords: thresholds; ecosystem services; savannahs; adaptive management; thresholds of potential concern; Future Earth; fire; forest management; restoration.

0169-5347/

 http://dx.doi.org/10.1016/j.tree.2014.03.010

Here, we discuss the integration of long-term data into adaptive management, restoration, and conservation, giving examples from specific ecosystems. We explore options for improving the accessibility and applicability of long-term data to policy- and conservation-relevant metrics, such as ecosystem services. We then embed these case studies into a broader sustainability–policy framework, including links with new policy-research vehicles such as Future Earth.

Adapting to uncertainty

Maintaining ecosystem integrity and associated ecosystem services in a changing environment requires realistic restoration and management targets [6,8,10,11] that are dynamic, adaptive, and responsive to changing boundary conditions, social demands, future scenarios, and ecological thresholds [12–17]. Adaptive management has emerged as the primary strategy in a changing environment where uncertainty is high and intervention decisions are urgently required [12,16,18–22]. For the adaptive management cycle to function effectively, it should specifically include a temporal dimension that allows consideration of the past, likely range of variability, how this compares with future states, and the potential tipping points when dramatic and nonreversible changes might occur (Figure 2).

Without good-quality long-term information, it is impossible to know whether current states are typical, or whether they are already dangerously near the thresholds of resilience [23–26]. Such a lack of understanding can be a barrier to effective conservation, exacerbated by institutional inertia and risk aversion. For example, a national environmental agency may have a set number of management interventions; as an ecosystem experiences change, the default decision is to apply one of these existing tools, even though it may no longer be fit for purpose. This situation can lead to myopic conservation goals driven by political cycles, static management, and transient funding mechanisms, which aim to preserve a notional *status quo* [12,21,27,28]. Understanding variability and change in ecosystems provides a sound basis for visionary conservation philosophy and practice that can accommodate changing conditions and multiple future scenarios; factors that embrace uncertainty, heterogeneity, interactions, and flux

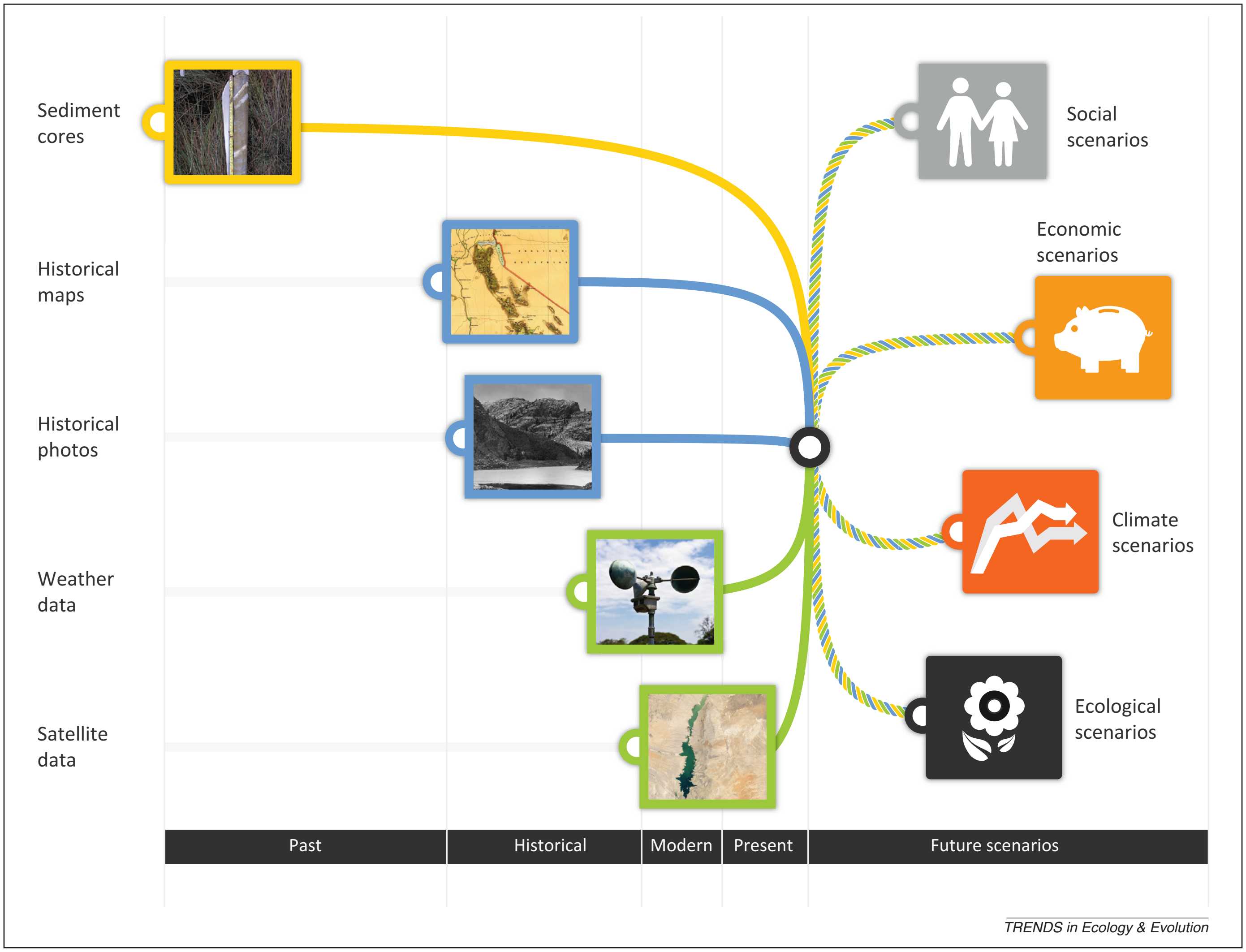

Figure 1. How different environmental proxies combine to reconstruct climate and ecosystem dynamics through time. Accessing deep time is only possible via sedimentary records, where several proxy tools, such as pollen, can be used to place the more recent indicators of environmental ecosystem change in context. As one moves through time, additional varied sources of information can be included, such as historical maps, photographs, meteorological data, and satellite perspectives on recent land-use changes. Such an integrated approach, which combines different sources of information, is essential to gain a comprehensive understanding of past ecosystem dynamics and human interactions, and to engender the development of appropriate and sensitive modelling tools for future scenarios. When these different strands of information are woven together, they can be used to understand potential climate, social, ecological, or economic futures that have foundations embedded in a meaningful timeframe.

[1,5]. Specifically, reference conditions are needed that enable us to understand how humans have interacted with, and have managed, biodiversity, and how ecosystems and societies have co-adapted to changing myriad influences over decades, centuries, and millennia [10,29–34]. Similarly, when planning for the future, we cannot assume stasis in environmental boundary parameters and, therefore, scenarios must be developed that reflect likely future states and tipping points [5,13,14,35].

Rather than simply extrapolating present trends, future scenarios must be embedded in past perspectives on variability over a range of temporal scales, necessitating an interdisciplinary approach that merges information from the social and environmental sciences (Figure 1). Current observations provide only a snapshot and even decadal-scale observations may give a misleading impression of resilience or linearity to gradually changing environmental conditions; ecological and physiological thresholds are more likely to be observed over timescales of centuries to millennia. Even though future conditions may not have a past analogue, a past perspective is essential in designing management plans, because it provides a range of reference states against which the cause and effect of management intervention can be measured [31,35].

Applications of long-term data in adaptive management

Adaptive management (Figure 2) has emerged as the main conservation approach that realistically accommodates change, variability, and uncertainty. It comprises cycles of planning, intervention, monitoring, and adaptation in an iterative feedback loop that allows response to changing conditions and emerging new information. The importance of the temporal element in adaptive management is clearly demonstrated by processes such as groundwater recharge, or forest succession and/or evolution, which can operate over timescales far beyond any ecological or remotely sensed (e.g., repeat photographs or satellite images) data [28,36]. Although the mainstreaming of palaeoecological

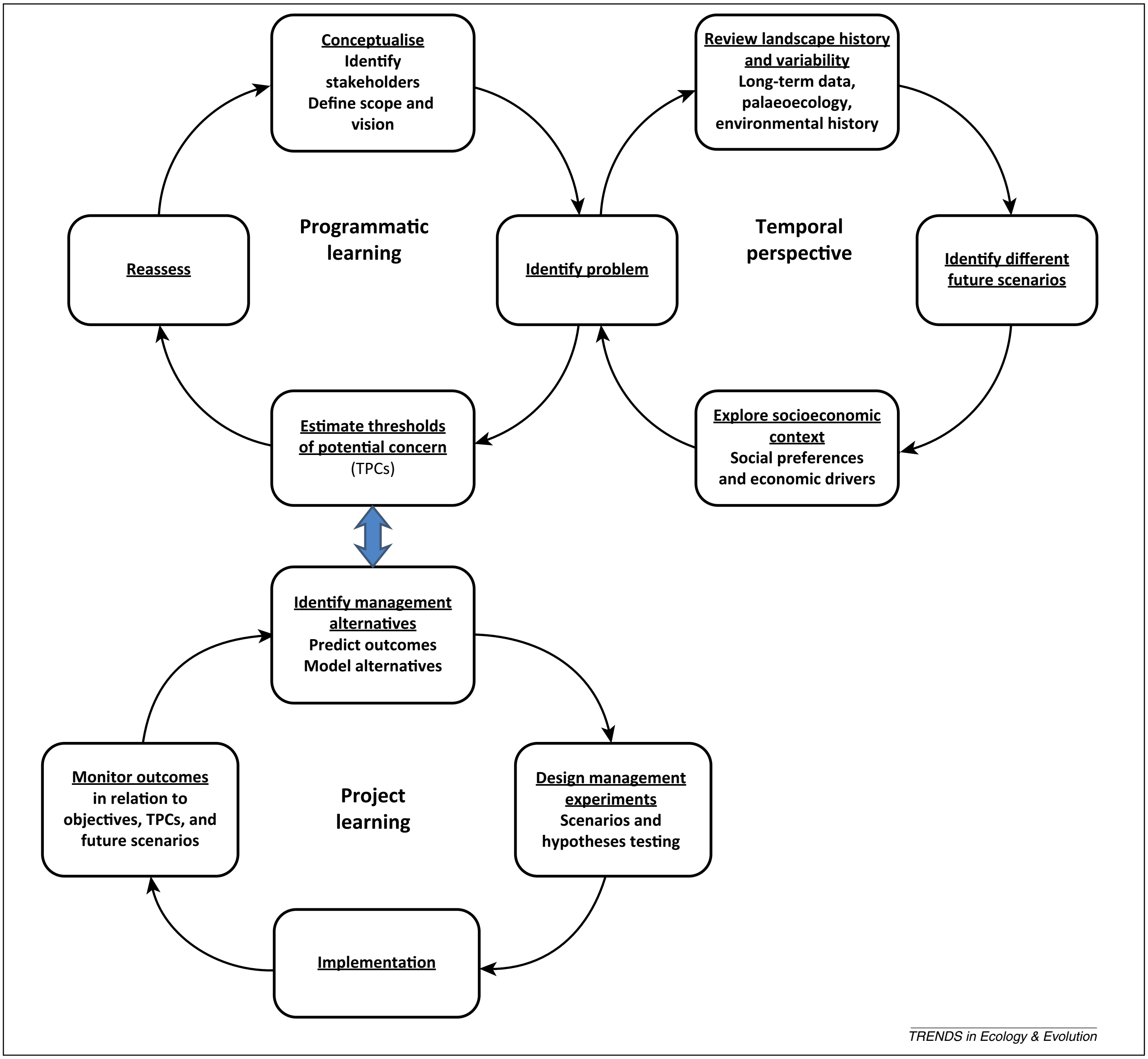

Figure 2. 'Triple loop' adaptive management, expanded and revised from [22], with the addition of a temporal perspective. The three learning loops are programmatic, project, and temporal. Actions are modified to obtain desired outcomes while simultaneously questioning the values, assumptions, and policies that led to the actions in the first place, as well as the underlying beliefs about baseline conditions and the long-term variability and response of the system. Abbreviation: TPCs, thresholds of potential concern.

work into adaptive management is still in the early stages, analysis of current adaptive management projects shows many opportunities for applying long-term data (Table 1).

To consider examples of the use of long-term data sets for enhanced ecosystem management, we draw on information from a series of aquatic and terrestrial case studies (Boxes 1–3). These example of water, forest, fire, and savannah management show how restoration targets are blending disturbance history and human management to conserve secondary, seminatural, and cultural ecosystem composition, disturbance patterns, and structure that reflect and value the past while maintaining traditional management techniques that are culturally important and enrich biodiversity [37–40].

Temporally cognisant management approaches can incorporate variability over time through concepts such as the historical range of variability, limits of acceptable change, and thresholds of potential concern (TPC) (Figure 3; Box 3) [29,32,33,41–44]. These concepts accept heterogeneity and flux as inherent aspects of ecological systems and aim to work within a range of ecosystem variability, rather than striving for a specific ecosystem state. All of these approaches could benefit from collaborative, interdisciplinary research between palaeoecologists, historical ecologists, ecologists, and conservation practitioners, producing insights that are not only additive, but far greater than the sum of the constituent parts.

Table 1. Examples of adaptive management, as reviewed by [20,21] with potential contributions of long-term data from historical ecology and palaeoecology

Adaptive management implementation	Potential for long-term data	Refs
Prescribed burning and fire return interval	Fire return intervals, historic and prehistoric fire regimes (spatial pattern, frequency, and intensity)	[36,41,44,56–61]
Water quality and catchment management	Restoration of pre-industrial water quality (nutrient and sediment loadings, salinity, turbidity, pollution, and pH); effects of changes in water level	[29,32,33,43,62–64]
Forest and woodland restoration	Informing restoration targets in terms of forest composition and structure, in response to management and climate change	[37,39,40,57,65,66]
Climate change and adaptation	Testing model outputs, resilience to climate change, and critical thresholds, individualistic species responses, species reshuffling, and distribution changes	[67–75]
Reintroductions and rewilding	Identifying historic range for *inter-situ* conservation, establishing effects of local extinctions on habitats, information on species type and density for rewilding and reintroduction	[76,77]
Conservation of cultural landscapes	Effects of historic and prehistoric management and land use on biodiversity	[34,38,78–80]
Ecological thresholds and management thresholds	Predicting tipping points; evaluating the realism of thresholds of potential concern	[51,81–84]
Biodiversity, ecological health, and ecosystem integrity	Changes in biodiversity over time, conservation of endangered species, and ecological effects of extinctions	[67,76,85–89]

Management applications and palaeodatabases

There is a wealth of palaeoenvironmental archives, many of which are freely available online (see Table S1 in the supplementary material online) [45–47], that could be interrogated with specific adaptive management goals and TPCs in mind. However, it is up to the palaeoecological community to translate these data into forms that are accessible and useful to conservation scientists, ecosystem managers, and conservation decision makers. Fossil pollen databases are invaluable archives of painstaking microscopic analyses, but unless these data can be embedded in ecological frameworks that allow policy-relevant questions to be asked and answered, they will remain underutilised and the preserve of specialists.

The application of palaeoecology and historical ecology needs to be made explicit, and their data sets made accessible and amenable to management-centred purposes [9]. Therefore, user-friendly interfaces are needed that use calibrated data to provide estimates of long-term change and quantified measures of uncertainty [48]. Useable metrics are needed that show how ecosystems varied in different climatic regimes and under different human–environment

Box 1. Water quality and catchment management

Freshwater ecosystems are particularly amenable to the palaeoecological approach for several reasons. Catchment areas provide clearly defined spatial units that are manageable in size and well understood in terms of process. Lake sediments provide natural multiproxy palaeoarchives that accurately record changes in surrounding vegetation, climate, erosion, and water quality, particularly when accompanied by a tightly constrained chronology. These proxies can be woven together to provide a coherent narrative of cause, effect, and feedbacks over time, which are essential for setting realistic restoration targets [6,23,29].

Palaeohydrology has proved invaluable in the management of water catchments and wetland, river, and estuary restoration projects [29,62]. Water depth and quality can be tracked over time using indicators such as diatoms, aquatic algae, pollen, and spores, all of which provide a long-term record of changing catchment conditions and human impact on salinity, acidity, turbidity, nutrient loading, and pollution. The condition of biodiversity and erosion in surrounding catchment areas can also be tracked through palaeoecological studies [29]. In the Murray River basin, Australia, for example, palaeoecological data showed that a 1985 baseline was a poor restoration target, because it represented a state that was already severely degraded by long-term human impact [6,32]. In Canada, palaeoenvironmental records from lake sediments have been used to quantify the natural range of variability in hydrological conditions of the Slave River Delta and Peace-Athabasca Delta, enabling long-term drying trends and the effects of local water management to be disentangled [33,90,91]. In this case, the palaeoecological data were embedded within a holistic, interdisciplinary framework that included natural science, social science, and traditional knowledge. The aim of these integrated studies was to enhance stewardship of water and associated natural resources and to respond to community and government concerns over environmental change [90].

Box 2. Forest management

Sedimentary sequences are invaluable records of changes in the terrestrial landscape: as well as vegetation and climate, they can also provide information on fire history, herbivory, and the possible influence of humans in manipulating vegetation and fire under different climatic regimes. Thus, a range of insights from palaeoecological data are increasingly being applied in the management and restoration of terrestrial ecosystems, notable examples being the conservation and re-wilding of forests and the management of fire regimes (Table 1, main text) [10,56,78].

In Europe, fossil pollen data have informed debates over woodland restoration and rewilding; specifically regarding how open forest canopies should be, the role of large herbivores, and the effects of past human management [37,92,93]. Frans Vera's wood–pasture hypothesis [92] postulated that woodland glades, created and maintained by large herbivores, would have provided habitat for light-demanding plants, birds, and invertebrates. He suggested that the reintroduction of ponies, deer, and cattle in woodlands would simulate the effects of extinct animals such as the auroch and tarpan. A comparison of fossil pollen in Britain, mainland Europe, and Ireland confirmed the consistent presence of grass pollen, suggesting that open areas were part of the natural woodland structure, although there is still controversy over the role of herbivores in creating or maintaining woodland glades [94,95].

The debate over woodland management in Europe has also considered enrichment of biodiversity following disturbance by humans, who created open habitat, introduced favoured species, and facilitated the spread of less competitive species such as lime (*Tilia*) by harvesting elm (*Ulmus*), a highly valued timber species [93]. In the USA, fire suppression during the early 20th century changed disturbance regimes and forest structure. Now, forest restoration programmes consider the historical range of variability and frequency of fires over timescales of hundreds to thousands of years [41].

Box 3. Implementing adaptive management in the Kruger National Park, South Africa

African savannahs are heterogeneous and dynamic, with a long history of human management. They provide important grazing resources for wild and domestic herbivores underpinning livelihoods for 268 million pastoralists, and habitat for spectacular megafauna that are central to African wildlife conservation and tourist revenue. Although the effects of fire, herbivory, nutrients, and rainfall on savannah structure and function are well studied at local scales, there are few long-term records; therefore, the historic and prehistoric ranges of variability are seldom known. Many protected areas were established in exceptional circumstances, when decades of over-hunting and disease had disrupted local ecology. The landscapes of the first half of the 20th century, when many African protected areas were proclaimed, were likely to have been atypical and transient; tree cover was probably much higher, elephants and other herbivores were at low numbers, and rural populations had been decimated by several famines associated with rinderpest and climate variability: the 'present' at the time of establishment of many protected areas was a poor and unreliable benchmark [96] (Box 1, main text).

The heterogeneity and dynamism of savannahs, as well as their complex history and uncertain future, makes them challenging management targets. Since the 1990s, the Kruger National Park in South Africa has cast aside its old 'command and control' approach to conservation and has become a world leader in the conceptualisation and implementation of strategic adaptive management [19], a transformation facilitated by the rise of nonequilibrium thinking in ecology and the mood of bold, optimistic reinvention that has permeated the fledgling democracy of South Africa. Failed policies, such as regular prescribed burning, elephant culling, and artificial water provision, were overturned and replaced by TPCs that embraced flux and variability [18]. TPCs are core to the mission of the South African National Parks of 'maintain[ing] biodiversity in all of its facets and fluxes' and are defined as a set of operational goals that define the range of desired variability in key ecological parameters, such as fire frequency, extent, river flow, and vegetation structure (Figure 3, main text) [42,97]. Baseline TPCs are developed by observation, monitoring, experiment, and consultation with multiple stakeholders, and are periodically reviewed to consider emerging information, changing societal preferences, and changing ecosystem states. Movement of a parameter to the threshold value triggers management action aimed towards moving back to the desirable zone, and/or more intensive monitoring, followed by possible adjustment of the TPC. For example, the TPC for elephants allows variation in tree cover of up to 80% locally or 30% park-wide, replacing the old, equilibrium goal of stabilising elephant populations at 7000 by culling [18]. Palaeoecological data have been calibrated using modern pollen and vegetation data in accordance with these TPCs to test whether they are ecologically realistic in the light of long-term changes in tree density [96]. Fossil pollen data have revealed that the variability and resilience of tree cover over past centuries and millennia is much less than 80% at the sites studied, and also suggests the need for site-specific TPCs, including TPCs for grassland areas, which are currently being subsumed by rapid tree encroachment [52,96].

interactions. Measures of erosion, tree cover, fire frequency, and water quality, for example, can be derived from palaeoproxies such as magnetic susceptibility, fossil pollen, charcoal, diatoms, fungal spores, pigments, sediment character, phytoliths, and so on. There is vast potential to integrate palaeoecological data and TPCs into the management of a multitude of landscapes. This management–data nexus would provide definite, locally relevant management goals that are nevertheless flexible and responsive to bounded understanding of environmental change and new scientific knowledge.

To develop these interfaces, collaboration will be needed with different potential user groups, including conservation decision makers, ecosystem managers, development agencies, policy makers, and community groups. Such groups can identify relevant questions and develop modelling and simulation tools that allow the outcomes of different management interventions to be simulated under different future scenarios (Figures 1 and 3).

Socioecological context and the wider conservation policy and sustainability arena

With long-term sustainability of ecosystem services and concerns over planetary boundaries high on the policy agenda [3,4,17,49], the palaeocommunity needs to find innovative ways of bridging the gap between human well-being, policy, management, and long-term data. As livelihood and adaptation strategies evolve and entwine within the specific cultural–environmental context, we need to make use of historical archives and archaeological and palaeoecological records to understand the natural range of system variability, and the resilience of socio-ecological systems to past changes in climate, disturbance, and land use (Figure 4) [8,10,24]. For example, palaeodata can provide insights into long-term changes in ecosystem services over time, providing context for interpreting current trajectories in the context of a past–present–future continuum (Figure 1) [1,24,50]. As mentioned above, potentially exciting contributions from palaeoecology could be made in using palaeodata to inform targets on carbon storage, water quality, forest restoration, and fire management, underpinning initiatives aimed towards sustainable use of ecosystem services [51]. Similarly, past water quality and availability can be tracked over decadal–centennial timescales and used to inform current management, supply, and restoration targets. There is potential to integrate these approaches within the framework of Future Earth, a research initiative that aims to mobilise research on sustainability and global change in the context of stronger science–policy partnerships and stakeholder networks (http://www.icsu.org/future-earth).

Although many integrative frameworks exist for combining environmental, ecological, and social concerns (e.g., [3,4,49]), few explicitly incorporate a long-term dimension, and the past–present–future continuum. We suggest that the policy–ecology–environment dynamic framework needs to integrate long-term variability, thresholds and limits of acceptable change with policy-relevant concepts, such as ecosystem services, livelihoods, planetary boundaries, and adaptive management (Figure 4).

Threshold behaviour is of importance to managers and planners because these periods of dramatic change have major impacts on ecosystem services, with little time for society to react, mitigate, or adapt. Palaeoproxies can indicate the position of ecological thresholds and when dramatic changes might occur. The concept of tipping points is well established and numerous palaeoecologists have interpreted their data in terms of thresholds and transitions between alternate stable states [52,53]. These transitions provide clues as to how multiple drivers interact, and what might happen to ecosystem services when climatic or disturbance thresholds are crossed [6,25,53].

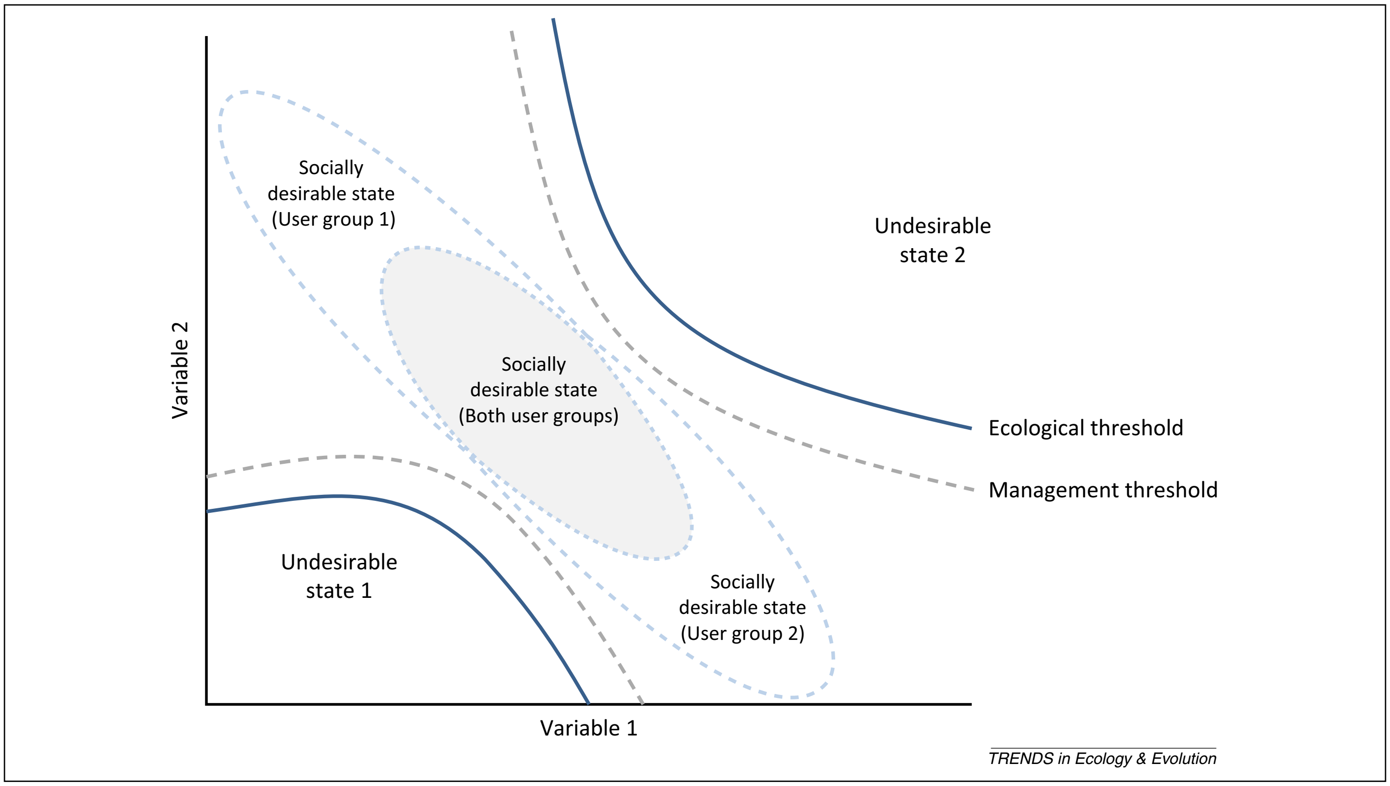

Figure 3. Conceptual diagram showing the interaction between ecological thresholds, management thresholds, and societal preferences in the context of thresholds of potential concern (TPCs), a management tool that defines limits of acceptable change for two interacting variables (axes 1 and 2). The axes can be defined according to locally relevant factors, and/or scaled as appropriate to the variables under study. For example, taking tree cover and elephants as variables 1 and 2, ecologically desirable states could be a stable landscape with few trees and a high elephant population, or a forested landscape with plentiful forest resources and a low elephant population. Management thresholds can be adjusted to accommodate social preferences within the ecologically desirable zone; tourists (user group 1) may prefer a landscape with few trees and many elephant, whereas user group 2 (farmers) may prefer the reverse. A mutually acceptable state can be defined, within the ecologically realistic zone of savannah with some tree cover or different desired states may be defined in different areas, for example, inside and outside of protected areas. The management thresholds are narrower than the ecological thresholds to implement management changes before ecological transitions begin. Developed from [18,97].

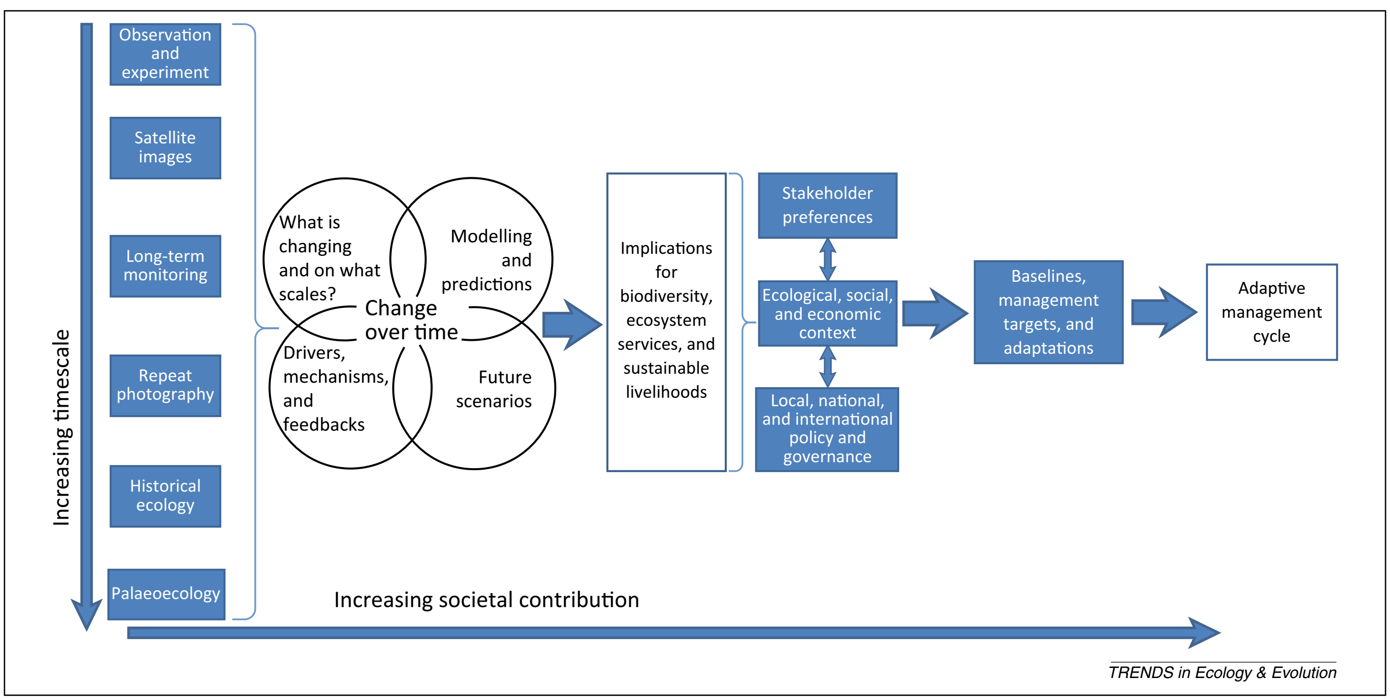

Figure 4. Long-term data in the context of the broader biodiversity conservation and sustainability arena. Knowledge of change over time is central to understanding the changes in ecosystem services, such as water provision, biodiversity, carbon storage, and climate regulation. These services underpin agriculture, forestry, pastoralism, and other livelihoods. Planning realistic management targets and implementing adaptive management cycles will depend on the linkage between changing ecosystem services, stakeholder preferences, social, and economic drivers in the context of local, national, and international policy, such as commitments to biodiversity conservation, carbon emissions reductions, and sustainability.

Before reorganisation, systems may show increasing instability that can provide an early warning of impending change near an ecological threshold [54]. An exciting new development is the interface between palaeoecological data and early warning systems; increasing variability, or 'flickering', can provide a critical window of opportunity for management interventions that can forestall transitions that would otherwise be hard to reverse [54]. Evidence of ecosystem flickering responses can be found in palaeoecological records, and can be used to develop monitoring systems that can distinguish flickering signals from normal background variability [55]. Thus, there is potential to bring palaeoecology into proactive approaches that prevent deleterious changes, rather than struggling later to fix them. Such approaches are especially relevant to safeguard ecosystem services such as good water quality, biodiversity, soil formation, and climate regulation, as well as the human well-being associated with valued wilderness and cultural landscapes (Figure 4).

Concluding remarks

The integration of long-term perspectives into adaptive ecosystem management and biodiversity conservation has begun, and concrete examples of applied palaeoecology and historical ecology are now starting to emerge, particularly in freshwater management, restoration ecology, fire management, and forest conservation. Adaptive ecosystem management provides an ideal interface between long-term ecology and conservation ecology, but two major barriers need to be overcome: the generally short-term nature of conservation goals and management plans, and the inaccessibility of palaeodata to nonspecialists. A way forward will be in seeking cross-cutting frameworks, such as TPCs, ecosystem services, historical range of variability, and early warning systems, that naturally incorporate a temporal perspective and provide a way of managing for an uncertain future at a range of scales and integrating a social dimension into adaptive management. Such frameworks allow consideration of livelihoods, and human well-being, including the cultural, societal, aesthetic, and recreational aspirations of societies in the context of national and global biodiversity conservation and environmental commitments to biodiversity conservation, sustainability, and climate change mitigation.

Acknowledgements

We thank the World Universities Network research mobility scheme for the grant that facilitated this collaboration. Two anonymous reviewers and Philip Platts provided helpful insights into an earlier version of the text. We thank Steve Rocliffe for drafting figure 1.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.tree.2014.03.010.

References

1 Dawson, T.P. *et al.* (2011) Beyond predictions: biodiversity conservation in a changing climate. *Science* 332, 53–58
2 Sgrò, C.M. *et al.* (2011) Building evolutionary resilience for conserving biodiversity under climate change. *Evol. Appl.* 4, 326–337
3 Griggs, D. *et al.* (2013) Policy: sustainable development goals for people and planet. *Nature* 495, 305–307
4 Glaser, G. (2012) Policy: base sustainable development goals on science. *Nature* 491, 35
5 Gillson, L. *et al.* (2013) Accommodating climate change contingencies in conservation strategy. *Trends Ecol. Evol.* 28, 135–142
6 Dearing, J.A. *et al.* (2012) Navigating the perfect storm: research strategies for socio-ecological systems in a rapidly evolving world. *Environ. Manag.* 49, 767–775
7 Conroy, M.J. *et al.* (2011) Conservation in the face of climate change: the roles of alternative models, monitoring, and adaptation in confronting and reducing uncertainty. *Biol. Conserv.* 144, 1204–1213
8 Birks, H.J.B. (2012) Ecological palaeoecology and conservation biology: controversies, challenges, and compromises. *Int. J. Biodivers. Sci. Ecosys. Serv. Manag.* 8, 292–304
9 Marchant, R. and Lane, P. (2013) Past perspectives for the future: foundations for sustainable development in East Africa. *J. Archaeol. Sci.* (in press)
10 Angelstam, P. *et al.* (2013) Knowledge production and learning for sustainable landscapes: seven steps using social–ecological systems as laboratories. *Ambio* 42, 116–128
11 Davies, A. and Bunting, M. (2010) Applications of palaeoecology in conservation. *Open Ecol. J.* 3, 54–67
12 Westgate, M.J. *et al.* (2013) Adaptive management of biological systems: a review. *Biol. Conserv.* 158, 128–139
13 Settele, J. *et al.* (2012) Scenarios as a tool for large-scale ecological research: experiences and legacy of the ALARM project. *Global Ecol. Biogeogr.* 21, 1–4
14 Spangenberg, J.H. *et al.* (2012) Scenarios for investigating risks to biodiversity. *Global Ecol. Biogeogr.* 21, 5–18
15 Diffenbaugh, N.S. and Field, C.B. (2013) Changes in ecologically critical terrestrial climate conditions. *Science* 341, 486–492
16 Gaylard, A. and Ferreira, S. (2011) Advances and challenges in the implementation of strategic adaptive management beyond the Kruger National Park: making linkages between science and biodiversity management. *Koedoe* 53, 52–59
17 Hughes, T.P. *et al.* (2013) Multiscale regime shifts and planetary boundaries. *Trends Ecol. Evol.* 28, 389–395
18 van Wilgen, B.W. and Biggs, H.C. (2011) A critical assessment of adaptive ecosystem management in a large savanna protected area in South Africa. *Biol. Conserv.* 144, 1179–1187
19 Keith, D.A. *et al.* (2011) Uncertainty and adaptive management for biodiversity conservation. *Biol. Conserv.* 144, 1175–1178
20 McFadden, J.E. *et al.* (2011) Evaluating the efficacy of adaptive management approaches: is there a formula for success? *J. Environ. Manag.* 92, 1354–1359
21 Rist, L. *et al.* (2012) Adaptive management: where are we now? *Environ. Conserv.* 1, 1–14
22 Fontaine, J.J. (2011) Improving our legacy: incorporation of adaptive management into state wildlife action plans. *J. Environ. Manag.* 92, 1403–1408
23 Dearing, J.A. (2008) Landscape change and resilience theory: a palaeoenvironmental assessment from Yunnan, SW China. *Holocene* 18, 117–127
24 Dearing, J.A. *et al.* (2012) Extending the timescale and range of ecosystem services through paleoenvironmental analyses, exemplified in the lower Yangtze basin. *Proc. Natl. Acad. Sci. U.S.A.* 109, E1111–E1120
25 Briske, D.D. *et al.* (2010) Catastrophic thresholds: a synthesis of concepts, perspectives, and applications. *Ecol. Soc.* 15, 1–12
26 Willis, K.J. *et al.* (2010) Biodiversity baselines, thresholds and resilience: testing predictions and assumptions using palaeoecological data. *Trends Ecol. Evol.* 25, 583–591
27 Brown, G.G. and Squirrell, T. (2010) Organizational learning and the fate of adaptive management in the US Forest Service. *J. Forest.* 108, 379–388
28 Seidl, R. and Lexer, M.J. (2012) Forest management under climatic and social uncertainty: trade-offs between reducing climate change impacts and fostering adaptive capacity. *J. Environ. Manag.* 114, 461–469
29 Bennion, H. *et al.* (2011) Defining reference conditions and restoration targets for lake ecosystems using palaeolimnology: a synthesis. *J. Paleolimnol.* 45, 533–544
30 Wilmshurst, J.M. *et al.* (2013) Use of pollen and ancient DNA as conservation baselines for offshore islands in New Zealand. *Conserv. Biol.* 28, 202–212

31 Gillson, L. *et al.* (2011) Baselines, patterns and process. In *Conservation Biogeography* (Ladle, R.J. and Whittaker, R.J., eds), pp. 31–44, Blackwell Publishing
32 Gell, P. *et al.* (2012) A legacy of climate and catchment change: the real challenge for wetland management. *Hydrobiologia* 708, 133–144
33 Wolfe, B.B. *et al.* (2012) Developing temporal hydroecological perspectives to inform stewardship of a northern floodplain landscape subject to multiple stressors: paleolimnological investigations of the Peace–Athabasca Delta. *Environ. Rev.* 20, 191–210
34 Bjorkman, A.D. and Vellend, M. (2010) Defining historical baselines for conservation: ecological changes since European settlement on Vancouver Island, Canada. *Conserv. Biol.* 24, 1559–1568
35 Roberts, D.R. and Hamann, A. (2011) Predicting potential climate change impacts with bioclimate envelope models: a palaeoecological perspective. *Global Ecol. Biogeogr.* 21, 121–133
36 Huerta, M.A. *et al.* (2009) Holocene vegetation–fire–climate linkages in northern Yellowstone National Park, USA. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 271, 170–181
37 Davies, A.L. (2011) Long-term approaches to native woodland restoration: palaeoecological and stakeholder perspectives on Atlantic forests of Northern Europe. *Forest Ecol. Manag.* 261, 751–763
38 Davies, A.L. and Watson, F. (2007) Understanding the changing value of natural resources: an integrated palaeoecological-historical investigation into grazing-woodland interactions by Loch Awe, Western Highlands of Scotland. *J. Biogeogr.* 34, 1777–1791
39 Brown, A.D. (2010) Pollen analysis and planted ancient woodland restoration strategies: a case study from the Wentwood, southeast Wales, UK. *Vegetation Hist. Archaeobotany* 19, 79–90
40 Waller, M. (2010) Ashtead Common, the evolution of a cultural landscape: a spatially precise vegetation record for the last 2000 years from southeast England. *Holocene* 20, 733–746
41 Long, J.N. (2009) Emulating natural disturbance regimes as a basis for forest management: a North American view. *Forest Ecol. Manag.* 257, 1868–1873
42 McLoughlin, C.A. *et al.* (2011) History, rationale, and lessons learned: thresholds of potential concern in Kruger National Park river adaptive management. *Koedoe* 53, 69–95
43 Battarbee, R.W. and Bennion, H. (2011) Palaeolimnology and its developing role in assessing the history and extent of human impact on lake ecosystems. *J. Paleolimnol.* 45, 399–404
44 Cyr, D. *et al.* (2009) Forest management is driving the eastern North American boreal forest outside its natural range of variability. *Front. Ecol. Environ.* 7, 519–524
45 Battarbee, R.W. *et al.* (2011) A palaeolimnological meta-database for assessing the ecological status of lakes. *J. Paleolimnol.* 45, 405–414
46 Mitchell, F.J. (2011) Exploring vegetation in the fourth dimension. *Trends Ecol. Evol.* 26, 45–52
47 Daniau, A.L. *et al.* (2012) Predictability of biomass burning in response to climate changes. *Global Biogeochem. Cycles* 26, GB4007
48 Brewer, S. *et al.* (2012) Paleoecoinformatics: applying geohistorical data to ecological questions. *Trends Ecol. Evol.* 27, 104–112
49 Carpenter, S.R. *et al.* (2009) Science for managing ecosystem services: beyond the Millennium Ecosystem Assessment. *Proc. Natl. Acad. Sci. U.S.A.* 106, 1305–1312
50 Moritz, C. and Agudo, R. (2013) The future of species under climate change: resilience or decline? *Science* 341, 504–508
51 Jackson, S.T. *et al.* (2009) Paleoecology and resource management in a dynamic landscape: case studies from the Rocky Mountain headwaters region. *Paleontol. Soc. Papers* 15, 61–80
52 Gillson, L. and Ekblom, A. (2009) Resilience and thresholds in savannas: nitrogen and fire as drivers and responders of vegetation transition. *Ecosystems* 12, 1189–1203
53 Virah-Sawmy, M. *et al.* (2009) Threshold response of Madagascar's littoral forest to sea-level rise. *Global Ecol. Biogeogr.* 18, 98–110
54 Dakos, V. *et al.* (2013) Flickering as an early warning signal. *Theor. Ecol.* 6, 309–317
55 Wang, R. *et al.* (2012) Flickering gives early warning signals of a critical transition to a eutrophic lake state. *Nature* 492, 419–422
56 Gavin, D.G. *et al.* (2007) Forest fire and climate change in western North America: insights from sediment charcoal records. *Front. Ecol. Environ.* 5, 499–506
57 Williams, M.A. and Baker, W.L. (2013) Variability of historical forest structure and fire across ponderosa pine landscapes of the Coconino Plateau and south rim of Grand Canyon National Park, Arizona, USA. *Landscape Ecol.* 28, 297–310
58 Marlon, J.R. *et al.* (2012) Long-term perspective on wildfires in the western USA. *Proc. Natl. Acad. Sci. U.S.A.* 109, E535–E543
59 Girardin, M.P. *et al.* (2011) Wildfires in boreal ecosystems: past, present and some emerging trends. *Int. J. Wildland Fire* 19, 991–995
60 Whitlock, C. *et al.* (2010) Paleoecological perspectives on fire ecology: revisiting the fire-regime concept. *Open Ecol. J.* 3, 6–23
61 Carcaillet, C. *et al.* (2009) Spatial variability of fire history in subalpine forests: from natural to cultural regimes. *Ecoscience* 16, 1–12
62 Sayer, C.D. *et al.* (2012) The application of palaeolimnology to evidence-based lake management and conservation: examples from UK lakes. *Aquat. Conserv. Marine Freshwater Ecosyst.* 22, 165–180
63 Grundell, R. *et al.* (2012) Interaction between a river and its wetland: evidence from the Murray River for spatial variability in diatom and radioisotope records. *J. Paleolimnol.* 47, 205–219
64 Battarbee, R. *et al.* (2012) Combining limnological and palaeolimnological data to disentangle the effects of nutrient pollution and climate change on lake ecosystems: problems and potential. *Freshwater Biol.* 57, 2091–2106
65 Urquhart, G.R. (2009) Paleoecological record of hurricane disturbance and forest regeneration in Nicaragua. *Quaternary Int.* 195, 88–97
66 Petit, R.J. *et al.* (2008) Forests of the past: a window to future changes. *Science* 320, 1450–1452
67 Bush, M.B. and Lovejoy, T.E. (2007) Amazonian conservation: pushing the limits of biogeographical knowledge. *J. Biogeogr.* 34, 1291–1293
68 Behling, H. and Pillar, V.D. (2007) Late Quaternary vegetation, biodiversity and fire dynamics on the southern Brazilian highland and their implication for conservation and management of modern Araucaria forest and grassland ecosystems. *Philos. Trans. R. Soc. Lond. B: Biol. Sci.* 362, 243–251
69 Blois, J.L. *et al.* (2012) Modeling the climatic drivers of spatial patterns in vegetation composition since the Last Glacial Maximum. *Ecography* 36, 460–473
70 Böhner, J. and Lehmkuhl, F. (2005) Environmental change modelling for Central and High Asia: Pleistocene, present and future scenarios. *Boreas* 34, 220–231
71 Botkin, D.B. *et al.* (2007) Forecasting the effects of global warming on biodiversity. *Bioscience* 57, 227–236
72 Bush, M. *et al.* (2010) Nonlinear climate change and Andean feedbacks: an imminent turning point? *Global Change Biol.* 16, 3223–3232
73 Collins, J. *et al.* (2013) Abrupt shifts of the Sahara–Sahel boundary during Heinrich stadials. *Clim. Past* 9, 1181–1191
74 Jackson, S.T. *et al.* (2009) Ecology and the ratchet of events: climate variability, niche dimensions, and species distributions. *Proc. Natl. Acad. Sci. U.S.A.* 106 (Suppl. 2), 19685–19692
75 Williams, J.W. *et al.* (2011) Extrinsic and intrinsic forcing of abrupt ecological change: case studies from the late Quaternary. *J. Ecol.* 99, 664–677
76 Wood, J.R. *et al.* (2012) A lost link between a flightless parrot and a parasitic plant and the potential role of coprolites in conservation paleobiology. *Conserv. Biol.* 26, 1091–1099
77 Burney, D.A. and Burney, L.P. (2007) Paleoecology and 'inter-situ' restoration on Kaua'i, Hawai'i. *Front. Ecol. Environ.* 5, 483–490
78 Grant, M. and Edwards, M. (2008) Conserving idealized landscapes: past history, public perception and future management in the New Forest (UK). *Vegetation Hist. Archaeobotany* 17, 551–562
79 Chambers, F.M. *et al.* (2007) Recent vegetation history of Drygarn Fawr (Elenydd SSSI), Cambrian Mountains, Wales: implications for conservation management of degraded blanket mires. *Biodiversity and Conservation* 16, 2821–2846
80 Chambers, F. *et al.* (2013) Long-term ecological study (palaeoecology) to chronicle habitat degradation and inform conservation ecology: an exemplar from the Brecon Beacons, South Wales. *Biodivers. Conserv.* 22, 719–736
81 Blarquez, O. and Carcaillet, C. (2010) Fire, fuel composition and resilience threshold in subalpine ecosystem. *PLoS ONE* 5, e12480
82 Tzedakis, P.C. *et al.* (2004) Ecological thresholds and patterns of millennial-scale climate variability: the response of vegetation in Greece during the last glacial period. *Geology* 32, 109–112

83 Carrión, J.S. *et al.* (2001) Crossing forest thresholds. Inertia and collapse in a Holocene sequence from south-central Spain. *Holocene* 11, 635–653
84 Chapin, F.S. *et al.* (2004) Global change and the boreal forest: thresholds, shifting states or gradual change? *Ambio* 33, 361–365
85 Hanley, N. *et al.* (2009) What drives long-run biodiversity change? New insights from combining economics, palaeoecology and environmental history. *J. Environ. Econ. Manag.* 57, 5–20
86 Burney, D.A. and Flannery, T.F. (2005) Fifty millennia of catastrophic extinctions after human contact. *Trends Ecol. Evol.* 20, 395–401
87 Ellison, A.M. *et al.* (2005) Loss of foundation species: consequences for the structure and dynamics of forested ecosystems. *Front. Ecol. Environ.* 3, 479–486
88 Jackson, S.T. and Sax, D.F. (2010) Balancing biodiversity in a changing environment: extinction debt, immigration credit and species turnover. *Trends Ecol. Evol.* 25, 153–160
89 Jackson, S.T. (2006) Vegetation, environment, and time: the origination and termination of ecosystems. *J. Vegetation Sci.* 17, 549–557
90 Wolfe, B.B. *et al.* (2007) From isotopes to TK interviews: towards interdisciplinary research in Fort Resolution and the Slave River Delta, Northwest Territories. *Arctic* 60, 75–87
91 Wiklund, J.A. *et al.* (2012) Timescales of hydrolimnological change in floodplain lakes of the Peace-Athabasca Delta, northern Alberta, Canada. *Ecohydrology* 5, 351–367
92 Vera, F. (2000) *Grazing Ecology and Forest History*, CAB International
93 Tipping, R. *et al.* (1999) Woodland biodiversity, palaeo-human ecology and some implications for conservation management. *J. Biogeogr.* 26, 33–43
94 Mitchell, F.J. (2005) How open were European primeval forests? Hypothesis testing using palaeoecological data. *J. Ecol.* 93, 168–177
95 Birks, H.J.B. (2005) Mind the gap: how open were European primeval forests? *Trends Ecol. Evol.* 20, 154–156
96 Gillson, L. and Duffin, K.I. (2007) Thresholds of Potential Concern as benchmarks in the management of African savannahs. *Philos. Trans. R. Soc. Lond. B: Biol. Sci.* 362, 309–319
97 Biggs, H. *et al.* (2011) Taking stock after a decade: does the 'thresholds of potential concern' concept need a socioecological revamp? *Koedoe* 53, 60–68