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EDITORIAL

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Human–environment interactions: learning from the past

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Abstract The analysis of palaeoenvironmental archives—sediments, archaeological remains, tree-rings, documents and instrumental records—is presented as a key element in the global scientific endeavour aimed at understanding human–environment interactions at the present day and in the future. The paper explains the need for the focus on palaeoenvironmental studies as a means of 'learning from the past', and presents the rationale and structure of the IGBP-PAGES Focus 5 programme 'Past Ecosystem Processes and Human–Environment Interactions'. The past, as described through palaeoenvironmental studies, can yield information about pre-impact states, trajectories of recent change, causation, complex system behaviour, and provide the basis for developing and testing simulation models. Learning from the past in each of these epistemological categories is exemplified with published case-studies.

Keywords PAGES Focus 5 · Human–environment interactions · Palaeoenvironmental reconstruction · Sustainability

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Introduction

> Where time is required for an experiment there's no substitute for history (Deevey 1969).

One of the most influential insights into recent climate change has come from linking carefully calibrated and spatially aggregated proxy-based temperature reconstructions to the instrumental record (e.g. Mann et al. 1998; Mann and Jones 2003; Moberg et al. 2005). Linkage has involved both calibration over a time interval where proxy records in tree-ring series and sediments, and instrumental records can be directly compared, as well as harmonisation of the two types of series on a hemispheric or global basis. The power of the final products may be judged both from their crucial contribution to the most recent report from the International Panel on Climate Change (IPCC 2001), and from the lengths to which climate change sceptics have tried (unsuccessfully) to discredit the main conclusions drawn regarding late 20th century temperatures in the longer term context (e.g. Soon and Baliunas 2003; Soon et al. 2003). What has become popularly known as the 'hockey stick' graph has, despite subsequent qualifications, shifted the scope and focus of debate on climate change.

Looking beyond the single issue of late 20th century warming, what are the fundamental insights arising from finely resolved reconstructions of the long-term climate variability? They provide a vital insight into the incidence and duration of extreme events beyond the range captured during the brief, recent period of instrumental records. They allow a much more realistic appraisal of the dominant modes of climate variability as their amplitudes, frequencies, spatial domains and teleconnections change over time. They set current values and trends into a longer-term context. They provide a basis for exploring the changing relative importance of the main forcing and feedback mechanisms that influence climate. They also add to the empirical 'ground truth' against which models developed to simulate future climate scenarios may be tested for their skill in reproducing realistic representations of past variability (Oldfield 2005). A concerted approach to these issues, uniting both present day climatologists and palaeo-scientists and typified by the joint CLIVAR (CLimate VARiability and predictabiity)–PAGES (PAst Global chanGES) initiative (Alverson and Villvock 2000), has been crucial to the success of this work.

Where the issue is less about the natural and anthropogenic drivers of climate change but more about the sustainability of ecosystem processes and services in the face of human pressures, past records have also been utilised to good effect. Steffen et al. (2004) summarise the recent changes in several sets of global processes and human conditions (Fig. 1). The selected records show accelerated change over the past few decades for different types of human activities and impacts on the earth system. However, while an appraisal of impacts at the global scale is desirable, the shift in focus from climate change to processes operating within human-dominated environmental systems (Messerli et al. 2000) also requires a significant change in perspective *from the global towards the regional and local*. This change accommodates the shift from dominantly systemic impacts like global warming, to cumulative impacts like losses of habitat and biodiversity, water and air pollution, and accelerated soil erosion (Turner et al. 1990). It engages with the appropriate scale at which 'downscaled' climate projections provide for impact assessments and the formulation of scientific and political strategies for mitigation and adaptation. To understand human–environment interactions at regional scales is therefore relevant to our understanding of environmental change at all scales, and is particularly relevant to the scale of action (and inaction) that controls human states. It is this human dimension of sub-global environmental changes, the need, the international organisation, and the means to learn from the past that are the subjects of this paper.

Human–environment interactions

In terms of human–environment interactions through time, much attention has been focused on well-documented case-studies, particularly those based on archaeological records that demonstrate societal collapse through vulnerability to climate change, environmental maladaptation or a mixture of both (e.g. Redman 1999; Diamond 2005). Drought, in particular, has been one of the factors contributing to major declines in civilisations as diverse as the Maya (Hodell et al. 1995; Haug et al. 2003), Anasazi (Larson et al. 1996), Hohokum (Nials et al. 1989), Tiwanaku (Chepstow-Lusty et al. 1997) and prehistoric cultures in the Atacama and Andean Altiplano (Nuñez et al. 2002) in the New World; likewise the Akkadian (Weiss and Courty 1993; Weiss and Bradley 2001) and Harrapan Empires (Singh et al. 1990; Staubwasser et al. 2003), and groups in the east Mediterranean (Rosen 1995), the Sahara (Hoelzmann et al. 2001; Nicoll 2004), South Africa (Tyson et al. 2002) and China (Huang et al. 2003) in the Old World.

While these and other studies do much to focus attention on the potentially catastrophic nature of social and environmental change they do not necessarily provide relevant analogues for interactions between modern societies and their environment. Moreover, there are other lessons to be learned from past records about the long-term sustainability and management of ecosystems and services. The intention here is to extend this scope to embrace the full spectrum of human–environment interactions. These include the demise of agriculturally marginal systems, but additionally include both the histories of more subtle, adaptive and cumulative changes that provide the background to the majority of human-dominated landscapes, and the natural variability of ecosystems where or when human impact has been low (Oldfield and Dearing 2003).

Many of the scientific methodologies, frameworks and techniques used in reconstructing human–environment interactions are shared with palaeoclimatologists, but with exceptions. For example, consideration of lake-watershed ecosystems as frameworks for integrative research (Oldfield 1977) and comparative studies emphasises that terrestrial ecosystems, drainage systems and lakes are interrelated in a variety of complex ways. Here we describe the PAGES Focus 5 initiative that seeks to embrace all these systems and their interactions as they have responded to changing climate and to human impacts. The initiative involves both agenda setting and coordination. The three strands comprise HITE (Human Impact on Terrestrial Ecosystems), LUCIFS (Land Use and Climate Impacts on Fluvial Systems) and LIMPACS (Impacts on Lake Ecosystems). The papers presented in this volume include research within each strand, as well as more integrative studies. Most of the research has been conceived and pursued independently of PAGES, but the majority of papers were presented to the Reno INQUA Symposia in 2003 that included a special PAGES Focus 5 session. The main purpose behind gathering them together in the present volume is to illustrate some of the ways in which palaeo-research can shed light on current ecosystem dynamics. This publication is one of several early steps along the road to developing the full potential of PAGES Focus 5.

PAGES Focus 5: past ecosystem processes and human–environment interactions

PAGES is a Core Project of the International Geosphere–Biosphere Programme. In 2001, PAGES Focus 5, entitled 'Past Ecosystem Processes and Human–Environment Interactions', was initiated in recognition of the need to move beyond the use of

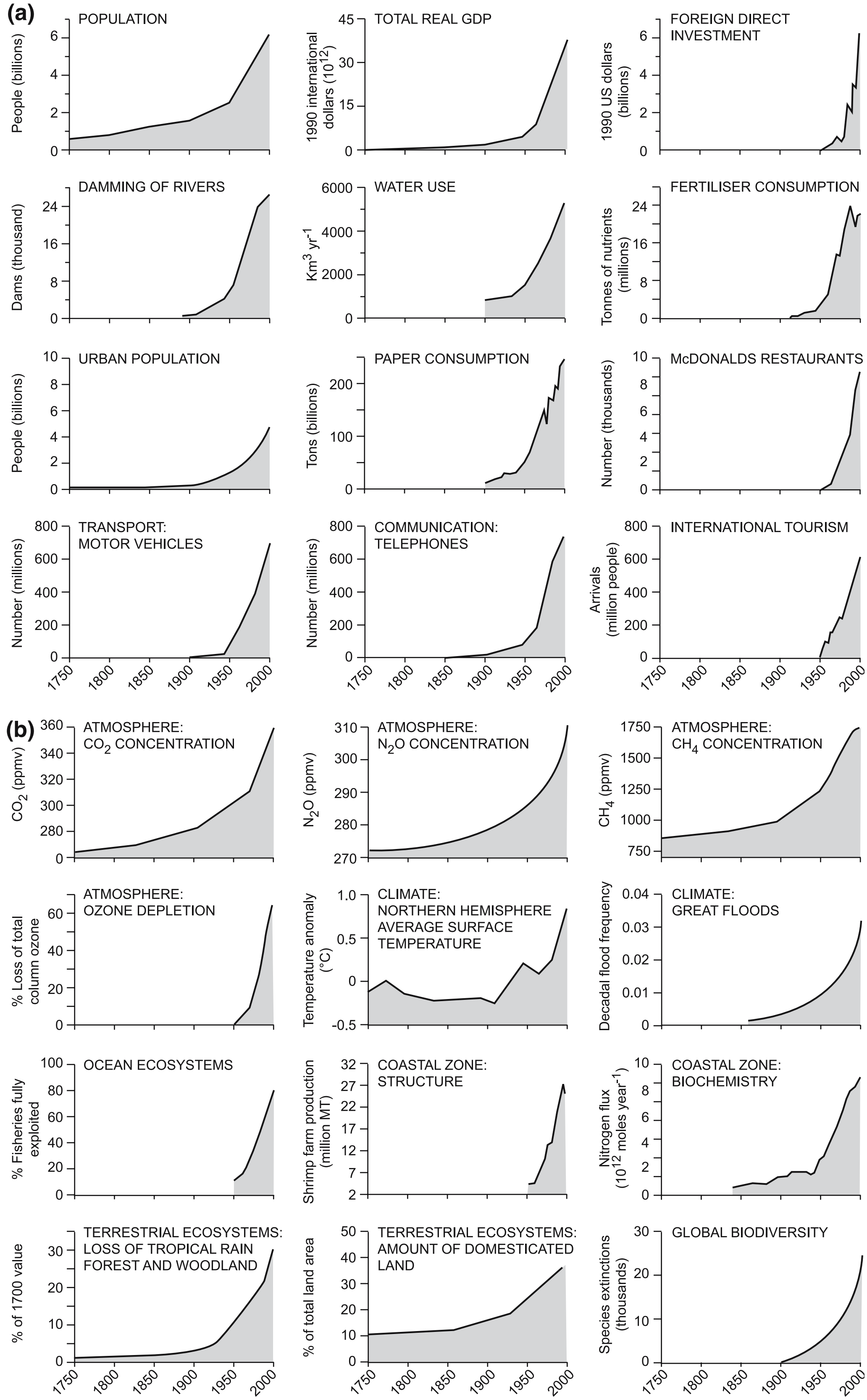

Fig. 1 Global human–environment interactions. Increasing rates of diverse global human activity (**a**), and the corresponding systemic changes to earth system processes (**b**) over the past 250 years, with notable accelerating rates since the 1950s (after Steffen et al. 2004)

palaeoenvironmental studies to reconstruct climate dynamics, and to enhance and coordinate long-term perspectives on terrestrial ecosystems that encompass the human dimension. The need was justified in different ways.

1. The complex relationships that exist between climate and human activities, lying at the heart of modern environmental concerns, are still poorly understood in terms of the role of human activities in generating climate change and the adaptability of human populations to future climate change.
2. The functioning of the majority of modern global ecosystems is in part contingent on a significant history of human impact, demanding that integrated strategies for preservation, conservation or sustainable management of ecosystems incorporate an understanding of long-term responses to climate and human activities.
3. The management and remediation of complex socio-environments increasingly demands the highest level of ecosystem understanding, which may require definition of targets in terms of pre-impact or postulated 'natural' conditions.
4. A large number of researchers have been indirectly involved in Focus 5 science, but fragmented and often poorly coordinated research (often as a result of traditional subject boundaries) has not achieved its potentially high impact.

The diversity of contemporary environmental problems, the unequal geographical distribution of projected human and climate impacts, and the wide range of scientific expertise therefore argued for a significant convergence of priorities and approaches. Thus Focus 5 was set up to promote the integrated use of environmental archives (e.g. sediments and tree-rings), archaeological data (e.g. habitation artefacts), documented histories (e.g. land use inventories) and instrumental records (e.g. meteorology, long-term ecosystem monitoring) to inform about the behaviour of terrestrial ecosystems within the earth system, and their sustainable management. A central aim is to combine these with aspects of *contemporary* ecological/environmental science with a view to understanding better the behaviour of natural ecosystems on different timescales—past, present and future.

The power of perspective

With exceptions, the growth of modern science has not been matched by the monitoring of those environmental processes and conditions that are now seen as essential for generating strategies for sustainable environmental management. The longest monitored record using instruments of any environmental condition is probably the temperature series for central England that stretches back to the 17th century (Manley 1974). But instrumental records for most other environmental conditions are far shorter. Meteorological records for major regional stations and hydrological records for the largest rivers are often available for the last 100 years (e.g. Walling and Fang 2003) but, more locally, and for time-series of other conditions such as vegetation cover, biodiversity, biogeochemical cycles, phytoplankton populations and atmospheric pollution, records are often non-existent or significantly shorter. Some long documentary records provide dates of 'environmentally driven' events, such as the famous phenological series from China, or semi-quantitative information such as the Nile river flood height, stretching back into antiquity (e.g. Nicholson 1998), but these are exceptional. Yet, where long records are available the value of hindsight through a temporal perspective becomes obvious. In any assessment of the modern human–environment condition, a logical step is to make comparisons with the past. The next sections briefly review and exemplify the different ways such comparisons may be made. While they represent epistemological categories, these are mainly for convenience: in practise, they are often combined.

Base-lines and trajectories

Perhaps the simplest use of past time-series is to assess the difference between present conditions and some time in the past that represents less disturbed conditions. This type of analysis has become an increasingly common part of environmental regulation, where there is often a demand to identify and describe a 'base-line' or 'pre-impact' condition that can be used as a reference condition or rehabilitation target. Such demands commonly exist for nature conservation (e.g. Foster et al. 2003b), biodiversity loss (e.g. Scholes and Biggs 2005), forest management (e.g. Bradshaw et al. 2003), fire suppression (e.g. Swetnam et al. 1999) and water quality (e.g. Bennion et al. 2004: EC Water Framework Directive). The concept of 'reference conditions' is now well developed in studies of lake water quality where the chemical and biological status of a lake prior to recent human impact can be inferred from the lake sediment record (Battarbee 1999; Bennion et al. 2004) and used as a restoration target (Fig. 2). However, in some cases, for example lowland lakes suffering from eutrophication, nutrient loading may have taken place over centuries or millennia (Fritz 1989; Bradshaw et al. this issue) and it is consequently difficult to identify a specific stage in time that can be used for reference. This approach is even more difficult to apply in terrestrial ecosystems. For example, Bradshaw et al. (2003) review the palaeoenvironmental evidence of ungulate–vegetation interactions in NW European and conclude that a clear-cut explanation for the role of grazing mammals on forest structure is not possible. In this example, the authors conclude that no pre-impact baseline for contemporary management targets actually exists within the Holocene period.

At regional scales we may also ask about the current *rates of change* in human-affected processes and their

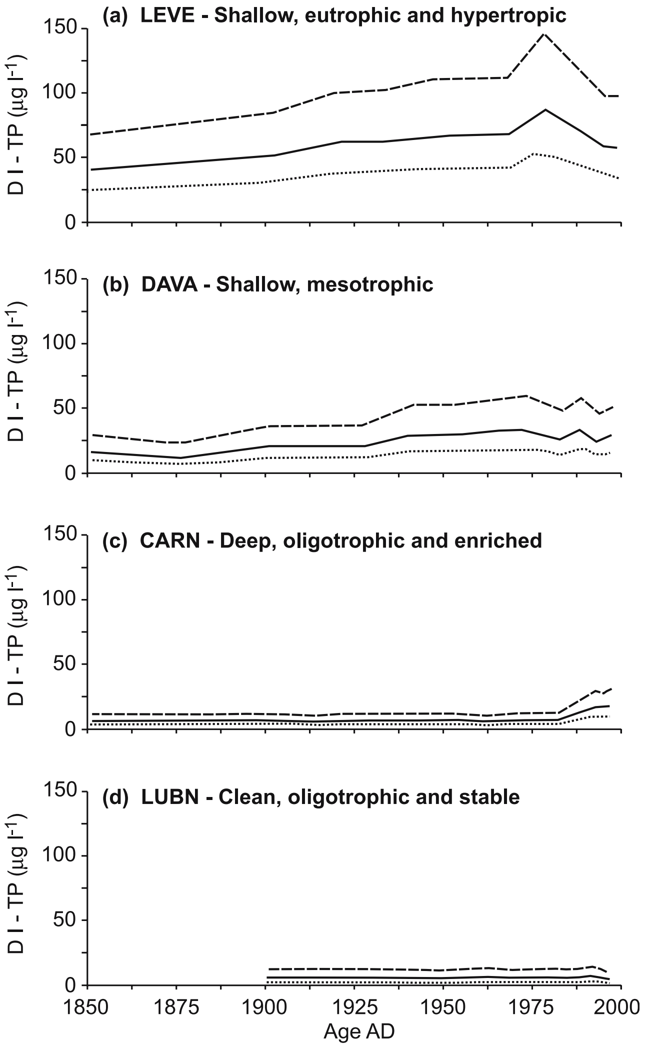

Fig. 2 Baselines and reference conditions. Diatom inferred (DI) records since AD 1850 of total phosphorus (TP) for selected Scottish lochs representing the range of current trophic conditions. The variety of curve shapes and absolute values demonstrates the difficulties of defining the pre-impact or reference conditions for rehabilitation without recourse to long records (re-drawn from Bennion et al. 2004)

direction in relation to both the past and other regional and global records (cf. Fig. 1). For example, records of atmospheric lead (Pb) and mercury (Hg) fallout for the last 3,000 years in Spain show not only the early human impacts and accelerated rises since ~1750 (Fig. 3), but also the contrasting levels of effectiveness in measures to reduce these metal emissions in recent decades. For a different process, regional comparisons of erosion records over the past few hundreds of years reconstructed from lake sediment accumulation rates show a wide range of antecedent curve shapes: accelerating in Papua New Guinea, declining in southern Yucatán, and stationary following initial sharp rises in Michigan (Fig. 4). These records in themselves provide a basis for defining a typology of current trends (in this case, for soil erosion) that can contribute greatly to any evaluation of sustainable land use practises. In some regions it may be possible to reconstruct records for many processes and conditions. A major study in southern Sweden illustrated the diversity of human and environmental 'parallel histories' available from a rigorous analysis of documentary, archaeological, instrumental and sedimentary records (Berglund 1991 and Fig. 1; Dearing et al. this issue).

Spatio-temporal variability and scaling

Ideally, reference to historical points should not assume static environments, but rather dynamic systems. Thus one important type of analysis is to define an envelope of temporal variability. Such concepts have been fundamental to the hydrological sciences for decades where variability is often characterised in terms of 'magnitude and frequency' (e.g. Wolman and Miller 1960). They are also central to the palaeoecological sciences with the use of terms like 'non-equilibrium paradigm' (Swetnam et al. 1999). Thus, the palaeoenvironmental sciences routinely reconstruct past frequency and magnitude time-series to compare with modern conditions. For example, Nott and Hayne (2001) demonstrate that the recurrence interval of 'super-cyclones' along the Great Barrier Reef is an order of magnitude shorter than had previously been calculated, using the period of instrumental measurements. Similarly, Macklin and Lewin (2003) reconstruct the frequency of flooding in Britain through time by aggregating all the available ^{14}C dated alluvial units. Although the magnitude of the events is unknown, the data (Fig. 5) help to answer questions about the relative dominance of climate or land use drivers, and over which timescales. A significant break in the slope of a plot of flood frequency and age suggests that land use has increased the sensitivity of both lowland and upland British environments since ~4,500 years BP. The authors conclude that land use plays a key role in moderating or amplifying the sensitivity to climate.

Compiling *separate* time-series from different sites provides an alternative way of observing spatio-temporal variability. For example, records of fire scars (moderate surface fires) from many sites in SW United States (Fig. 6) show the effects of different combinations of historical grazing regimes and modern fire suppression (Swetnam et al. 1999). Most show a reduction in fire scars from the end of the 19th century, largely as a result of intensive grazing, and modern statistics show that many sites are now at risk from catastrophic 'stand-replacing' fires as dense scrub thickets fuel non-natural fire patterns. Historically reconstructed fire data are now routinely used to define optimum fire suppression strategies.

The problem of scaling is one that lies central to linking local case-studies to global processes. In general, ecological variability increases as spatial and temporal scales become smaller. Thus our appraisal of the factors

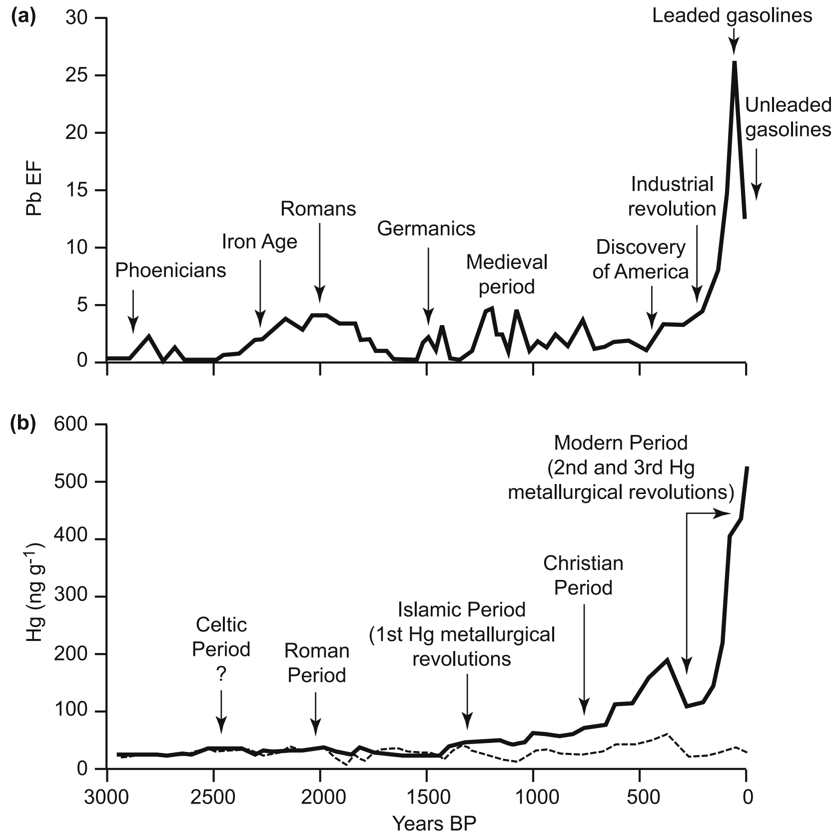

Fig. 3 Baselines and reference conditions. Lead (Pb) enrichment (**a**) and total mercury (Hg) concentrations (**b**) from Penido Vello, a peat profile in N Spain set against a series of historical events, cultural stages and technological changes from 3000 years BP onwards (re-drawn from Martínez-Cortizas et al. 1999)

that control variability is significantly modified by the scale of observation (e.g. Levin 1999). For time, there is the issue of defining the timescale that is relevant to the problem of concern. Over what timescales are the effects of soil conservation measures observable? Which particular flood frequency in the past resonates with climatic variation, and which with the history of deforestation? Extending instrumental records with palaeoenvironmental data can provide a very powerful means for answering such questions, simply because available instrument records may be too short to include the frequencies and timescales of interest. For example, Foster et al. (2003a) showed that the first order drivers of significant change in flooding and erosion at the Annecy lake-catchment, eastern France, shift from land use over millennia to weather conditions over annual timescales, with the two combining in complex ways over timescales of decades and centuries. In Bangladesh, knowledge of the shifts in river courses since the 18th century is fundamental to making accurate assessments of the modern flood risk. Assessments based only on the instrumented flood record for the last 40–50 years are liable to serious misinterpretation (Messerli et al. 2000). These types of conclusion can only be reached with the benefit of an extension of the timescale of observation beyond the instrumental record.

In terms of space, the upscaling of cumulative local changes to the global system, and the downscaling of projected impacts at a continental scale, for example from global climate models, to local environments present significant challenges to earth system science. Dearing and Jones (2003) used lake sediment accumulation rates to calculate the effects of catchment size on the magnitude of the erosional response to disturbance. The dataset produced (Fig. 7) suggests that the sensitivity of the system to disturbance is heavily masked by the increased sediment storage capacity in large catchments: a result that may help explain the high levels of sediment flux to the coasts of SE Asia where catchments are relatively small. But examples of this sort of spatio-temporal scaling are uncommon. Spatially variable system response is not only caused by variations of process types and couplings related to system scale but also by system structure. In geomorphology, Richards (2002) emphasises the role of the drainage network in influencing the effect of environmental change on sediment fluxes in fluvial systems. Network structure and topology (Schmidt and Dikau 1999a, b) can provide important configurational system attributes that help explain within-basin sediment flux and storage.

Process responses

Long time-series of data reflect not just the continuous changes in a process or condition, but the operation and behaviour of the wider system. Multivariate data sets therefore offer the possibility to define system dynamics

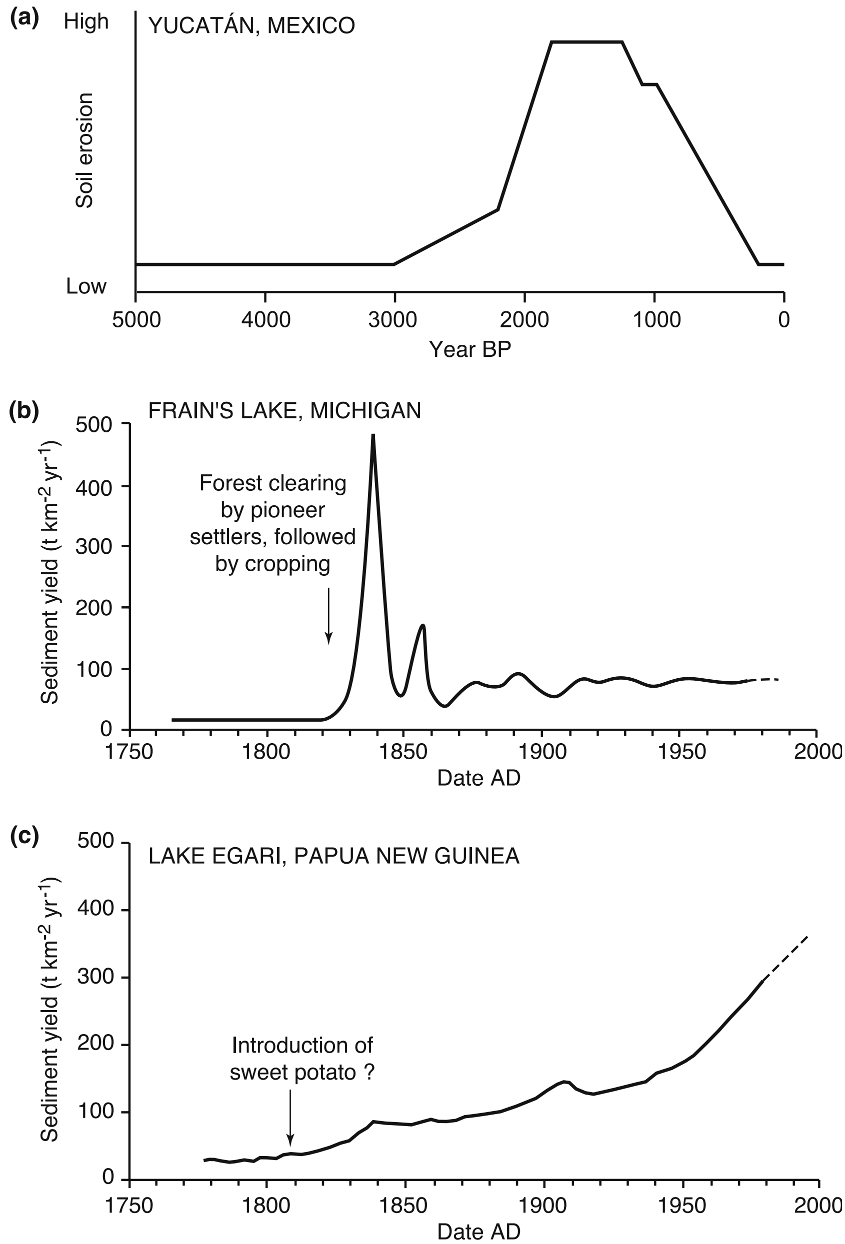

Fig. 4 Trajectories of change. Different trajectories of erosion in small catchments based on reconstructions from lake sediment accumulation rates: **a** declining trend in southern Yucatán, Mexico (Binford et al. 1987); **b** steady trend following initial rise caused by deforestation at Frain's Lake Michigan, USA (Davis 1976); **c** rising trend in Papua New Guinea Highlands (Oldfield et al. 1985)

and to seek cause–effect explanations through inference or experiment. As Swetnam et al. (1999) note, palaeoenvironmental explanation and insight are often derived through inductive reasoning using corroborative and converging lines of evidence from multi-proxy or diverse independent records. Frequently this involves the use of instrumental, documentary and archaeological records to provide independent data for external forcings, like climate and human activities (e.g. Crook et al. 2002, 2004; Elvin et al. 2002), and the use of palaeoenvironmental data for response records (e.g. Catalan et al. 2002). Similarly, this applies to postulated human–environment interactions at large regional and global scales. For example, Ruddiman's recent theory (2003) that global climate was affected by early human impact rests to a large extent on observable correlations between independent proxies for regional forest re-growth driven by epidemics and minima in the CO_2 ice record (Fig. 8).

Learning from the past in this context is often implicit: the argument is made that through past records we learn about the functioning of the system in question for which the present is simply the latest point in time. An exception is the use of analogues, where it is assumed that the past set of conditions closely resembles a present state, or projected future state. Indeed, one of Deevey's arguments (1969) for the power of palaeoenvironmental perspectives included learning from analogues of modern conditions. This line of argument has, as noted above, also been convincingly used by archaeologists and social anthropologists to demonstrate the vulnerability of past human societies and civilisations to natural

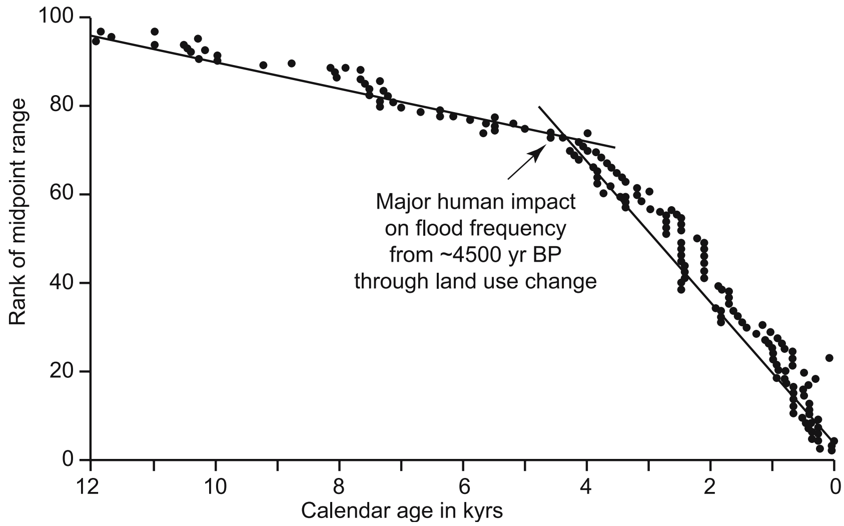

Fig. 5 Past variability. Plots of ^{14}C dated Holocene alluvial units from both upland and lowland catchments in Britain. Trend lines added to original and time axis reversed (Macklin and Lewin 2003)

climate change or events. Self-imposed impacts on support systems through positive feedback from unsustainable practises are recorded widely (e.g. Redman 1999; Diamond 2005). Such case-studies clearly demonstrate the interrelatedness of human actions and biogeophysical processes, and serve to dismiss the notion of environmental determinism: they are strong conveyors of messages about unsustainable practises, and the vulnerability of human society. However, we should be cautious in using them as analogues to inform the construction of adaptation strategies to current and future stresses. This is especially so given the growing realisation that we need to develop new perspectives and research tools that integrate insights from studies of both earth and world system processes. Less common an approach than one centred on inductivism, but scientifically more rigorous and meaningful, is to follow another of Deevey's (1969) arguments and 'let history conduct experiments' within a deductive framework. In this sense, the real value of inductive cause–effect 'explanations' based largely on correlations lies with their generation of testable hypotheses.

Testing hypotheses and post hoc experiments

One of the best palaeoenvironmental examples of using the past to test hypotheses concerns the issue of surface water acidification. From the early 1980s, surface water acidification was recognised as a major international problem that needed scientific and political solutions. A lack of long-term instrumental data for precipitation acidity and water quality meant that there were a number of alternative theories as to its causes: industrial emissions were often cited, but there were also the effects of forestry and even long-term natural biogeochemical cycling to eliminate. Work based on the analysis of diatoms, pollen, trace metals and fly-ash particles in lake sediment records used a hypothesis-testing approach to provide definitive evidence (Fig. 9) for the causes of acidification in the UK (e.g. Battarbee et al. 1985). Different lake records were compiled that allowed scientific control for certain variables, such as geology and the absence or presence of coniferous plantations, and showed that increased precipitation acidity caused by industrial emissions of sulphur and nitrogen oxide gases over 100–200 years was the only plausible explanation. These findings contributed significantly to government decisions in the UK and elsewhere to introduce sulphur emission reduction policies in the late 1980s. Other examples include Barber's (1981) seminal test of competing hypotheses of ombrotrophic peat bog growth that opened the way to what has become a rapidly developing field of research on climate change based on archives and proxies that are, crucially, quite independent of human activities and impacts (Barber and Charman 2003). Similar methodologies are also crucial to unravelling the relative importance of climate change and human activities in the creation and maintenance of human-affected ecosystems, such as the savannah landscape of Dahomey Gap in West Africa (Salzmann and Hoelzmann 2005).

Complex system behaviour

Although cause–effect explanations remain a dominant epistemology, the view from complexity science argues against simple causative explanation. Open, dynamic systems are expected to behave non-linearly with respect to external forcings and their internal organisation (e.g. Phillips 1998, 2003; Levin 1999; Scheffer et al. 2001). External forcings may exert their influence through the transgression of thresholds, there may be time-lags between drivers and responses, and perhaps most importantly a modern system is not separated easily from its past: *we should expect* that it has been conditioned or sensitised by past events, or at least bears the legacy of past forcings and responses. Complexity science also predicts that systems may exhibit self-organisation in the

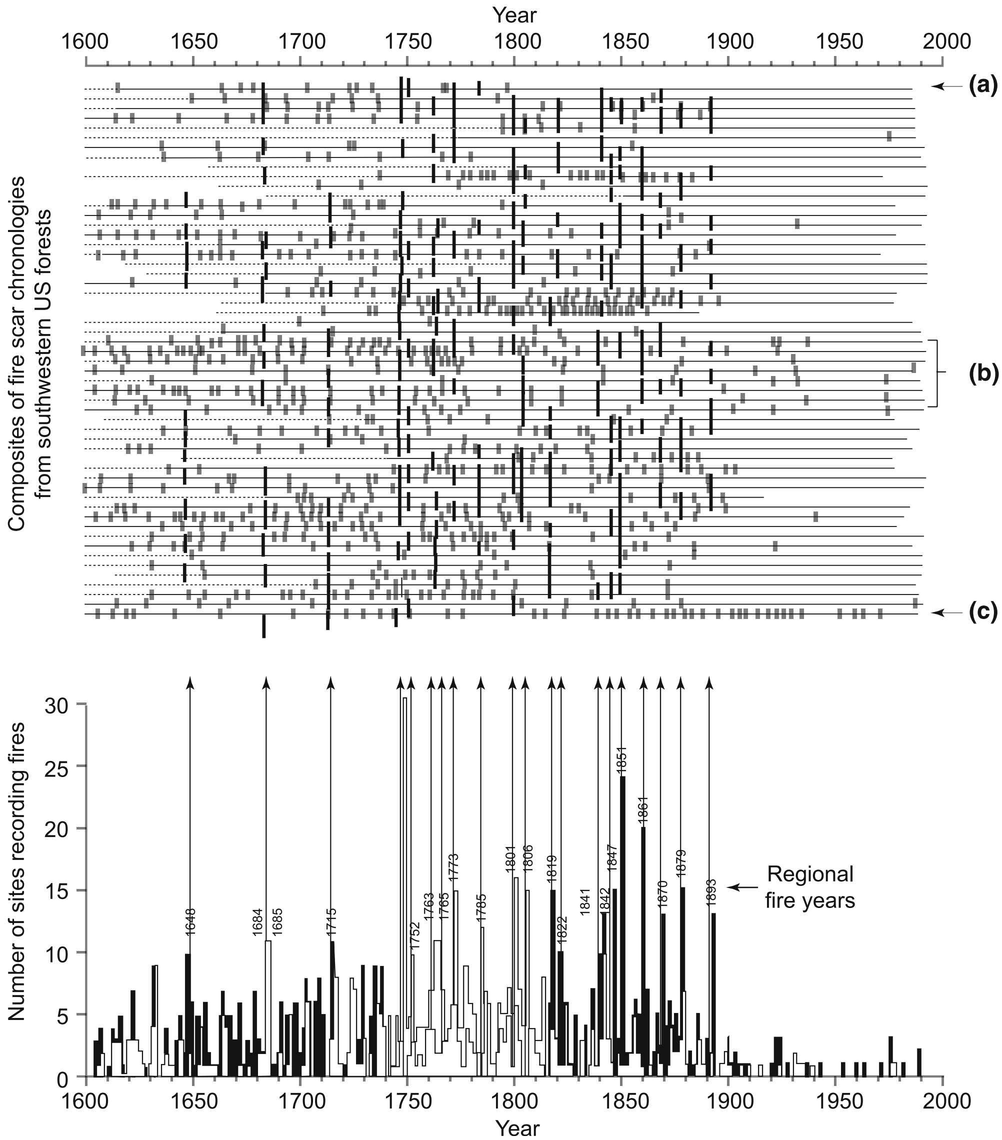

Fig. 6 Past variability. Records of fire scars (*moderate surface fires*) from many sites in SW United States show the effects of different combinations of historical grazing regimes and modern fire suppression. Most show a reduction in fire scars from the end of the 19th century, largely as a result of intensive grazing. Exceptions strengthen this inference, for example, **a** Spanish colonists on traditional Navajos pasturelands since early 19th century; **b** remote area with no grazing, but fire suppression in 20th century; **c** no intensive grazing not fire suppression in 20th century. Modern statistics show that many sites now at risk from catastrophic 'stand-replacing' fires as dense scrub thickets fuel non-natural fire patterns (Swetnam et al. 1999)

form of emergent phenomena: forms and structures that have evolved merely through a network of process interaction within a set of boundary conditions (Hergarten 2002). Understanding the complexity of current systems in these terms is a high priority if we are to avoid environmental surprises at local and global levels (e.g. Amsterdam Declaration 2001). The central point to be made here is that long timescales of observation often enable, uniquely, these non-linearities to be identified.

For terrestrial ecosystems, Foster et al. (2003b) review the importance of land use legacies to ecology and conservation, providing many north American examples of how modern soils, terrestrial ecosystems and aquatic communities are a product of past cultural history. In some examples used, human actions from decades past still reverberate into the present system, while in others the sensitivity of the present system to current forcings has increased because of past impacts. The authors conclude that 'the persistence of land use legacies should inject some cautionary reality to restoration activities'. Elsewhere, studies have utilised mathematical tools to identify certain kinds of system behaviour in high-resolution time-series. For example, several workers (e.g. Dearing and Zolitschka 1999; Gomez et al. 2002) have argued that sedimentary records of erosion events in pre-impact systems exhibit power law behaviour interpretable as self-organised phenomena rather than the direct result of any external

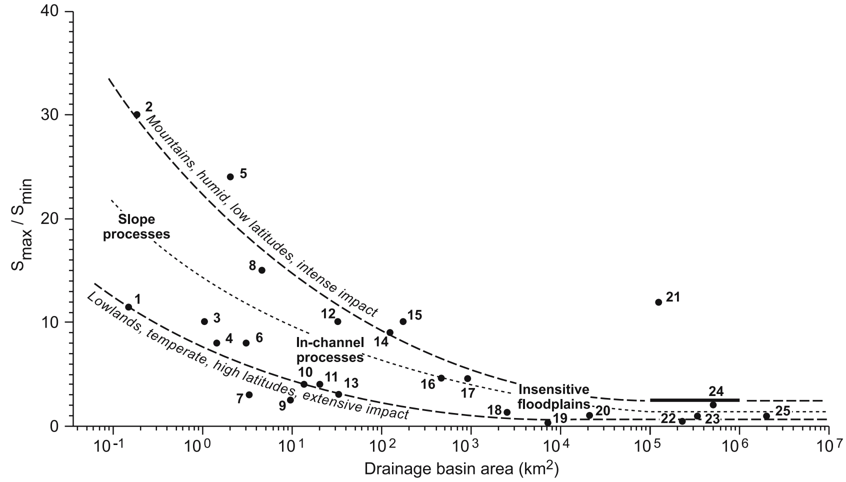

Fig. 7 Spatial scaling. Maximum sediment flux (dimensionless ratio S_{max}/S_{min}) plotted against drainage basin size (km^2) from 25 published case-studies of late-Holocene sediment accumulation rates. Also shown are apparent controls on *upper* and *lower limits*, and the likely trend of increasing decoupling between slope and channel, and increasing sediment storage, as basin area of basin increases. *Horizontal line* (10^5–10^6 km^2) shows maximum range of estimated long-term sediment yields for large Asian rivers (Dearing and Jones 2003)

forcing. Other studies utilise a combination of multivariate analyses and inductive explanation to illustrate complexity. Through a combination of detailed fieldwork and modelling, Trimble (1999) identifies the non-linear responses of the Coon Creek fluvial system to land use and climate, particularly the role of sediment storage within the system that can lead to counter-intuitive sediment responses (Fig. 10). Similarly, Olley and Wasson (2003) show how the sediment flux in the Murrumbidgee River has changed in the last 180 years as a result of only small climate variations and a variety of human impacts that together have produced spatially variable and non-linear relationships between rainfall, runoff and sediment transport capacity. On the basis of these and other examples, Wasson (2002) stresses that although sediment budget analyses through time are rare they are vital for observing the full complexity of erosion and sediment transport processes within catchments.

As regards testing complexity theories applied to aquatic ecosystems, palaeolimnology has already provided key studies. For example, Scheffer et al.'s (1993) work on the trophic trajectories of shallow lakes resulting from eutrophication confirmed the earlier theoretical ideas of hysteretic recovery paths and alternative stable states. Further, recent fossil analyses of experimentally enriched lakes show that nutrient-polluted lakes may exhibit intrinsically greater variance than undisturbed lakes, leading to declines in ecosystem predictability (Cottingham et al. 2001). Together, these studies suggest that the effective management of enriched and recovering lakes may require a much longer temporal perspective than is commonly appreciated, particularly with regard to re-establishment of true, pristine baseline conditions. The timescale of cultural impacts on lakes and the implications for classification and recovery are only now being fully appreciated by lake managers.

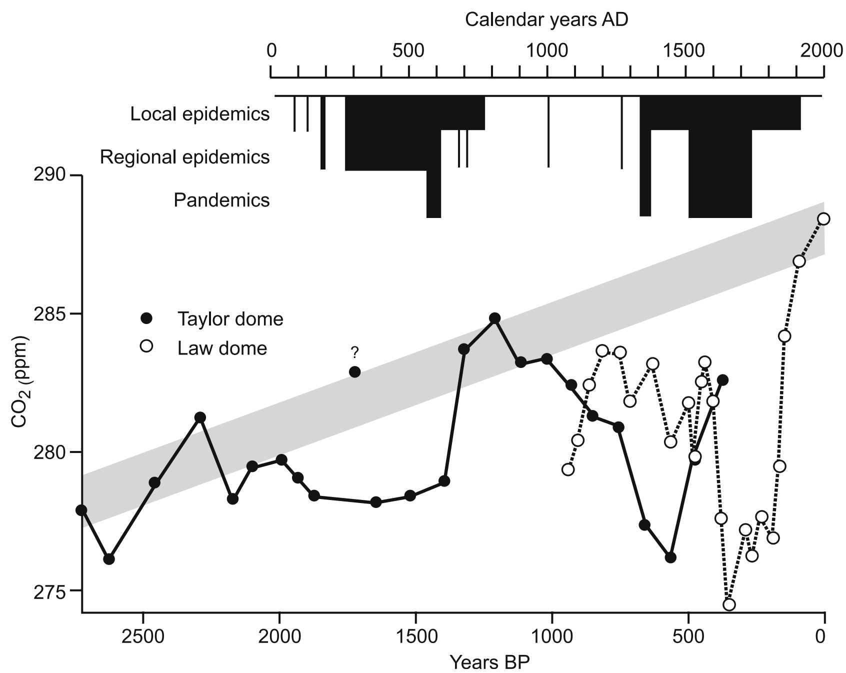

Fig. 8 Process responses. Correlation between intervals of epidemics and pandemics and CO_2 minima in ice cores from Taylor Dome and Law Dome, Antarctica, used as evidence to argue that there is a chain of causality that links the processes of deforestation and land use change to responses in greenhouse gas concentrations. Here, the magnitude and frequency of plague outbreaks are used as a proxy for the amount of land abandonment and forest re-growth linked to a draw down of atmospheric CO_2. *Shaded bar* is a projection of the average rate of CO_2 increase from 8000 years BP to AD 1800 (Ruddiman 2003)

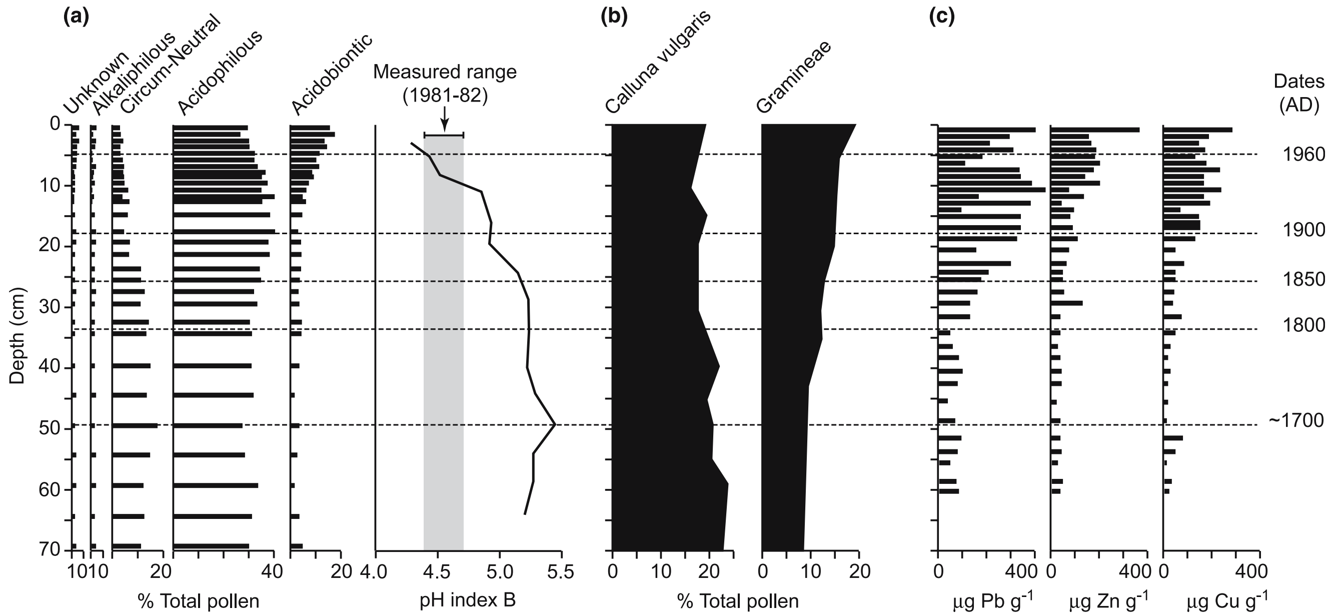

Fig. 9 Testing hypotheses. Summary data from recent (<1700–1980s) sediments in Loch Enoch, Galloway, Scotland showing: **a** diatoms and the reconstructed lake pH; **b** the percentage data for heathland (*Calluna vulgaris*) and grass (Gramineae) pollen and **c** heavy metal concentrations (Pb, Zn and Cu). The timescale is from ^{210}Pb dating (Battarbee et al. 1985)

Simulation modelling

However powerful the insights gained from empirical study and palaeoenvironmental reconstruction, there will always remain gaps in the historical record and uncertainty with regards to explanations as outlined in previous sections. Enhanced levels of confidence in understanding system behaviour are therefore most likely to come through synergy between empirical studies and mathematical simulation modelling. A key measure of the quality of our theoretical understanding of environmental systems has to be the extent to which we can simulate reality. Simulation modelling is

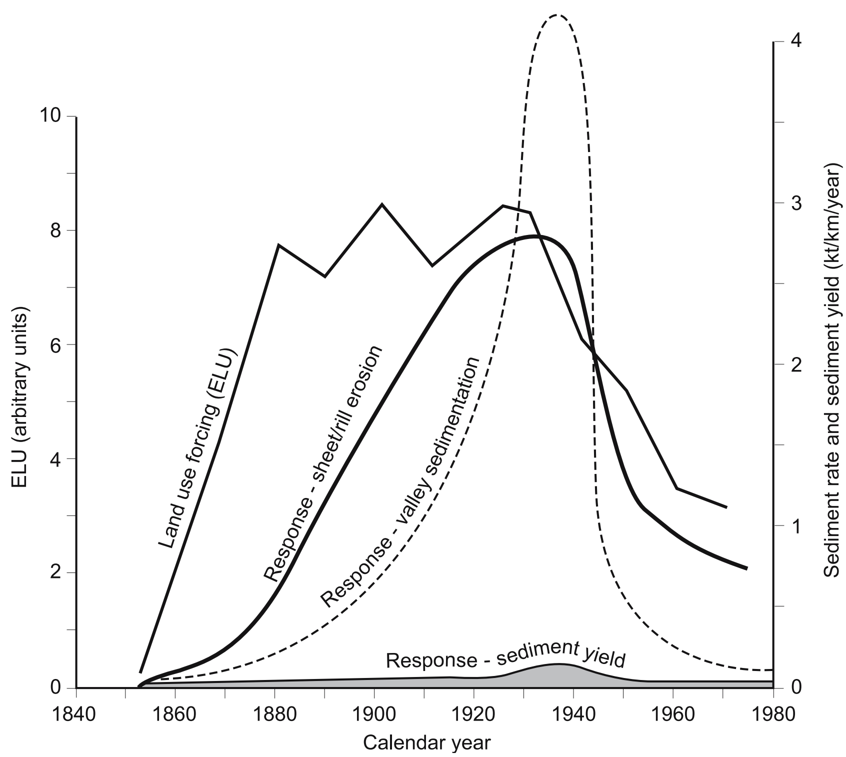

Fig. 10 Complex system behaviour. The complex sediment history of Coon Creek, Wisconsin since AD 1840 based on field mapping, stratigraphy, land use records and erosion models. Note the complex, non-linear and lagged relationships between the land use forcing and response curves for sheet/rill erosion, valley sedimentation and sediment yield recorded at the lower point of the catchment (based on Trimble and Lund 1982; Wasson and Sidorchuk 2000)

therefore a key complement to empirical studies of human–environment interactions and may be used together with palaeoenvironmental data in different ways. For example, model–data comparisons are often used to isolate an individual forcing by controlling for other variables. This is a particularly valuable approach in human interaction studies where a common issue is how to 'isolate' the effect of land use or land cover change, forced by human actions, from the impact of climate change. For terrestrial ecosystems, forest gap models (Bugmann 2001) have been successfully used to simulate the climatic controls on forest composition and treelines through the late-Holocene (e.g. Bugmann and Pfister 2000), validated by comparison with pollen records, and in some studies used to judge the impact of human activities. Cowling et al. (2001) use the forest gap model FORSKA2 to simulate the growth of lime (*Tilia*) and beech (*Fagus*) forest in southern Sweden in order to explain the decline in the former and rise in the latter over the past few centuries. The outputs of the model driven by paleoclimate data are tested against pollen diagrams, representing the observed forest dynamics. The results (Fig. 11) show significant divergence between simulated and observed biomass for both species after 1700, interpreted by the authors as most likely showing the effects of grazing by domesticated animals on lime and the subsequent succession by beech: beech should not dominate the modern-day forest.

Simulation models have also been used extensively in acid waters research (e.g. MAGIC: Cosby et al. 1985), most recently to gauge the future response of surface waters to acid deposition reduction (Jenkins et al. 2003). Although MAGIC is well tested against contemporary data a key question is its accuracy in simulating surface water chemistry in situations of low sulphur and nitrogen both in the past (reference state) and in the future (restoration target). Comparisons between diatom-inferred pH from sediment core data and hindcasts of pH using MAGIC for a Scottish loch over the last 200 years (Fig. 12) show that the modelled pH is higher than the diatom-inferred pH (Battarbee et al. 2005). It is impossible to know whether the palaeo-inference or the model-based value is the more accurate, but the difference between the two highlights the need to re-examine both methods. In this case Battarbee et al. (2005) suggest that the discrepancy may be due to the pre-acidification pH being overestimated by MAGIC as a result of errors in the estimation of background soil–water DOC in the model.

For fluvial systems, Coulthard et al. (2002) use a cellular automata type model (CAESAR) to simulate hydrological processes and sediment transport through catchment systems driven by palaeoclimate data, where human actions may be incorporated by modifying the degree of vegetation cover. In this way, the effects of different combinations of climate regime and land cover on flooding and sediment delivery can be explored, and tested against reconstructed records from floodplain sequences. Cellular models like these have the advantage that large-scale catchment-wide changes are produced from local interactions between individual cells, typically only 100 or 2500 m^2. This means that there is effectively continuous feedback within time and space, and the chance to simulate and capture non-linear system behaviour through realistic interactions. It is clear that palaeorecords can provide both the forcings and the

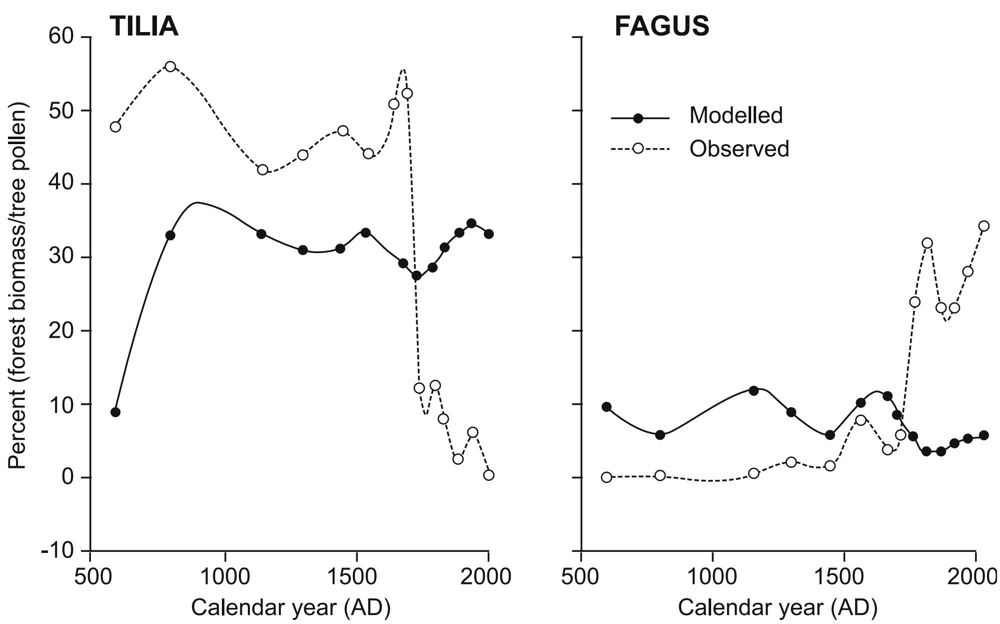

Fig. 11 Data-simulation model comparisons. Palaeovegetation-model comparisons for the last 1,500 years at Draved Forest, Denmark. The discrepancy since ~AD 1700 between the observed pollen records and the modelled (FORSKA 2) biomass, driven only by climate, strongly suggests that the rise of beech (*Fagus*: *right figure*) and demise of lime (*Tilia*: *left figure*) are linked more to human disturbance than climate. Time axis in original reversed (Cowling et al. 2001)

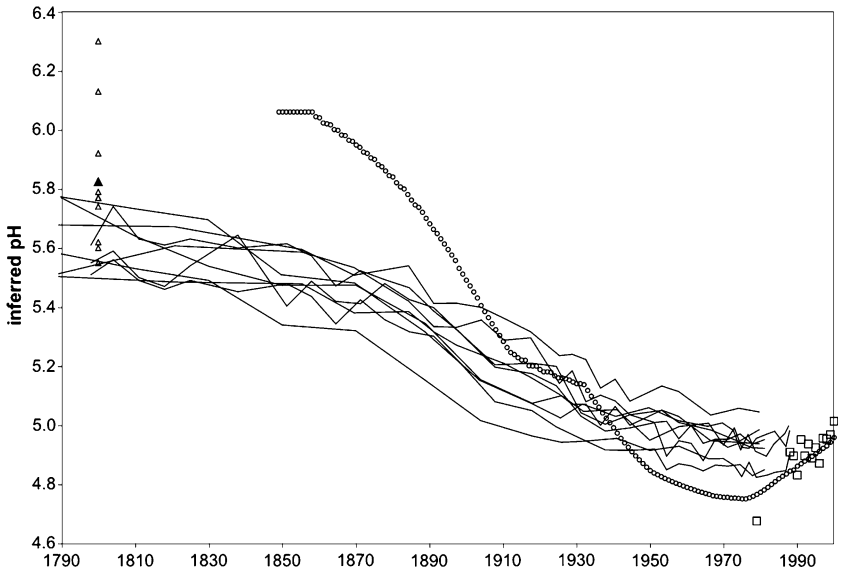

Fig. 12 Data-simulation model comparisons. Comparison of measured, reconstructed and modelled lake pH data since AD 1800 at Round Loch, Scotland. Chronology of DI pH according to SWAP, UK and EDDI models (*fine lines*) for ^{210}Pb dated samples from three sediment cores, (RLGH 81, RLGH 3 and K05). Modern annual pH of nine local lakes providing the strongest biological analogues for a pre-acidification (circa AD 1800) sediment sample (*open triangles*) and the weighted average of these (*filled triangle*). MAGIC model reconstruction (*open circles*) and mean annual average pH for the period 1988–2000 and the year 1979 at Round Loch (*open squares*; Battarbee et al. 2005)

means to test model veracity, highlighting the need to ensure independent variables.

Maximising the synergy between numerical modellers and palaeoenvironmental scientists means overcoming several problems. For example, in the examples given, it is noteworthy that the role of humans is implicit and there exists no true feedback between the environment and decision-making (see also Dearing et al. this issue). There is also the challenge for those models that do try to simulate human–environment interactions, for example with reference to Integrated Impact Assessment, to produce outputs in a form that can be tested by recourse to long records. Integrated Impact Assessment considers many of the processes and interactions that lie at the core of environmental change, and there is a growing literature on the methodologies employed by an ever-increasing group of practitioners (e.g. Harremoes and Turner 2001; Van Asselt and Rotmans 2002). At the same time, few if any of the published studies make any reference to the longer-term perspective on human–environment interactions to which palaeo-research crucially contributes. Much the same may be said for related approaches focusing on vulnerability (Turner et al. 2003), risk (Jones 2001) or sustainability (Clark and Dickson 2003; Jäger 2004).

The special issue

The following eight papers represent PAGES Focus 5 studies from different global regions (SE Australia, California, northern China, NW and central Europe, New Zealand and Indonesia) and widely differing types and scales of environments and ecosystems, including estuaries, lakes, volcanoes, arable land, conservation zones and whole physiographic units. The papers cover a wide range of scientific methods and techniques that are used to reconstruct past human–environment interactions, most are interdisciplinary, and all attempt to learn about the present from the past. The problems of describing baseline conditions are highlighted in several of the papers. The paper by Bradshaw et al. (this issue) describes the historical changes in lake water quality in Denmark brought about by anthropogenic disturbance and show that any definition of reference conditions for restoration targets needs to consider a long history, one that may extend back centuries or millennia. Similarly, Ogden et al. (this issue) consider the sequential impacts of Maori and European on estuarine systems, Great Barrier Island, New Zealand. In terms of the needs of conservation management, the authors highlight the fact that the pattern of modern ecosystems has been largely driven by anthropogenic activity, and cannot be considered natural or static. In a different context, Black and Mooney (this issue) contribute to the ongoing debate about the use of fire by Aboriginal people and its links with climate change by reconstructing fire activity in the Australian Blue Mountains Heritage Area. Whether or not Aboriginals used fire extensively, the results strongly suggest that the importance of climate in providing suitable conditions for fire cannot be discounted. The nature of interactions between climate, land use and fluvial processes is a theme that runs through several papers. The paper by Klimek et al. (2006) argues that despite major climate fluctuations, deforestation was the main trigger of valley alluviation in the loess region of Poland. Similarly a review of the levels and historical causes of soil erosion on the Chinese Loess Plateau by He et al. (this issue) highlights the importance of favourable climate for land use, but also the fragility of the landscape to excessive exploitation which the authors argue was often linked to wider political and cultural change. The difference between impacts linked to one culture or another at the same site is also a recurring theme. For example, differences in the sensitivity of runoff and erosion to climate between Mexican and Euro-American agriculture are the main feature of the paper by Plater et al. (this issue) dealing with lake sedimentation in Central Coastal California. The dramatic impacts of Euro-American settlement are perhaps unsurprising, but by providing a retrospective view on the effects of erosion mitigation the paper shows importantly that recent measures to control lake infilling have been relatively ineffective. At the heart of Lavigne and Gunnell's (this issue) paper is the natural resistance and resilience of ecosystems to anthropogenic disturbance on Javan volcanoes. The authors use relatively short records to infer about the long-term trajectories of change, arguing that current levels of deforestation and population growth are raising the probability of new non-linear responses that will be difficult to anticipate. In the last regional paper, Chiverrell (this issue) attempts to synthesise existing data for the historical instability of slopes in upland NW England in order to speculate about future conditions and sensitivity. It represents an important first step to integration of palaeoenvironmental information in a discrete physiographic area, providing a model for regionalisation elsewhere. The importance of integration and regionalisation of existing data and information is the subject of the final paper by Dearing et al. (this issue)—a review of future priorities and methodological developments.

Focus 5 links

Human Impacts on Terrestrial Ecosystems (HITE): j.dearing@liv.ac.uk; http://www.liv.ac.uk/geography/hite

Human Impacts on Lake Ecosystems (LIMPACS): r.w.battarbee@ucl.ac.uk; http://www.geog.ucl.ac.uk/ecrc/limpacs/

Land Use and Climate Impacts on Fluvial Systems (LUCIFS): rdikau@giub.uni-bonn.de; http://www.geo.uni-frankfurt.de/ipg/lucifs/

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References

Alverson KA, Villvock A (eds) (2000) Joint CLIVAR/PAGES Newsletter PAGES Newsletter 8: CLIVAR Exchanges 5(1):24pp

Barber KE (1981) Peat stratigraphy and climatic change. AA Balkema, Rotterdam

Barber KE, Charman D (2003) Holocene palaeoclimate records from peatlands. In: Mackay AW, Battarbee RW, Birks HJB, Oldfield F (eds) Global Change in the Holocene. Arnold, London, p 528

Battarbee RW (1999) The importance of palaeolimnology to lake restoration. Hydrobiologia 395/396:149–159

Battarbee RW, Flower RJ, Stevenson AC, Rippey B (1985) Lake acidification in Galloway: a palaeoecological test of competing hypotheses. Nature 314:350–352

Battarbee RW, Monteith DT, Juggins S, Evans CD, Jenkins A, Simpson GL (2005) Reconstructing pre-acidification pH for an acidified Scottish loch: a comparison of palaeolimnological and modelling approaches. Environ Pollut 137:135–149

Bennion H, Fluin J, Simpson GL (2004) Assessing eutrophication and reference conditions for Scottish freshwater lochs using sub-fossil diatoms. J Appl Ecol 41:124–138

Berglund BE (ed) (1991) The cultural landscape during 6000 years in Southern Sweden (Ecological Bulletin 41). Blackwell, Oxford, p 495

Binford MW, Brenner M, Whitmore TJ, Higuera-Gundy A, Deevey ES Jr, Leyden B (1987) Ecosystems, paleoecology, and human disturbance in sub-tropical and tropical America. Q Sci Rev 6:115–128

Black MP, Mooney SD (2006) Holocene fire history from the Greater Blue MountainsWorld Heritage Area, New South Wales, Australia: the climate, humans and firenexus. Reg Environ Change 6: 10.1007/s10113-005-0003-8 (this issue)

Bradshaw RHW, Hannon GE, Lister AM (2003) A long-term perspective on ungulate–vegetation interactions. Forest Ecol Manage 181:267–280

Bradshaw EG, Nielsen AB, Anderson NJ (2006) Using diatoms to assess the impactsof prehistoric, pre-industrial and modern land-use on Danish lakes. Reg EnvironChange 6: 10.1007/s10113-005-0007-4 (this issue)

Bugmann H (2001) A review of forest gap models. Climatic Change 5:259–305

Bugmann H, Pfister C (2000) Impacts of interannual climate variability on past and future forest composition. Reg Environ Change 1:1–19

Catalan J, Pla S, Rieradevall M, Felip M, Ventura M, Buchaca T,Camarero L, Brancelj A, Appleby PG, Lami A, Grytnes JA,Augusti-Panareda A, Thompson R (2002) Lake Redo ecosystem response to anincreasing warming in the Pyrenees during the twentieth century. JPaleolimnol 28:129–145

Chepstow-Lusty A, Bennett KD, Fjeldsa J, Kendall A, Galliano W, Tupayachi-Herrera A (1997) Tracing 4000 years of environmental history in the Cuzco area, Peru, from the pollen record. Mt Res Dev 18:159–172

Chiverrell RC (2006) Past and future perspectives upon landscape instability inCumbria, northwest England. Reg Environ Change 6: 10.1007/s10113-005-0005-6(this issue)

Clark WC, Dickson NM (2003) Sustainability science: the emerging research program. Proc Natl Acad Sci USA 100:8059–8061

Cosby BJ, Hornberger GM, Galloway JN, Wright RF (1985) Time scales of catchment acidification. Environ Sci Technol 19:1144–1149

Cottingham KL, Brown BL, Lennon JT (2001) Biodiversity may regulate the temporal variability of ecological systems. Ecol Lett 4:72–85

Coulthard TJ, Macklin MG, Kirby MJ (2002) Simulating upland river catchment and alluvial fan evolution. Earth Surf Process Landforms 27:269–288

Cowling SA, Sykes MT, Bradshaw RHW (2001) Palaeovegetation-model comparisons, climate change and tree succession in Scandinavia over the past 1500 years. J Ecol 89:227–236

Crook DS, Siddle DJ, Jones RT, Dearing JA, Foster GC, Thompson R (2002) Forestry and Flooding in the Annecy Petit Lac Catchment, Haute-Savoie 1700–2000 AD. Environ Hist 8:403–428

Crook DS, Siddle DJ, Dearing JA, Thompson R (2004) Human impact on the environment in the Annecy Petit Lac catchment, Haute-Savoie: a documentary approach. Environ Hist 10:247–284

Davis MB (1976) Erosion rates and land use history in southern Michigan. Environ Conserv 3:139–148

Dearing JA, Jones RT (2003) Coupling temporal and spatial dimensions of global sediment flux through lake and marine sediment records. Global Planet Change 39:147–168

Dearing JA, Zolitschka B (1999) System dynamics and environmental change: an exploratory study of Holocene lake sediments at Holzmaar, Germany. Holocene 9:531–540

Dearing JA, Battarbee RW, Dikau R, Larocque I, Oldfield F (2006) Human–environment interactions: towards synthesis and simulation. Reg Environ Change (this issue)

Deevey ES (1969) Coaxing history to conduct experiments. Bioscience 19:40–43

Diamond J (2005) Collapse: how societies choose to fail or survive. Allen Lane, London, p 575

Elvin M, Crook DS, Jones RT, Dearing JA (2002) The impact of clearance and irrigation on the environment in the lake Erhai catchment from the ninth to the nineteenth century. East Asian Stud 23:1–60

Foster GC, Dearing JA, Jones RT, Crook DC, Siddle DS, Appleby PG, Thompson R, Nicholson J, Loizeaux J-L (2003a) Meteorological and land use controls on geomorphic and fluvial processes in the pre-Alpine environment: an integrated lake-catchment study at the Petit Lac d'Annecy. Hydrol Process 17:3287–3305

Foster DR, Swanson F, Aber J, Burke I, Brokaw N, Tilman D, Knapp A (2003b) The importance of land-use legacies to ecology and conservation. Bioscience 53:77–88

Fritz SC (1989) Lake development and limnological response to prehistoric and historic land-use in Diss, Norfolk, U.K. J Ecol 77:182–202

Gomez B, Page M, Bak P, Trustrum N (2002) Self-organized criticality in layered, lacustrine sediments formed by landsliding. Geology 30:519–522

Harremoes P, Turner RK (2001) Methods for integrated assessment. Reg Environ Change 2:57–65

Haug GH, Günther D, Peterson LC, Sigman DM, Hughen KA, Aeschlimann B (2003) Climate and the collapse of Maya civilization. Science 299:1731–1735

He X, Zhou J, Zhang X, Tang K (2006) Soil erosion response to climatic change andhuman activity during the Quaternary on the Loess Plateau, China. Reg EnvironChange 6: 10.1007/s10113-005-0004-7 (this issue)

Hergarten S (2002) Self-organized criticality in earth systems. Springer, Berlin Heidelberg New York, p 272

Hodell DA, Curtis JH, Brenner M (1995) Possible role of climate in the collapse of Classic Maya civilization. Nature 375:391–394

Hoelzmann P, Keding B, Berke H, Kroepelin S, Kruse H-J (2001) Environmental change and archaeology: lake evolution and human occupation in the Eastern Sahara during the Holocene. Palaeogeogr Palaeoclimatol Palaeoecol 169:193–217

Huang CC, Zhao S, Pang J, Zhou Q, Chen S, Li P, Mao L, Ding M (2003) Climatic aridity and the relocations of the Zhou culture in the southern Loess Plateau of China. Climatic Change 61:361–378

IPCC TAR (2001) Climate change 2001: synthesis report. Cambridge University Press, Cambridge, p 1032

Jäger J (2004) Sustainability science. In: Steffen W, Sanderson A, Tyson PD et al (eds) Global change and the earth system; a planet under pressure, Springer, Berlin Heidelberg New York, p 296

Jenkins A, Camarero L, Cosby BJ, Ferrier RC, Forsius M, Helliwell RC, Kopácek J, Majer V, Moldan F, Posch M, Rogora M, Schöpp W, Wright RF (2003) A modelling assessment of acidification and recovery of European surface waters. Hydrol Earth Syst Sci 7:447–455

Jones RN (2001) An environmental risk assessment/management framework for climate change impact assessments. Nat Hazards 23:197–230

Klimek K, Lanczont M, Nogaj-Chachaj J (2006) Historical deforestation as a cause ofalluviation in small valleys on the Subcarpathian loess plateau, Poland. Reg EnvironChange 6: 10.1007/s10113-005-0008-3 (this issue)

Larson DO, Neff H, Greybill DA, Michaelsen J, Ambos E (1996) Risk, climatic variability and the study of southwestern prehistory: an evolutionary perspective. Am Antiquity 61:217–241

Lavigne F, Gunnell Y (2006) Land cover change and abrupt environmental impactson Javan volcanoes, Indonesia: a long-term perspective on recent events. Reg EnvironChange 6: 10.1007/s10113-005-0009-2 (this issue)

Levin SA (1999) Fragile dominion: complexity and the commons. Perseus Books, Reading, MA, p 250

Macklin MG, Lewin J (2003) River sediments, great floods and centennial-scale Holocene climate change. J Q Sci 18:101–105

Manley G (1974) Central England temperatures: monthly means 1659–1973. Q J R Meteorol Soc 100:389–405

Mann ME, Jones PD (2003) Global surface temperatures over the past two millennia. Geophys Res Lett 30:5-1–5-4

Mann ME, Bradley RS, Hughes MK (1998) Global-scale temperature patterns and climate forcing over the past six centuries. Nature 392:779–787

Martínez-Cortizas A, Pontevedra-Pombal X, García-Rodeja E, Nóvoa-Muñoz JC, Shotyk W (1999) Mercury in a Spanish peat bog: archive of climate change and atmopsheric metal deposition. Science 284:939–942

Messerli B, Grosjean M, Hofer T, Núñez L, Pfister C (2000) From nature-dominated to human-dominated environmental changes. Q Sci Rev 19:459–479

Moberg A, Sonechkin DM, Holmgren K, Datsenko NM, Karlén W (2005) Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data. Nature 453:613–617

Nials FL, Gregory DA, Graybill DA (1989) Salt river stream flow and Hohokam irrigation systems. In: Graybill DA, Gregory DA, Nials FL, Gasser R, Miksicek C, Szuter C (eds) The 1982–1992 Excavations at Las Colinas: environment and subsistence, vol 5. Arizona State Museum Archaeological Series, Arizona State Museum, Tucson, pp 59–78

Nicholson SE (1998) Historical fluctuations of Lake Victoria and other lakes in the northern Rift Valley of East Africa. In: Lehman JT (ed) Environmental change and response in East African Lakes. Kluwer, Dordrecht, pp 7–35

Nicoll K (2004) Recent environmental change and prehistoric human activity in Egypt and Northern Sudan. Q Sci Rev 23:561–580

Nott J, Hayne M (2001) High frequency of 'super-cyclones' along the Great Barrier Reef over the past 5,000 years. Nature 413:508–512

Nuñez L, Grosjean M, Cartajena I (2002) Human occupations and climate change in the Puna de Atacama, Chile. Science 298:821–824

Ogden J, Deng Y, Horrocks M, Nichol S, Anderson S (2006) Sequential impacts ofPolynesian and European settlement on vegetation and environmental processesrecorded in sediments at Whangapoua Estuary, Great Barrier Island, New Zealand.Reg Environ Change 6: 10.1007/s10113-005-0006-5 (this issue)

Oldfield F (1977) Lakes and their drainage basins as units of sediment-based ecological study. Prog Phys Geogr 1:460–504

Oldfield F (2005) Environmental change: key issues and alternative approaches. Cambridge University Press, Cambridge, p 363

Oldfield F, Dearing JA (2003) The role of human activities in past environmental change. In: Alverson K, Bradley R, Pedersen T (eds) Paleoclimate, global change and the future, IGBP Synthesis Book Series. Springer, Berlin Heidelberg New York, pp 143–162

Oldfield F, Appleby PG, Worsley AT (1985) Evidence from lake sediments for recent erosion rates in the Highlands of Papua New Guinea. In: Douglas I, Spencer E (eds) Environmental change and tropical geomorphology. Allen and Unwin, London, pp 185–195

Olley JM, Wasson RJ (2003) Changes in the flux of sediment in the Upper Murrumbidgee catchment, Southeastern Australia, since European settlement. Hydrol Process 17:3307–3320

Plater AJ, Boyle JF, Mayers C, Turner SD, Stroud RW (2006) Climate and humanimpact on lowland lake sedimentation in Central Coastal California: the record fromAD 650 to the present. Reg Environ Change 6: 10.1007/s10113-006-0013-1 (this issue)

Phillips JD (1998) Earth surface systems: complexity, order and scale. Blackwell, Oxford, p 192

Phillips JD (2003) Sources of nonlinearity and complexity in geomorphic systems. Prog Phys Geogr 27:1–23

Redman CL (1999) Human impact on ancient environments. The University of Arizona Press, Tuscon, p 239

Richards KS (2002) Drainage basin structure, sediment delivery and the response to environmental change. In: Jones SJ, Frostick LE (eds) Sediment flux to basins: causes, controls and consequences, Special publication, vol 191. Geological Society, London, pp 149–160

Rosen AM (1995) The social response to environmental change in early bronze age. Can J Anthropol Archaeol 14:26–44

Ruddiman WF (2003) The anthropogenic greenhouse era began thousands of years ago. Climatic Change 61:261–293

Salzmann U, Hoelzmann P (2005) The Dahomey Gap: an abrupt climatically induced rain forest fragmentation in West Africa during the late Holocene. Holocene 15:190–199

Scheffer M, Hosper SH, Meijer M-L, Moss B, Jeppesen E (1993) Alternative equilibria in shallow lakes. Trends Ecol Evol 8:275–279

Scheffer M, Carpenter S, Foley JA, Folke C, Walker B (2001) Catastrophic shifts in ecosystems. Nature 413:591–596

Schmidt J, Dikau R (1999a) Extracting geomorphometric attributes and objects from digital elevation models—semantics, methods, future needs. In: Dikau R, Saurer H (eds) GIS for earth surface systems. Schweizbart'sche, Stuttgart, pp 153–174

Schmidt J, Dikau R (1999b) Extracting geomorphometric attributes and objects from digital elevation models—semantics, methods, future needs. In: Dikau R, Saurer H (eds) GIS for earth surface systems—analysis and modelling of the natural environment. Schweizbart'sche, Stuttgart, pp 153–173

Scholes RJ, Biggs R (2005) A biodiversity intactness index. Nature 434:45–49

Singh G, Wasson RJ, Agrawal DP (1990) Vegetational and seasonal climatic changes since the last full glacial in the Thar Desert, northwestern India. Rev Palaebot Palynol 64:351–358

Soon W, Baliunas S (2003) Lessons and limits of climate history: was the twentieth century climate unusual? The George C Marshall Institute, Washington, DC, p 23

Soon W, Baliunas S, Idso C, Idso S, Legates DR (2003) Reconstructing climatic and environmental changes of the past 1000 years: a reappraisal. Energy Environ 14:233–296

Staubwasser M, Sirocko F, Grootes PM, Segl M (2003) Climate change at 4.2ka BP,termination of the Indus valley civilization and Holocene south Asian monsoonvariability. Geophysical Research Letters 30: 1425

Steffen W, Sanderson A, Tyson PD, Jäger J, Matson PA, Moore B III, Oldfield F, Richardson K, Schellnhuber HJ, Turner BL, Wasson RJ (2004) Global change and the earth system: a planet under pressure. Springer, Berlin Heidelberg New York, p 336

Swetnam TW, Allen CD, Betancourt JL (1999) Applied historical ecology: using the past to manage for the future. Ecol Appl 9:1189–1206

Trimble SW (1999) Decreased rates of alluvial sediment storage in the Coon Creek basin, Wisconsin, 1975–1993. Science 285:1244–1246

Trimble SW, Lund SW (1982) Soil conservation and the reduction of erosion and sedimentation in the Coon Creek basin, Wisconsin, US Geological Survey Professional Paper 1234, US Government Printing Office, Washington

Turner BL, Kasperson RE, Meyer WB, Dow KM, Golding D, Kasperson JX, Mitchell RC, Ratick SJ (1990) Two types of global environmental change. Global Environ Change 15:1–22

Turner BL II, Kasperson RE, Matson PA, McCarthy JJ, Corell RW, Christensen L, Eckley N, Kasperson JX, Luers A, Martello ML, Polsky C, Pulsipher A, Schiller A (2003) A framework of vulnerability analysis in sustainability science. Proc Natl Acad Sci USA 100:8074–8079

Tyson P, Odada E, Schulze R, Vogel C (2002) Regional-global change linkages: Southern Africa. In: Tyson P, Fuchs R, Fu C, Lebel L, Mitra AP, Odada E, Perry J, Steffen W, Vriji H (eds) Global-regional linkages in the earth system. Springer, Berlin Heidelberg New York, pp 3–73

Van Asselt MBA, Rotmans J (2002) Uncertainty in integrated assessment modelling: from positivist to pluralism. Climatic Change 54:75–105

Walling DE, Fang D (2003) Recent trends in the suspended sediment loads of the world's rivers. Global Planet Change 39:111–126

Wasson RJ (2002) Sediment budgets, dynamics, and variability: new approaches and techniques. In: Dyer FJ, Thoms MC, Olley JM (eds) The structure, function and management implications of fluvial sedimentary systems. IAHS Public No 276, pp 471–478

Wasson RJ, Sidorchuk A (2000) History for soil conservation and catchment management. In: Dovers SR (eds) Australian environmental history: still settling Australia. Oxford University Press, Melbourne, pp 97–117

Weiss H, Bradley RS (2001) What drives societal collapse? Science 291:609–610

Weiss H, Courty MA (1993) The genesis and collapse of the Akkadian empire. In: Liverani M (ed) Akkad: the first world empire. Sargon, Padua, pp 131–155

Wolman MG, Miller JP (1960) Magnitude and frequency of forces in geomorphic processes. J Geol 68:54–74