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Landscape change and resilience theory: a palaeoenvironmental assessment from Yunnan, SW China

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Abstract: The paper explores the use of Resilience Theory to provide an improved theoretical framework for the analysis of socio-ecological interactions over decadal–millennial timescales. It identifies landscape system behaviour through analysis of proxy records for land use, erosion and monsoon intensity over the past 3000 years in the Erhai lake-catchment system, Yunnan, SW China. Analysis of the records shows the possibility of alternative steady states in the landscape, as expressed by the relationship between land use and erosion. In particular, a period of agricultural expansion ~1400 cal. yr BP triggered rapid gully erosion that led to the formation of an eroded landscape state that has existed since ~800 cal. yr BP to the present day. Comparison of detrended time-series data suggests that over 3000 years erosion and land use should be considered 'slow' processes relative to the 'faster' monsoon intensity and flooding. In the past, the effects of high monsoon variance on flooding have been suppressed by paddy farming and the maintenance of terraced field systems. Mapping the Adaptive Cycle on to the millennial record of land use and erosion suggests that the modern landscape may be approaching a 'conservation' phase characterized by minimum resilience. Such 'historical profiling' of modern landscapes offers a new dimension for hypothesis testing, for the development and testing of simulation models and for the creation of appropriate management strategies.

Key words: Resilience Theory, Adaptive Cycle, decadal–millennial, land use, landscape change, climate, erosion, flooding, Erhai, China, Holocene.

Introduction

The Millennium Ecosystem Assessment (2005) testifies to the current degraded state of many global landscapes. There are ~2 billion hectares of land affected by human-induced degradation of soils, which place the livelihoods of 1 billion people at risk with an estimated loss of income exceeding US$40 billion a year. Each year an additional 20 million hectares of agricultural land become too degraded for crop production, or are lost to urban sprawl. Degraded, in this sense, refers to a highly undesirable landscape trajectory caused by the interaction of climate and inappropriate land use. The result is an increase in a wide range of deleterious processes that includes soil erosion, gullying, flooding, leaching, salinization and waterlogging. As climate changes and population pressures increase there is an urgent need to be able to assess both the resilience of specific world landscapes to future perturbations and the feasibility of alternative management options.

The development of Resilience Theory over the past decade, particularly the concepts of Panarchy and Adaptive Cycle (Gunderson and Holling, 2002), provides the potential foundation to assess landscape change. Holling (2001) describes the adaptive cycle (Figure 1) as a fundamental unit of dynamic change comprising a forward and backward loop in four phases: *rapid growth* (r), *conservation* (K), *release* (Ω) and *reorganization* (α). In the forward loop, systems self-organize through rapid growth in which processes exploit and accumulate free energy (r) towards a point of maximum conservation and connectedness (K) epitomised by complex or mature states, such as forest ecosystems. In geomorphic terms, this process may be viewed as the evolution of landforms to a point of incipient instability where intrinsic or extrinsic thresholds are more easily exceeded (Schumm, 1979). In the back loop, perturbations force destabilization and the release (Ω) of potential energy, such as nutrients, soil particles and water, before the system gradually stabilizes through re-organization (α). The attribute of *resilience* is rising between the α and r phases (Figure 1), and declining between K and Ω phases. In resilience theory, the system's resilience is defined as being able to tolerate disturbance 'without collapsing into a qualitatively different state controlled by a different set of processes' (Resilience Alliance, 2007).

One of the attractive aspects of the adaptive cycle is that it integrates several ideas that have their roots in non-linear dynamical theory and complexity theory. These include the concept that systems may exist in multiple steady states, flipping from one state to

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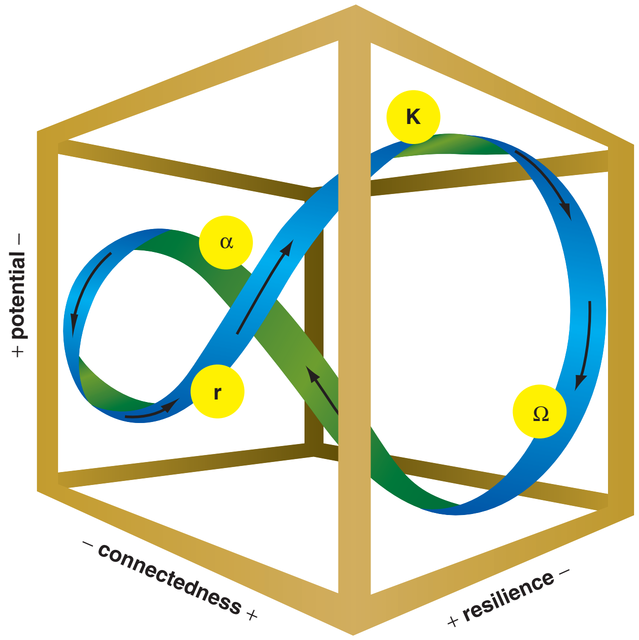

Figure 1 The 3D Adaptive Cycle (Gunderson and Holling, 2002) plotted on axes of potential, connectedness and resilience, showing phases of rapid growth (r), conservation (K), release (Ω) and reorganization (α)

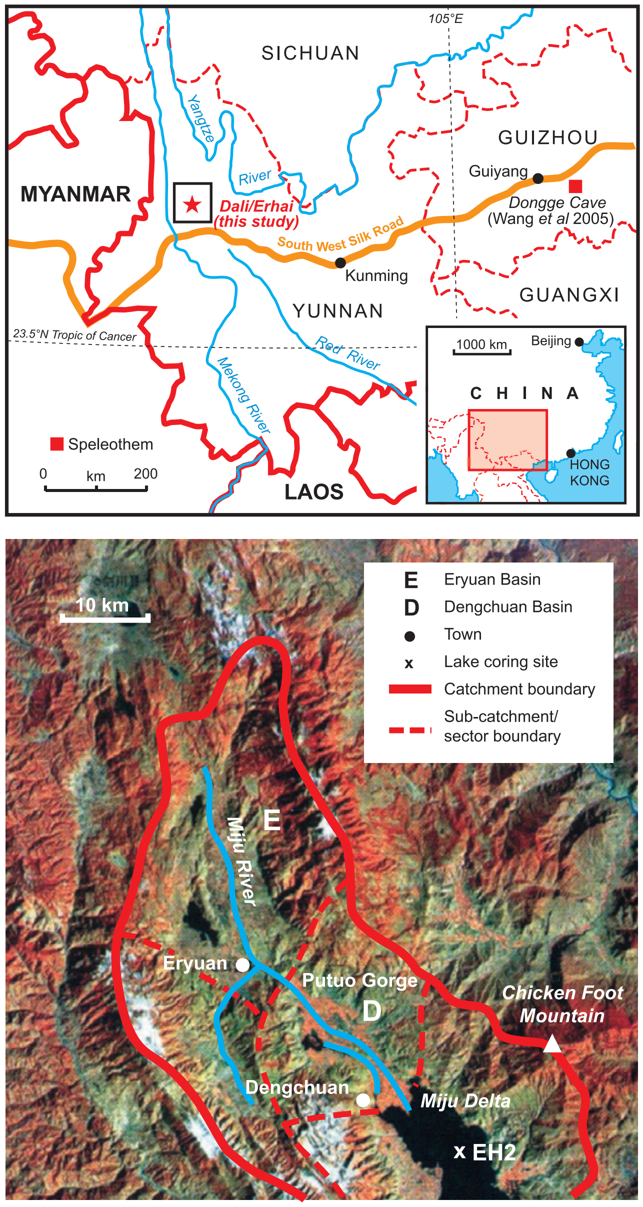

Figure 2 Location (top) and site (bottom) of the Erhai-Miju lake-catchment

another as thresholds are transgressed (May, 1977; Scheffer *et al.,* 2001). There is also the concept of self-organization as an emergent property of interacting subsystems where ordered phenomena arise out of apparent disorder. This may give rise to clumped phenomena centred on a few important scales in time and space (Holling, 1992), typified by scale-invariant fractal properties. One linked theory about the behaviour of scale-invariant self-organized systems argues for critical states (Bak, 1996) that are 'brittle' or fragile with respect to external perturbations, such that system response, or release, may be disproportionately large (cf. Schumm, 1979).

Panarchy is a conceptual term given to a nested set of adaptive cycles that cross multiple spatial and temporal scales. It focuses the need to understand different scales of change in order to explain the causation of modern states, a concept long familiar to geomorphologists (Schumm and Lichty, 1965). A key element is the link between 'slow' processes operating over large spatial areas (slow-large) and 'fast' processes operating over small spatial areas (fast-small). Resilience theory states that slow-large processes dominate the forward part of the adaptive cycle, providing the relatively predictable boundary conditions to the system. Within these conditions, fast-small processes operate to allow change and reorganization, particularly in the back loop of the cycle that is typically unpredictable (Gunderson and Holling, 2002). Perturbations to fast processes can cause cascading change in the slow processes. While natural ecological systems tend to reorganize through fast-small processes working within the constraints imposed by the slow-large processes, human activities often shift high-frequency (ie, fast) processes to low-frequency (ie, slow) but higher magnitude regimes (eg, flooding or forest fires). It is the need to understand the interaction between slow and fast processes (cf. Carpenter and Brock, 2006) that suggests a critical role for palaeoenvironmental reconstruction in the assessment of current environmental system behaviour and resilience.

Palaeoenvironmental records of ecological states and processes derived from geomorphic and limnic sediment sequences, together with information about climate and social change, provide a wide range of information about the functioning of system behaviour (eg, Dearing and Zolitschka, 1999) and socio-ecological systems (eg, Dearing *et al.,* 2006a). However, the use of records to provide an explicit assessment of sustainability or resilience is less developed, despite calls for *historical profiling* as one of the main approaches for obtaining surrogate measures of resilience (Carpenter *et al.,* 2005). Redman and Kinzig (2003) review the ways archaeologists can contribute to resilience studies. Archaeology provides long time perspectives that can describe whole adaptive cycles, help distinguish between *ultimate* and *proximate* causes of collapse in socio-ecological systems, and identify emergent features (eg, ecological simplification and social stratification). Such studies also allow examination of transformations or truly novel situations and, when coupled to anthropology, archaeology can provide cross-scale analysis of socio-ecological interactions. These points should also apply to sediment records where there is the possibility to reconstruct continuous and highly resolved time series of natural environmental processes operating over 10^0–10^4 years.

This paper is therefore exploratory. It utilizes the large palaeoenvironmental data base available for the lake Erhai catchment and its region in SW China over the major period of human habitation, the past 3000 years (Elvin *et al.*, 2002; Shen *et al.,*

Figure 3 Eroded landscapes in the Eryuan basin showing dry-farmed terraces on steep hillslopes dissected by gully systems (photo: author)

2006; Dearing *et al.,* 2008). Data are examined in phase space to help identify coherent system behaviour, particularly alternative steady states. Comparison of detrended time series is used to elucidate the interaction of slow and fast processes. The adaptive cycle is mapped on to time series as a basis for defining the state of the modern environment. In these ways, the paper examines the interactions between climate, human activities and environmental responses (erosion and flooding) and tries to draw out some general points about the utility of Resilience Theory in a palaeoecological context. Ultimately, it tries to identify some of the implications for the functioning and management of the modern catchment system.

The Erhai lake-catchment system

Site and location

Lake Erhai (25°36′–25°58′N, 100°05′–100°18′E) is a large lake (~150 km^2) located within a tectonically active intermountain basin on the Yunnan Plateau, SW China, at an altitude of 1974 m (Figure 2). The vegetation and land use of the modern catchment, area 2321 km^2, can be subdivided into four main groups. On the fluvial plain and lakeshore areas the vegetation is exclusively agricultural, with extensive irrigated areas supporting a double-cropping system of rice, wheat, legumes and other vegetables. Up to 2500 m, the vegetation is primarily evergreen oak and chestnuts with a secondary forest composed primarily of *Pinus yunnanensis* and *Quercus* (Shen *et al*., 2006). On the lower mountain slopes and hilly land, often underlain by basalt and hard limestones, there is widespread gullying originating from abandoned terraces and cultivated areas on the flatter interfluves (Figure 3). The higher metamorphic mountain ranges support montane humid evergreen broad-leaved forest (2500–2800 m) and mixed conifer woodland (>2800 m), grading to *Abies* forest above 3200 m. The largest sub-catchment, and the focus of the present study, is dominated by the Dengchuan and Eryuan basins with an annual water discharge of 5.18×10^8 m^3 to the lake via the Miju river (Figure 2). The heavily embanked and elevated Miju river provides irrigation water for intensive agriculture on the Miju floodplain. A mean annual temperature of 15.1°C, with small seasonal variation, characterizes the lakeshore climate. 85–90% of precipitation falls in the summer months under the influence of the SW monsoon (Lin and Walker, 1986). During the winter monsoon, winds shift to the north-northwest, bringing mostly dry air to the region.

The details of social and environmental changes in the Erhai lake-catchment system through the Holocene are presented elsewhere (Elvin *et al*., 2002; Shen *et al*., 2006; Dearing *et al*., 2008). Briefly,the palaeoenvironmental changes are based on proxy records derived from lake sediment cores and alluvial fan sections dated using ^{14}C and palaeomagnetic ages. A polynomial depth–age curve for the main 6.48 m lake sediment sequence stretches back from the present to ~12 000 cal. yr BP, with typical errors ±100 yr (2 sd). Proxy records of vegetation and land use are derived from sediment pollen. Changing sources of eroded material from the catchment are assessed from sediment analyses of geochemistry, stable isotopes and environmental magnetism. The sand (% >63 μm) component of the sediments is used as a simple proxy of high fluvial energies bringing coarse-grained sediment to the deep lake area during floods in the monsoon period. The regional record of long-term monsoon intensity is derived from a Holocene stalagmite record of δ^{18}O from Dongge Cave (Wang *et al*., 2005) lying ~750 km E of Erhai, dated using ^{230}Th with an age uncertainty of ~50 yr. At this latitude, changes in δ^{18}O of the stalagmite reflect the amount of precipitation and hence the strength of the monsoon. These are supplemented with records of social change derived from documentary and archaeological sources dating back at least two millennia.

The past 3000 years

Together, the palaeoenvironmental and documentary records for the past 3000 years show five periods of distinct socio-ecological interaction (Figure 4): the Bronze Age period (~3000–2500 cal. yr BP); the inward migration and establishment of the Han Chinese

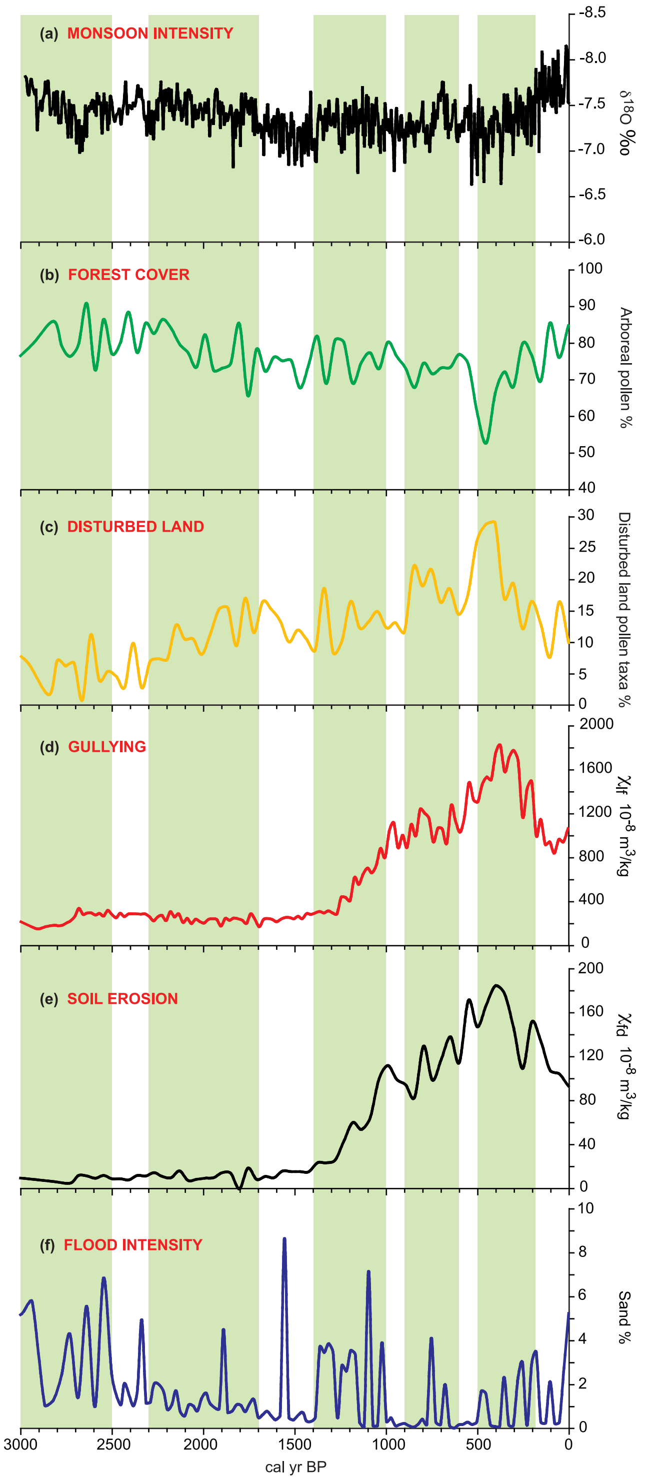

Figure 4 Environmental proxies over the past 3000 years: (a) summer monsoon proxy (Dongge Cave speleothem oxygen isotopes) (Wang *et al.*, 2005); (b) forest cover (total arboreal pollen taxa) (Shen *et al.*, 2006); (c) disturbed land (disturbed land pollen taxa) (Shen *et al.*, 2006); (d) gully erosion (magnetic susceptibility) (Shen *et al.*, 2006); (e) surface soil erosion (frequency dependent magnetic susceptibility) (Dearing *et al.*, 2008); (f) flood intensity (sand fraction) (Shen *et al.*, 2006). Vertical shaded bars define five main periods of documented human impact on environment: Bronze Age culture; Han irrigation technology; Nanzhao Kingdom; Dali Kingdom; the late Ming/early Qing environmental crisis (Dearing *et al.*, 2008)

(2300–1700 cal. yr BP); the rise and fall of the Nanzhao Kingdom (AD 738–902; ~1400–1000 cal. yr BP); the Dali Kingdom (AD 937–1253; ~900–600 cal. yr BP) and the environmental crisis in late Ming and early Qing times (~500–200 cal. yr BP).

The decline in forest pollen taxa from ~2200 cal. yr BP (Figure 4b) and the rise in disturbed land taxa (Figure 4c), especially Poaceae, during the period 2000–1600 cal. yr BP are most likely associated with the introduction of Han culture. Hydraulic modification may have been practised earlier, but it is likely that this period marks the widespread development of irrigated, paddy rice cultivation throughout the catchment. Climatically, the data suggest a continuing weakening of the monsoon (Figure 4a), but there is also no evidence for enhanced high flood maxima (Figure 4f) caused by the disturbance.

The main environmental changes during the periods of the Nanzhao and Dali Kingdoms (1400–1000 cal. yr BP and 900–600 cal. yr BP) are the steady rise in magnetic proxies for gully erosion (Figure 4d) and soil erosion (Figure 4e). The start of the increase ~1600–1500 cal. yr BP marks enhanced erosional processes operating on lower and middle slopes, particularly on the basaltic and limestone formations (Dearing *et al.*, 2008). Logically, gully development driven by rain-fed agriculture and overgrazing would be expected to enhance hydrological connectivity, runoff and hence extreme flood events. It is therefore noteworthy that during the Nanzhao period the rise in erosion proxies coincides with anomalously high flood maxima (Figure 4f). Documentary records point to a substantial urban economy by these times. For example, there is the first reference to drainage activities in the Dengchuan basin, and by 1300 cal. yr BP there is also direct evidence of substantial hydraulic engineering on the west shore of Erhai. It has been estimated that these actions enabled irrigation over ~54 000 ha in Tang times (AD 618–907) and ~70 000 ha in the Ming (after AD 1368).

The late Ming/early Qing period (~500–200 cal. yr BP) is defined by the largest peak in disturbed land pollen taxa (Figure 4c), reaching nearly 30% of total arboreal pollen at ~400 cal. yr BP before declining to the present day. The sediment response curves describe peak influxes of gully-derived and surface soil material (Figure 4d and e), and a rise in high flood maxima (Figure 4f). Elvin *et al.* (2002) highlight intensifying pressures on water supplies, flood defences and available farmland during the Ming period (~600–300 cal. yr BP). The fact that the early Ming period actually witnessed a centennial-scale *minimum* in monsoon intensity (~550–450 cal. yr BP) might point to the stronger and more direct impact of human activities and land-use change. Whatever the cause, an environmental crisis was developing at this time (Elvin *et al.*, 2002). For example, the Miju river was already dyked by ~550 cal. yr BP, and by ~400 cal. yr BP there was the need for regular maintenance caused by channel infilling driven by catchment erosion. Between AD 1713 and 1817 (~240–140 cal. yr BP) there were 13 documented river breaches during the late summer/autumn monsoonal floods, and this timing is consistent with the sediment record of high flood maxima trend (Figure 4f). This later period of flooding is also unique in the mid–late Holocene for the strengthened and highly variable monsoon regime (Figure 4a), and channel sequences close to the northeastern shore testify to the increased sediment delivery and aggradation at this time. More than 1.5 m of fine red sediment lie above two 'modern' ^{14}C-dated charcoal samples (Beta-155410/155411: <300 cal. yr BP), and progradation of the Miju delta reached a maximum of ~0.2 km/yr during the mid-1800s (Elvin *et al.*, 2002). Recent declines in the sediment record of erosion (Figure 4d and e) are probably linked to a recovery in forest cover (Figure 4b).

System behaviour in phase space

The palaeoenvironmental and documentary records from Erhai suggest different and complex associations through time between a number of human, climate and landscape processes. In order to

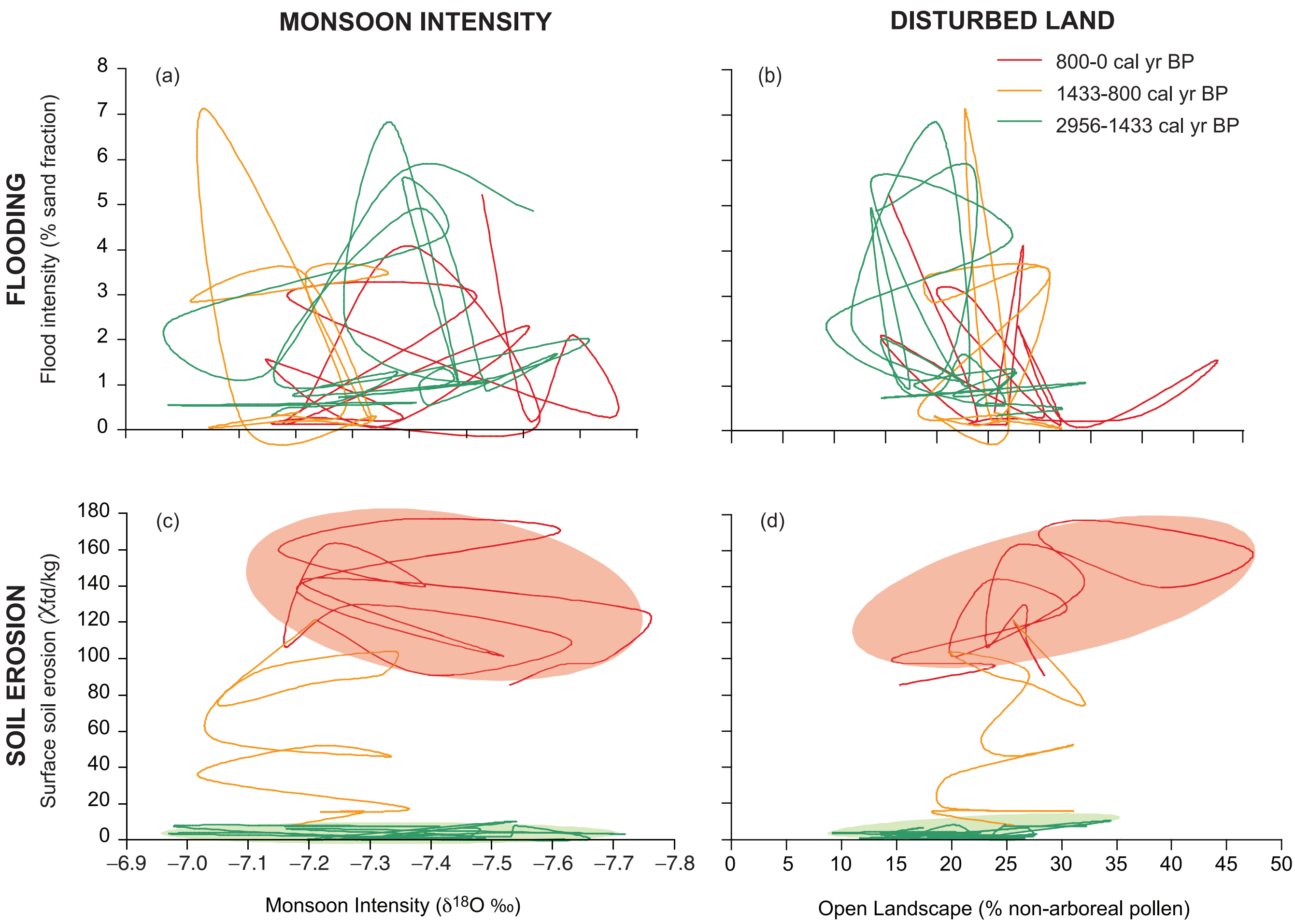

Figure 5 Phase diagrams for ~2960–1430 cal. yr BP, ~1430–800 cal. yr BP; ~800–0 cal. yr BP: (a) monsoon intensity versus flooding; (b) disturbed land versus flooding; (c) monsoon intensity versus soil erosion; (d) disturbed land versus soil erosion. Data from Figure 4. Shaded areas define possible steady states

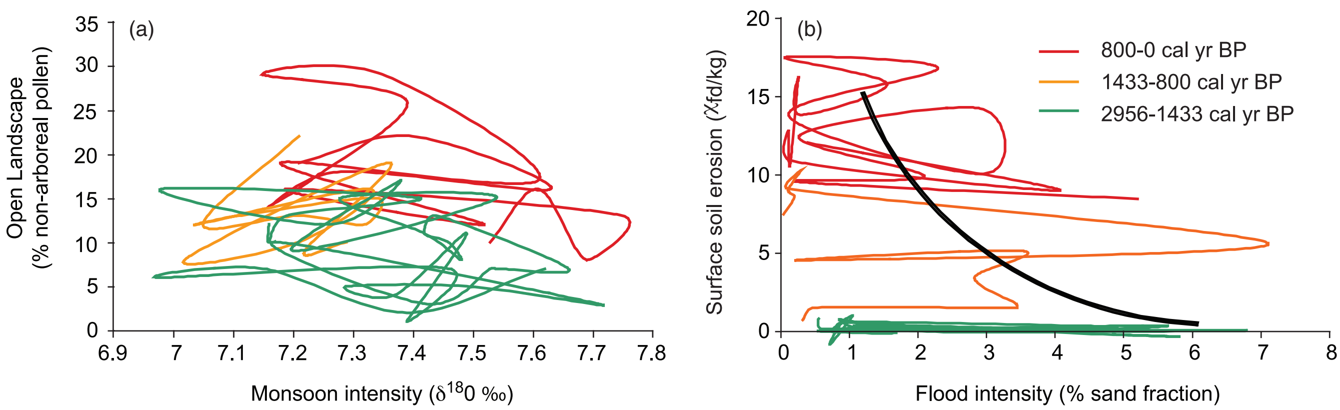

Figure 6 Phase diagrams for ~2960–1430 cal. yr BP, ~1430–800 cal. yr BP; ~800–0 cal. yr BP: (a) monsoon intensity versus disturbed land; (b) flooding versus soil erosion. Data from Figure 4

examine these associations in more detail, particularly for evidence of coherent system behaviour, the proxy data are expressed as phase diagrams: bivariate plots showing the temporal sequence of points. These are commonly used to show system behaviour in phase space, though their use in palaeoenvironmental studies has been limited (eg, Deevey, 1984; Dearing and Zolitschka, 1999). Four phase diagrams are shown in order to express the associations between proxies for the two main hypothesized drivers of hydro-geomorphological processes, disturbed landscape and monsoon intensity, and the responses in surface erosion and flood discharge at roughly centennial time steps over the past 3000 years (Figure 5). Two further phase diagrams (Figure 6) show the associations between the disturbed landscape and monsoon intensity, and between surface erosion and flood discharge.

Figure 5 shows a clear difference in the phase space trajectories for flooding and surface erosion responses to disturbed land and monsoon intensity. The two phase diagrams for flooding (Figure 5a and b) show little coherence with apparently random trajectories through time, and no clear trends. There is very weak organization in phase space, but some tendency for flooding trajectories

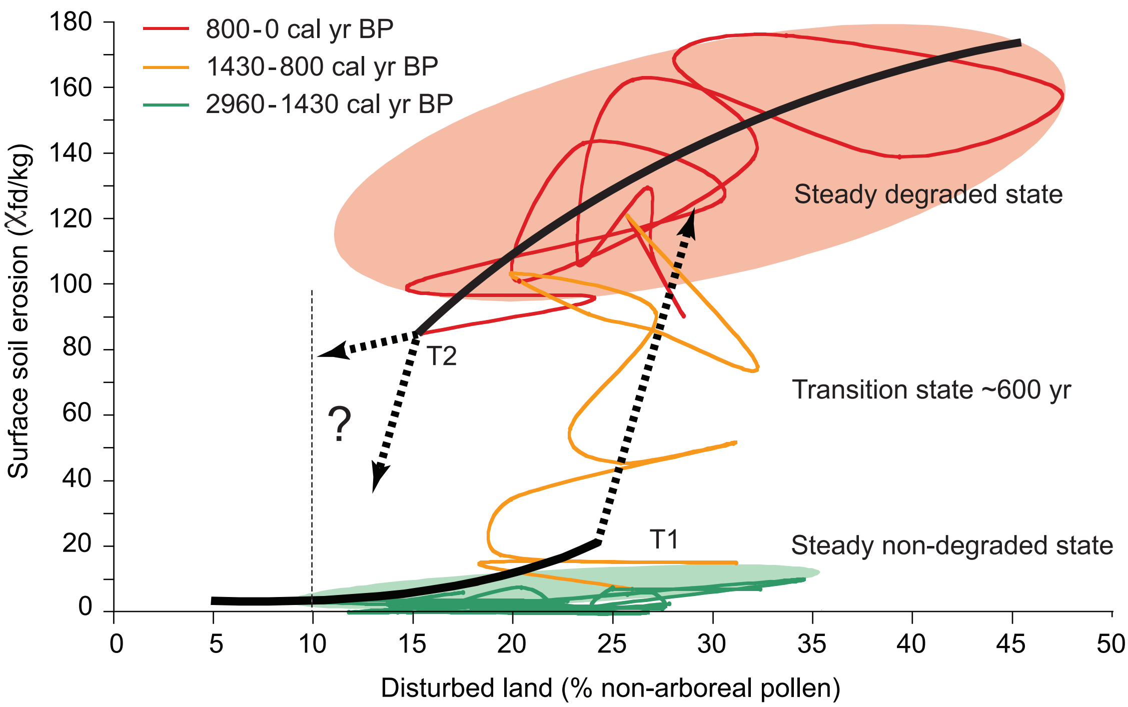

Figure 7 Landscape stability in alternative steady states. Redrawn Figure 5d with superimposed lines to show possible non-linear change from a non-degraded 'steady state' before 1430 cal. yr BP, through a 600 year transition period leading to the modern degraded 'steady state' after 800 cal. yr BP. T1 and T2 represent likely positions of major thresholds in the system. The dashed arrows from T2 show possible future trajectories of landscape recovery (see text for explanation)

in the earliest period (~2960–1430 cal. yr BP) to show larger loops and a positive association with respect to disturbed land (Figure 5b) than in later periods. This suggests that flooding may have been more strongly controlled by fluctuations in land use in the earliest period before the introduction of rice cultivation. But on this evidence, flooding over centennial scales is poorly explained by variations in monsoon intensity.

In contrast, the phase diagrams for surface erosion (Figure 5c and d) show strong evidence of trends and organization into different phase domains. The erosional response shows an early phase of insensitivity to variations in monsoonal intensity (Figure 5c), with a long and narrow phase domain 2960–1430 cal. yr BP. During the following period, 1430–800 cal. yr BP, the rising erosional trajectory forms two anticlockwise loops. After 800 cal. yr BP, the trajectory enters into a new phase space where erosion rates gradually stabilize within a large domain. Over the last few centuries, the declining trajectory in erosional response to monsoon intensity follows an erratic but unique path. Erosional responses to disturbed land also show organization in phase space (Figure 5d). Variability in erosion is essentially insensitive to land cover openness during the period 2960–1430 cal. yr BP. But the trajectory increases over the next 600 years with respect to relatively small increases in non-arboreal pollen (~25 to 30%), percentage values that do not even reach the maximum observed in the previous period. From 800 cal. yr BP to the present, the trajectory displays a number of large oscillations about a positive trend. Again, the very recent trajectory appears to follow a unique path.

The similar patterns in the two erosion phase diagrams might be easily explained if the monsoon intensity and disturbed land were autocorrelated. However, a bivariate plot of the two variables shows no significant correlation and no organization in phase space (Figure 6a). The centennial changes in disturbed and open land are therefore not a function of monsoonal intensity, either as a direct driver of biophysical processes or as an indirect driver of human actions. A further idea that surface erosion processes are strongly associated with flood intensity can also be rejected. The phase diagram of these two variables (Figure 6b) suggests no strong organization in phase space and even a tendency for a weak negative correlation. Thus, increasing erosion levels in the absence of clear positive links to monsoon intensity strongly suggest that monsoon intensity represents a subordinate control on erosion compared with landscape openness. The most likely explanation for the similarity in the erosion phase space patterns (Figure 5c and d) therefore lies in terms of disturbed land *conditioning* the erosional response to monsoonal intensity, through its forcing of internal threshold transgressions.

While a simple analysis of the proxy records (Figure 4) might suggest fairly smooth changes between land cover and erosion, the phase diagrams give more information, providing evidence for threshold transgression, hysteresis and alternative steady states (eg, Walker and Meyers, 2004). Analysing the association between disturbed land and erosion in detail (Figure 7), we can describe one early non-degraded steady state prior to ~1430 cal. yr BP and a second steady but degraded state after ~800 cal. yr BP, with a transition lasting ~600 years. This implies that around 1400–1450 cal. yr BP an internal threshold (T1 in Figure 7) was transgressed that led to rapid erosion. This seems to mark an irreversible switch in landscape dynamics, because recovery of the land cover since ~150 cal. yr BP has not led to a concomitant reduction in erosion but rather it has produced only a minor reduction along the axis of the second steady state. It is thus an example of a system exhibiting hysteresis over centennial timescales, a property that has implications for landscape rehabilitation.

Possible trajectories of recovery are drawn (two dashed arrows from T2 in Figure 7), which include one that parallels the earlier mean trajectory of change between the steady states. It suggests erosion levels might decline rapidly as a simple function of reforestation. However, more plausible is the linear extrapolation of the modern trajectory away from the current steady state at T2 that simulates the erosional response to total reforestation of the

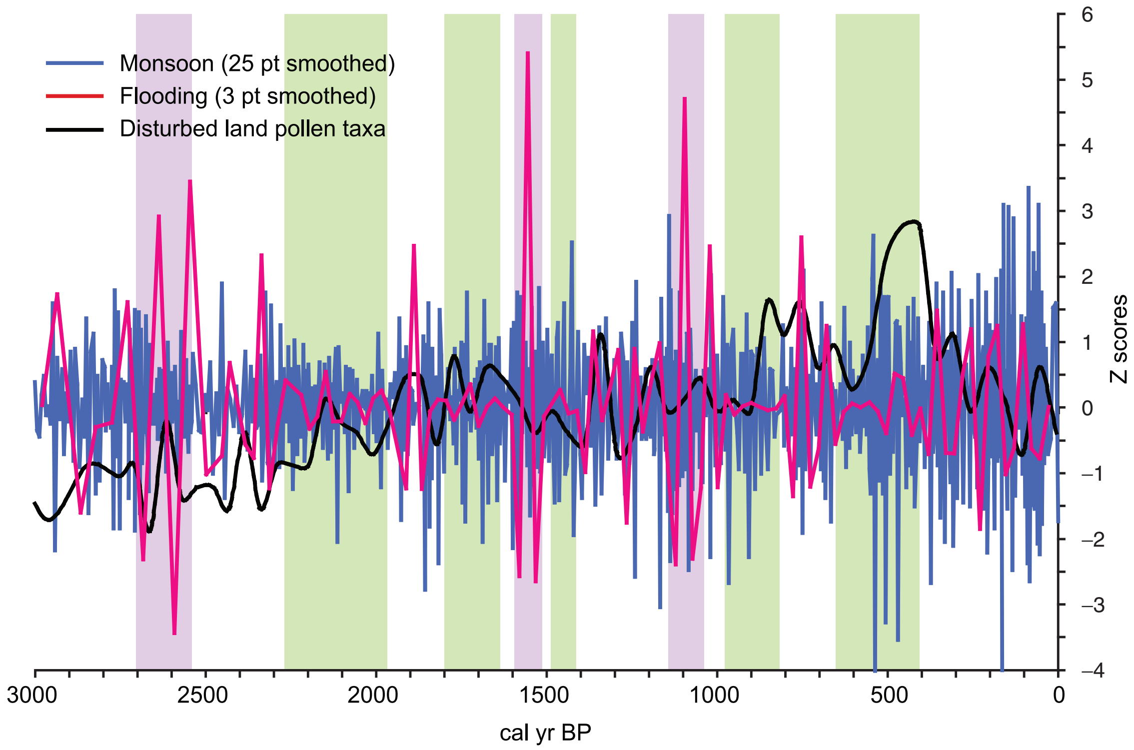

Figure 8 High frequency variability in monsoon and flood intensities over the past 3000 years based on detrended data (Figure 4a 25 pt smoothed and Figure 4f 3 pt smoothed) with superimposed curve for disturbed land pollen taxa (Figure 4c). All data plotted as *z* scores to aid comparison of relative changes. Darker vertical bars show periods when flooding > ±2.5 units and lighter vertical bars show periods when flooding < ±0.5 units

landscape (say, equivalent to NAP = 10%). Within a short time (~100 years) the system could theoretically achieve maximal forest cover, but the intersection of the arrow with NAP=10% (dotted line in Figure 7) suggests that erosion would be expected to remain relatively high. This is explained in terms of large gully systems that continue to act as conduits for eroded soil and sediment under forest cover for a significant period of time. Thus, the establishment or rejuvenation of gullies led to a second system state from which recovery in terms of partial stabilization is highly non-linear and, within human timescales, essentially irreversible.

Slow and fast processes

Resilience theory predicts that complex systems will exhibit cross-scale interactions in both temporal and spatial domains, but the use of centennial data in the phase analysis excludes the study of driver–response associations at annual and decadal timescales. This raises the question of whether there are important functional processes operating over shorter timescales (higher frequencies), particularly the annual and subannual magnitude-frequency variations in climate. While the modes of sediment dating and sampling preclude a finer temporal analysis of the land-use and erosion proxies in the Erhai sediments, the monsoon intensity proxy data based on speleothems (~ one measurement per 4 years) allows analysis at more or less decadal levels. Thus comparison of the residuals from detrended curves of monsoon and flood intensities may provide insight into the associations between high frequency monsoon variance and centennial flooding (Figure 8). Additional consideration of the pollen-based land-use changes may also give insight into the possible moderating effects of land use and cover on flooding.

The flood record (Figure 8) indicates three periods (~2650–2550, ~1575–1525 and ~1125–1025 cal. yr BP) where the magnitude-frequency regime is dominated by very high flood magnitudes (residual *z* values >±2.5) and five phases (~2300–1950, ~1850–1600, ~1525–1400, ~1000–800 and ~600–375 cal. yr BP) where the magnitudes in flood intensity are very low (residual *z* values <±0.5). However these periods are not linked consistently to corresponding regimes in the frequency-magnitude record of the monsoon intensity. Indeed the main feature of the monsoon record is the steadily rising variance from ~300 to 400 cal. yr BP onwards during a time when flood magnitudes remain at intermediate levels. Overall, the coupling between frequency-magnitude regimes in the monsoon and flood response over decadal timescales is weak. Additionally, all the periods of very low flood variance lie within the period (~2500–400 cal. yr BP) of rising values for disturbed land taxa, and there is some suggestion that the three periods of very high flood variance occur during periods of *low* disturbance: that is, before the onset of irrigated rice farming (~2650–2550 cal. yr BP), and at the end of later cultivation expansion phases (~1575–1525 and ~1125–1025 cal. yr BP).

We may therefore hypothesize that decadal–centennial changes in land use, rather than higher frequency changes in precipitation, have exerted stronger controls on flooding through the modulating effects of irrigated paddy fields and hill terraces that create large water storage areas. The most recent rising trend in the variance of monsoon intensity would be expected to amplify flood intensities, and certainly many floods are recorded in the documentary record for the last 400 years (Elvin *et al*., 2002). But the associated variance in the flood proxy record is intermediate (Figure 8), suggesting that residual paddy field and terrace systems, along with hydraulic engineering, may have continued to subdue the natural flood response during this period. This analysis provides further evidence for the conditioning effect of land use on both the erosional and flood response to monsoon intensity. In terms of resilience theory, the effects of the relatively fast variable of monsoon intensity on erosion and flooding are determined by the slow scale of land use and vegetation cover, as argued for in other mountain landscapes (eg, Foster *et al*., 2003).

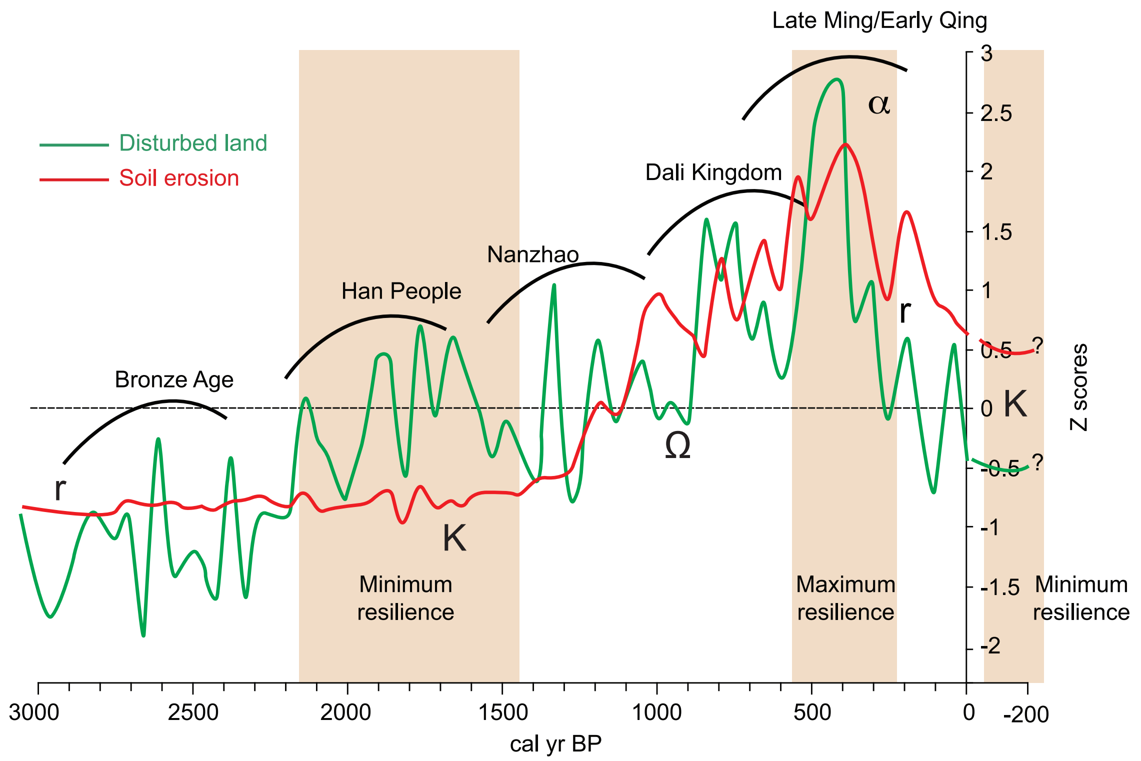

Figure 9 The land use–soil system in the Miju catchment over the past 3000 years, showing proxy curves for disturbed land and soil erosion (Figures 4c and 4e), documented periods of human impact, possible phases (r, K, Ω and α) of the erosion adaptive cycle (Figure 1), and likely periods of maximum and minimum resilience (Figure 1) in the erosion system

Land use–erosion adaptive cycle

The existence of major thresholds, alternative steady states and linked slow and fast processes is consistent with a complex, dynamic and adaptive system, suggesting that the adaptive cycle concept may be applicable. The evidence from phase diagrams suggests that one macroscale adaptive cycle can be drawn with respect to the impacts of land use and vegetation on soil erosion for the whole Miju catchment over 3000 years (Figure 9). Over this time period we can identify a low impact state before ~1400 cal. yr BP where we can surmise that soil and substrates were accumulating nutrients, organic and inorganic particles and developing soil horizons through long term pedogenesis. This was a conservation phase (K) possibly preceded by the development or rapid growth phase (r). Following the expansion of agricultural land and loss of forest during the later centuries of the conservation phase the soil was finally destabilized at ~1400 cal. yr BP and released (Ω) by processes of rilling and gullying. Soil and gully erosion continued to increase until the cessation of agricultural intensity allowed the re-organization (α) of the vegetation-soil system that led to stabilization of slope surfaces after 400 cal. yr BP. During the past 400 years, the modified slope and soil forms (soil depth, slope angles, gully network) have represented a transient but novel state for renewed soil and slope development: the exploitation phase (r). This implies that the modern or near future land use-soil system is approaching the conservation phase (K).

However, we can also deduce from the documentary records five shorter adaptive cycles of social and land-use organization that are represented by the disturbed land curve (Figure 9). Comparing the phasing of the two sets of adaptive cycles shows a variable level of correspondence. The Bronze Age and Han cycles of agriculture are within the r and K phases in erosion. The Nanzhao and Dali cycles correspond to the Ω phase in erosion (~1400–800 cal. yr BP), and there is a tendency for erosion to peak during the back loops of the land-use cycle (ie, when disturbed land is decreasing). Similarly, from 600 cal. yr BP the erosion cycle peaks during the back loop in the land use cycle (~400 cal. yr BP) within the documented Ming/Qing environmental crisis. This is not only further evidence for erosional responses lagging behind land-use change. It also suggests that peak erosion rates were less about the initial exploitation of steep slopes for dry terraced farming than to the subsequent abandonment of those systems a few centuries later. Reduced social capital expended in terrace maintenance may have impacted strongly on the release phase of the slower erosion cycle thus allowing the gully network to continue to extend. The greater fluvial connectivity of the gully systems led to an amplification in the flood magnitudes that in turn provided a positive feedback process for continued gully growth.

Discussion

The Erhai panarchy

In a panarchical sense (Gunderson and Holling, 2002), the changes in the reconstructed Erhai landscape may be viewed in terms of at least four nested cycles or sets of linked relationships operating at different temporal scales. From the analysis above, we can identify a macroscale (centennial–millennial) land use–erosion cycle, and possibly a mesoscale (decadal–centennial) land use–flooding cycle. To these, we can add a microscale (seasonal–annual) monsoon– flooding cycle apparent in instrument records from the twentieth century (J.A. Dearing, unpublished data, 2003), while a fourth (millennial) climate–vegetation and flooding cycle is apparent in full Holocene records (Shen *et al*., 2006; Dearing *et al*., 2008) where we may observe vegetation and flood regimes tracking the orbitally forced monsoon trend (Wang *et al*., 2005). At submillennial scales, the slow variable of land use and vegetation cover drives the major changes in erosion and flooding regimes.

There are several episodes in the record that illustrate how the different temporal scales can appear to interact strongly: suppression of future flooding through the introduction of paddy field agriculture; the lagged responses of erosion to successive periods of land use; and the Ming/Qing environmental crisis that led to the building of extensive and expensive flood protection measures that continue to require maintenance today. However, such storylines may not be totally accurate because in each case the spatial extent of the variable in question is assumed to be constant through time, which for reconstructions of erosion and land use is unlikely. Palaeoenvironmental records give less useful information about spatial scales than temporal scales, and normally require complementary information about the spatial extent of processes and conditions from other sources. For the Miju catchment, the documentary and archaeological evidence for changing spatial patterns of agriculture and habitation is minimal. The best geo-referenced evidence lies with the geomorphological evidence of preserved fluvially eroded features, such as gully systems, and datable alluvial sequences. Field examination of eroded field systems shows many instances where gullies have dissected older agricultural terrace systems. Today, gully systems exist on all lower slopes throughout the ~50 km long Miju catchment up to an altitude of ~3000 m, but particularly on the basaltic slopes. However it is difficult to ascertain whether the five periods of agricultural expansion have been synchronous throughout the catchment over centennial timescales. If not, the land use–soil erosion adaptive cycle may need re-interpretation in terms of spatially cumulative effects of land use on erosion processes and gully networks. Indeed, resilience theory predicts that systems in the conservative phase are associated with a decline in heterogeneity and resilience (Holling, 1986). Thus the release phase in erosion could be linked to the cascading effect of increasingly connected gully systems as land use becomes homogenized, rather than to their overall stage of development.

Lessons for the future

Over 3000 years the Miju catchment system has been shaped by the concatenation of slow and fast socio-ecological variables leading to changes in geomorphic, biological and hydrological regimes. When viewed from a centennial time perspective, the 'environmental health' of the modern catchment might be considered satisfactory. Trajectories for disturbed land and slope instability are now declining and are currently at levels last witnessed more than 800 years ago. They are, however, far removed from 'natural' or pre-impact levels and constitute a strongly human-dominated landscape. The flood regime, though displaying destructive low frequency-high magnitude events, still appears to be suppressed in relation to the relatively higher monsoon intensities experienced over the past few centuries.

With respect to these variables, the modern catchment may be described as lying between the exploitation and conservation phases of the adaptive cycle but within an alternative human-dominated state where erosion levels are unnaturally high and flood magnitudes probably unnaturally low. Together they allow the maintenance of high population levels and intensive agriculture. According to resilience theory, maximum resilience in the land use–erosion system may have been reached some 200–300 years ago (Figure 9) following the late Ming/early Qing environmental crisis. However, the system at that time was also dysfunctional with active gully systems and high erosion levels, demonstrating that past periods of maximum resilience should not necessarily be used as a guide or target for modern landscape management. It rather suggests that the current 'steady' degraded state (Figure 7) is resilient to change: it may be virtually impossible to manipulate the landscape to its pre-gullied state or to some other preferred state.

In the future, the current degraded landscape could move towards the conservation phase. This would be typified by apparent stability, with low resilience to land use change, but where the system variables were most vulnerable to large perturbations. What form would these future perturbations take? On the current level of system understanding, we can surmise that land-use modifications rather than climate changes would constitute the most detrimental perturbations. Loss of the paddy field system would increase surface runoff to the channels, and cause a shift in the frequency-magnitude of flooding to a flashier regime. The continued maintenance of existing flood protection measures would be essential as sediment is still being delivered from hill slopes. Removing the flood protection measures, such as the Miju river dykes, might be thought an ideal action to promote resilience but could only be considered if the sediment sources were stabilized at higher levels than exist now. It also follows that any inappropriate land use on slopes, and around those villages situated on the interfluves areas, that accelerates runoff and leads to the rejuvenation of the gullies would also constitute a detrimental practice.

Palaeoecology and resilience theory

The Erhai study demonstrates how palaeoecological, geomorphic, archaeological and documentary data sets may be usefully integrated within a theoretical framework to provide insight about the resilience of a modern landscape to human and climate perturbations. The existence of records over thousands of years provides an essential long-term perspective for viewing the evolution of decadal–millennial processes that underpin socio-ecological change. The availability of continuous time series of process-responses provides evidence for thresholds and alternative steady states at, at least, centennial timescales that might be difficult to identify where only discontinuous data exist. In this sense, resilience theory may provide additional options for creating hypotheses about system behaviour that can be included in the development of dynamic simulation models (Anderson *et al*., 2006; Dearing, 2006, 2007; Dearing *et al*., 2006b).

Stable soils and surface water flows are key conditions that contribute to the overall quality of ecological services in the Miju catchment. However the full set of ecological services would also include biogeochemical cycles, water quality, groundwater levels, biodiversity, fishing, etc. Sustainable management may be viewed as the capacity to create, test and maintain adaptive capability (Holling *et al*., 2002). Thus a major challenge would be the integration of different historical and palaeoenvironmental profiles to provide a holistic view of adaptive capability across the whole catchment.

Recently, there has been an attempt to classify modern socio-ecological systems according to syndromes of human–environment interaction (Lüdeke *et al*., 2004) based on unique functional patterns of human–nature interaction; a global diagnosis dependent on identifying a particular combination of trends in key conditions or processes. For example, the 'Sahel syndrome' is detected by a combination of increases in rural poverty, land degradation and agricultural activities. Adding information about slow-fast processes, thresholds and alternative steady states provided by palaeoenvironmental studies could provide essential insight into the dynamics of these syndromes, which are currently constrained by the length of recorded statistics. In particular a long timescale may allow the position of a system state or process on a cycle or trajectory of vulnerability to be identified: in the case of the Miju catchment, it is approaching the conservation phase. As Holling says: 'One of the principal aims is to define where in their respective adaptive cycles each of the sub-systems is now. Actions that would be appropriate at one phase of the cycle might not be appropriate at other phases. Knowing where you are helps you to define what action needs to be taken' (2001: 402).

Conclusions

(1) Landscape system behaviour reconstructed for the past 3000 years in the Erhai lake-catchment system, Yunnan, SW China, shows the possibility of alternative steady states in the landscape, as expressed by the relationship between land use and erosion in phase space. In particular, a period of agricultural expansion ~1400 cal. yr BP triggered rapid gully erosion that continued to accelerate for 600 years until the formation of a 'steady' eroded landscape state that has existed since ~800 cal. yr BP.

(2) On centennial timescales, disturbed land *conditions* the erosional response to monsoon intensity, through its forcing of internal threshold transgressions. Flooding over decadal–centennial scales is poorly explained by variations in monsoon intensity. Thus decadal–centennial changes in land use, rather than higher frequency changes in precipitation, have exerted stronger controls on both flooding and erosion. Overall, the effect of high monsoon variance on flooding has been suppressed by paddy farming and the maintenance of terraced field systems.

(3) Over the past 3000 years, land use should be considered a 'slow' process relative to the 'faster' monsoon intensity. Mapping the adaptive cycle on to the millennial record of land use and erosion suggests that the modern landscape may be approaching a conservation phase typified by low resilience to land-use change. Potentially detrimental land-use practices would be removal of paddy fields, removal of river dykes and any that accelerated runoff from the interfluves above gully systems.

(4) Such 'historical profiling' of modern landscapes offers a new dimension for hypothesis testing, the development and testing of simulation models and the creation of appropriate management strategies. The palaeoenvironmental records described here could be supplemented with others representing changes in water quality, biodiversity, etc., to provide comprehensive profiles.

(5) Long-term records of landscape processes, drivers and consequences coupled to theoretical frameworks, such as resilience theory, can provide strong foundations for policy-making. Continuous palaeoenvironmental time series have a major role to play in this endeavour.

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