LETTER

Flickering gives early warning signals of a critical transition to a eutrophic lake state

Rong Wang[1,2], John A. Dearing[1], Peter G. Langdon[1], Enlou Zhang[2], Xiangdong Yang[2], Vasilis Dakos[3,4] & Marten Scheffer[3]

There is a recognized need to anticipate tipping points, or critical transitions, in social–ecological systems[1,2]. Studies of mathematical[3–5] and experimental[6–9] systems have shown that systems may 'wobble' before a critical transition. Such early warning signals[10] may be due to the phenomenon of critical slowing down, which causes a system to recover slowly from small impacts, or to a flickering phenomenon, which causes a system to switch back and forth between alternative states in response to relatively large impacts. Such signals for transitions in social–ecological systems have rarely been observed[11], not the least because high-resolution time series are normally required. Here we combine empirical data from a lake-catchment system with a mathematical model and show that flickering can be detected from sparse data. We show how rising variance coupled to decreasing autocorrelation and skewness started 10–30 years before the transition to eutrophic lake conditions in both the empirical records and the model output, a finding that is consistent with flickering rather than critical slowing down[4,12]. Our results suggest that if environmental regimes are sufficiently affected by large external impacts that flickering is induced, then early warning signals of transitions in modern social–ecological systems may be stronger, and hence easier to identify, than previously thought.

The concern that global social–ecological systems are adversely affected by the cumulative impact of multiple interacting drivers[13] has spurred efforts to anticipate abrupt, nonlinear changes[1,2,14–16]. As a result, there are increasing efforts to use system dynamical theory to identify early warning signals of critical transitions[10,11]. For example, close to tipping points, the recovery rate from small perturbations becomes very slow[10]. In the natural fluctuations of a system, such critical slowing down may be signalled by rising levels of variance and autocorrelation[3,4,10,17]. In addition, deformation of the basin of attraction before a critical transition may be detected from increasing skewness[5]. Such theoretical predictions are supported by studies of past climate change[15,18] and manipulated lake ecosystems[6] and by laboratory experiments with zooplankton[7], phytoplankton[8] and fungi[9]. But other studies of palaeoclimate records[19] and ecological models[20] are less conclusive. One problem is that, typically, long time series of high-resolution data are needed. In addition, in stochastic systems with high levels of noise, shifts between alternative basins of attraction may occur far from the classical tipping points at which critical slowing down can be observed. Such situations can give rise to another phenomenon known as flickering, in which the system starts jumping back and forth between alternative basins of attraction[10,11,21]. Here we use a multi-decadal time series from a lake together with model simulations and show that flickering is reflected in relatively low-resolution time series as bimodality and increasing variance, coupled to a decrease in autocorrelation and skewness.

We reconstruct and analyse historical changes in the Erhai Lake-catchment system in Yunnan, China (Supplementary Fig. 1). Monitoring data and official socio-economic statistics provide historical trends for lake water quality and lake water level, population density, land use

and climate from the 1950s to 2009 (Supplementary Information). Longer records of the lake ecosystem are based on laboratory analyses of three lake sediment cores, each of which contains the contemporary mud–water interface. Microscopic counts of fossil diatoms (siliceous algae) and chironomid (non-biting midge) head capsules give multi-decadal proxy records of the aquatic ecosystem to ~125 years ago, and in one core to ~750 years ago (Supplementary Information). Other sediment analyses give information about sediment provenance, organic matter and water chemistry. The timescales for the cores were obtained from a combination of ^{14}C, ^{210}Pb and ^{137}Cs radionuclide determinations (Supplementary Information). We also use a simple model[22] (Supplementary Information) to simulate phosphorus dynamics in a lake approaching eutrophication under a regime of strong external perturbations. The model is defined as follows:

$$dP = \left[\alpha - sP + r\frac{P^n}{P^n + 1^n} \right] dt + \sigma P dW \qquad (1)$$

where P is phosphorus concentration, α is phosphorus input rate (the control parameter), r is the maximum recycling rate ($r = 1$), s is the phosphorus loss rate ($s = 1$), n is the strength of the recycling response to phosphorus concentrations ($n = 8$) and t is time. White noise is added through a Wiener process dW with scaling factor σ ($\sigma = 0.25$). We increased the phosphorus input rate, α, linearly in 2,000 time steps from 0.1 to 0.7, crossing the threshold at which the transition to eutrophication occurs at time step 1,848, when $\alpha = 0.6619$.

Microfossil and geochemical records (Fig. 1a–d) from dated lake sediment cores (Supplementary Figs 2 and 3) were used to reconstruct the trends in the state of lake diatom communities and water quality back to the 1880s, and these records seem to reproduce the abrupt change in algal states observed in recent monitored data, between 2001 and 2005 (Supplementary Fig. 4). From the combined monitored and lake sediment data, it seems that a profound transition in the algal community occurred around 2001. Historical records (Fig. 1e, f) of exogenous drivers (from 1950) strongly suggest that altered trends in algal community composition, starting in the 1960s, track with nutrient loading of the lake driven by agricultural intensification (Supplementary Information). Superimposed on nutrient loading, which is a 'slow' driving variable on a multi-decadal timescale, are the influences of 'fast' driving variables on annual and sub-annual timescales: these fast variables are short-lived changes in water volumes as a result of lake water-level regulation and low rainfall between 1980 and 2000, which together triggered temporary eutrophication events (Supplementary Information). We surmise that as aquatic productivity grew in response to increased nutrient concentrations (Fig. 1c, d), positive-feedback mechanisms (Supplementary Fig. 5) gradually strengthened the eutrophication process: oxygen depletion led to hypolimnetic anoxia (Fig. 1b) and to the recycling of biologically available phosphorus[22] from the upper sediments (Fig. 1c). Despite a return to higher water levels in 2004–05 (Fig. 1e), the strengthened positive feedback (Supplementary Information) prevented recovery of the diatom communities as late as 2009.

[1]Palaeoecological Laboratory, Geography and Environment, University of Southampton, Southampton SO17 1BJ, UK. [2]State Key Laboratory of Lake Science & Environment, Nanjing Institute of Geography & Limnology, Chinese Academy of Sciences, Nanjing 210008, China. [3]Department of Aquatic Ecology and Water Quality Management, Wageningen University, PO Box 47, NL-6700 AA Wageningen, The Netherlands. [4]Integrative Ecology Group, Estación Biológica de Doñana, CSIC, C/Américo Vespucio S/N, E-41092 Seville, Spain.
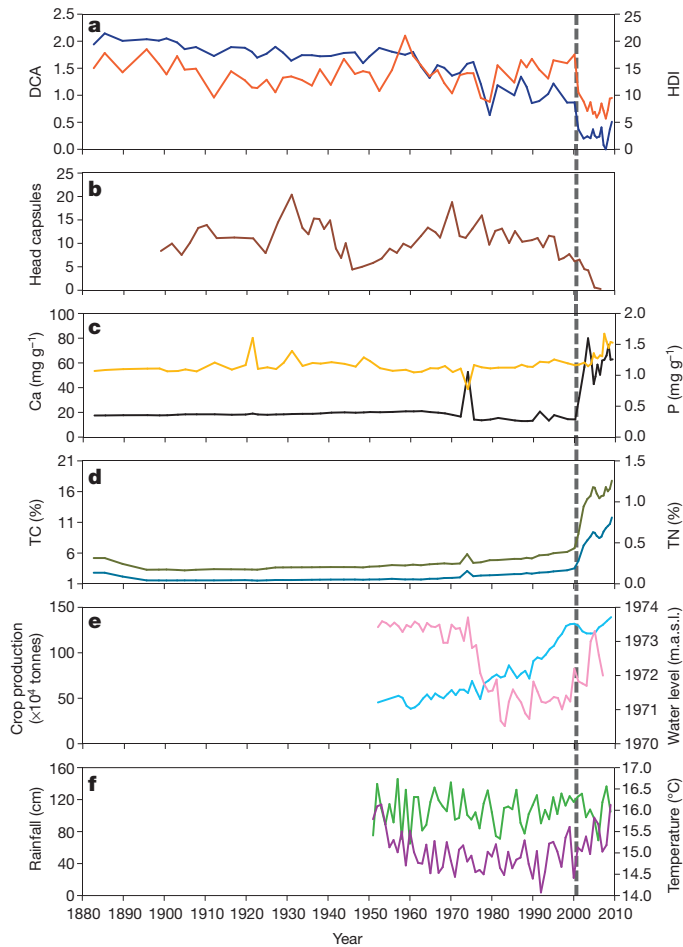
Figure 1 | Lake-sediment-based aquatic-system response variables and historical records of environmental drivers during the period 1883–2009. a, One-dimensional gradients of sediment diatom composition and diversity based on detrended correspondence analysis (DCA axis 1 scores) (blue) and calculated Hill's diversity index N2 (HDI) (orange) of non-interpolated sediment data. The DCA trend shows declining values from about 1965, with two sharp downward changes in about 1982 and about 2001 (dashed vertical line). The HDI data describe a more variable curve with a slight upward trend since the 1980s but an abrupt drop in about 2001. **b**, The abundance of chironomid (non-biting midge) larval head capsules in the sediment (number g^{-1} sediment) reflects the diverse lake conditions, and the very low abundance after 2001 indicates increasing anoxia in the hypolimnion[27]. **c**, The abundance of calcium in the sediment ($mg\,g^{-1}$ sediment) (black) rose in 1977 and after 2001, as a result of the biologically induced precipitation of $CaCO_3$ (calcite), which was linked to high rates of productivity by photosynthetic algae. Increased rates of photosynthesis decreased the level of dissolved CO_2, raised the pH and produced local over-saturation of $CaCO_3$. The total sediment phosphorus abundance ($P\,mg\,g^{-1}$ sediment) (yellow) gradually rose from the 1960s; however, compared with calcium, there was only a small rise after 2003, suggesting partial depletion of sediment phosphorus as a result of anoxic recycling. **d**, Sediment total organic carbon (TC) (% of total sediment mass) (blue) and total nitrogen (TN) (% of total sediment mass) (green) gradually rose from the 1960s and abruptly rose after 2001, indicating rising levels of sedimenting organic matter as a result of increased aquatic productivity. **e**, Historical records of the annual crop yield in the region (Dàlì Bai, an autonomous prefecture of Yunnan) from a constant land area (blue) imply that agricultural intensification occurred from the 1960s and peaked initially in 2000. Historical records of the lowest annual lake water level (in metres above sea level (m.a.s.l.); pink), showing the combined effects of sluice building on outflow regulation for hydroelectric power and dry years after 1975. It should be noted that relatively high water levels were maintained in 2004 and 2005, after the trophic shift. **f**, Mean annual rainfall (green) and temperature (purple).

Several observations indicate[11] that the transition in Erhai Lake in ~2001 corresponds to the classic development of a bistable system. First, the shift in the state of the diatom communities (Fig. 1a) and the abrupt changes in other water quality indicators (Supplementary Fig. 4) are consistent with the behaviour of a lake that is shifting to an alternative, and stable, eutrophic state. Second, the observed multi-decadal increases in nutrient loading as a result of rising crop yields, together with the compounding effects of lake water level and climate variability (Fig. 1e, f), are consistent with the action of a 'slow', non-stationary driving variable that continues through the shift in diatom states. Third, the relatively low variability of diatom data over the past ~750 years suggests that system bistability is a recent phenomenon (Supplementary Fig. 6), and recent multi-decadal data show evidence for increasing bimodality (Fig. 2a). Fourth, statistical analyses and autoregression modelling allow rejection of null hypotheses for the absence of a critical transition and for the shift in diatom states caused by a shift in non-stationary driving variables (Fig. 2b, c and Supplementary Tables 1 and 2). Last, a phase-space plot for the diatom state response to varying concentrations of total dissolved phosphorus shows evidence of alternative states and hysteresis (Fig. 2d).

Detrended records of diatom composition and diversity indices (Fig. 3a, b) show a significant and continuously rising variance from ~1980 (Fig. 3c), whereas skewness (Fig. 3d) and autocorrelation (Fig. 3e) decline. Sensitivity tests (Supplementary Information and
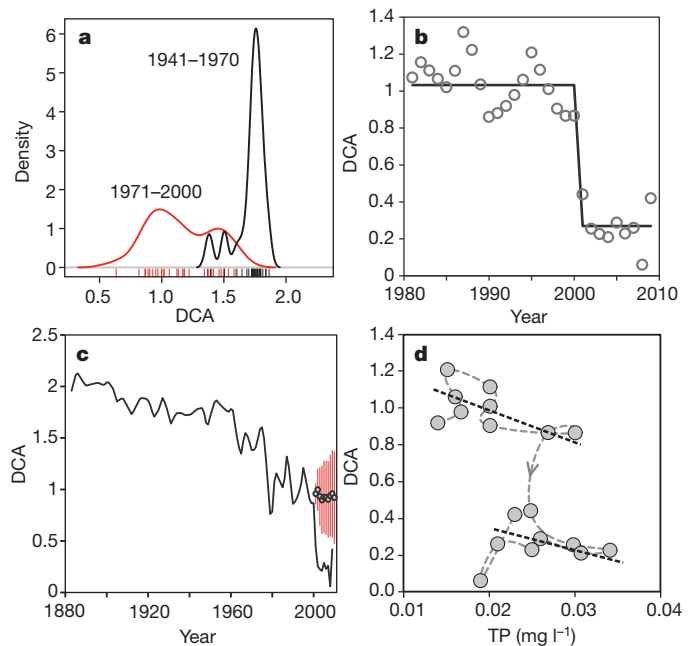

Figure 2 | Evidence for bistability, critical transition, alternative states and hysteresis in the DCA time series. a, Probability density functions (Gaussian kernel density estimation) for the periods 1941–70 (black) and 1971–2000 (red) show increasing bimodality, suggesting the development of a bistable system up to 2001. Short vertical bars show the density of individual points. **b**, A sequential analysis of DCA scores (circles) with mean values (horizontal line) for the period 1980–2030, using Student's t-test, shows a significant ($P \le 0.01$) break point in about 2001. **c**, Predicted values (circles) in the period 2001–10 (vertical red bars represent the probability levels $P \le 0.05$) using the optimum autoregressive integrated moving average (ARIMA) model (Supplementary Table 1) derived from the time series 1883–2000. The clear divergence between the observed values (solid black line) and the predicted values (circles) shows that the proposed transition at about 2001 cannot be explained in terms of the observed data. **d**, A phase-space plot of the dissolved nutrient driving variable (total phosphorus, TP) versus the diatom state response variable (DCA). The plot describes two linear clusters of points, 1992–2001 (upper black dashed line) and 2001–09 (lower black dashed line), suggesting two alternative diatom states for all TP values in the range 0.02–0.03 mg l^{-1}, which is equivalent to ~50% of the whole TP scale: this finding is strong evidence for alternative states and hysteresis.

Supplementary Fig. 7) indicate that these findings are robust. The declines in skewness and autocorrelation suggest that the increased variance cannot be explained by critical slowing down of a system close to equilibrium[19]. With strong evidence for exogenous drivers, we can reject an alternative explanation for increasing variance in terms of internal noise generated solely by endogenic changes[19]. Thus, the rising variance is most likely to represent the interaction of multiple exogenous drivers and the crossing of internal thresholds that magnify system responses and induce flickering between alternative attractors[12,17]. In large data sets, flickering can be detected by distinct probability distributions of system states given by potential analysis[23,24]. Our data are too sparse to carry out a full potential analysis, but evidence of flickering at Erhai Lake exists in the form of observed eutrophication events and algal blooms between 1980 and 2000 (Supplementary Information) and in the increased variance in the diatom indices (Fig. 3c). Flickering is also supported by the apparent bimodality[17] in the frequency distribution of states (Fig. 2a). Overall, the system dynamics changed on a multi-decadal timescale, and the critical transition, in about 2001, was presaged by signals of rising variance caused by flickering that started 10–30 years previously (Fig. 3c and Supplementary Fig. 7i), a similar timescale to that found in mathematical models of lake regime shifts[4,17].

We checked whether the observed changes in autocorrelation, variance and skewness are consistent with flickering over a bistable region, by comparing the behaviour of these metrics to metrics estimated in
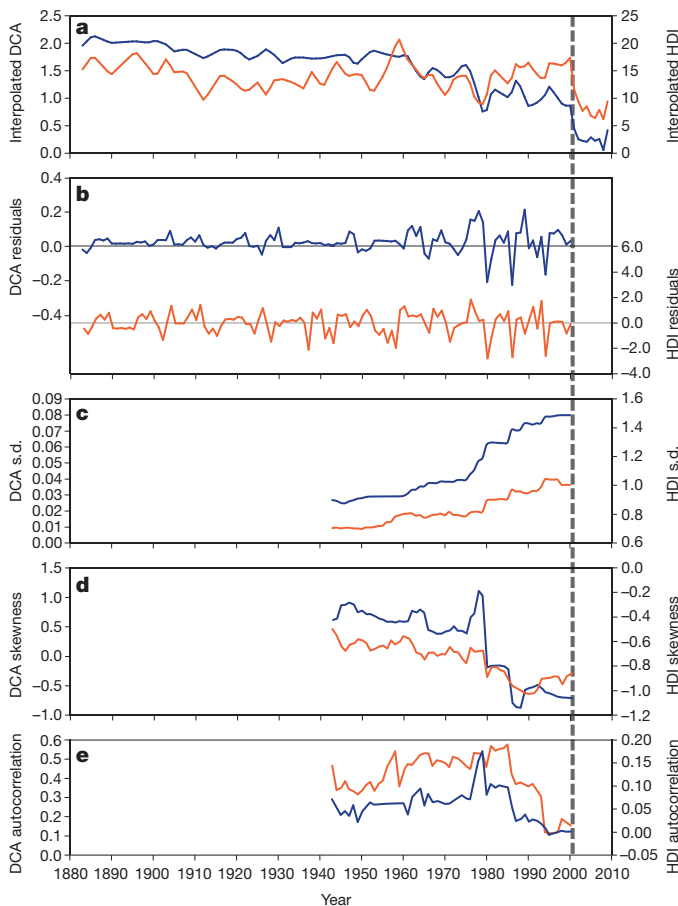
simulated time series from a simple model[22] that describes the transition of a lake to eutrophic conditions (Supplementary Information). In this model, a positive feedback between phosphorus concentration and phosphorus recycling from the sediment causes alternative stable states (Fig. 4a). Under the strong noise regime that we impose, the
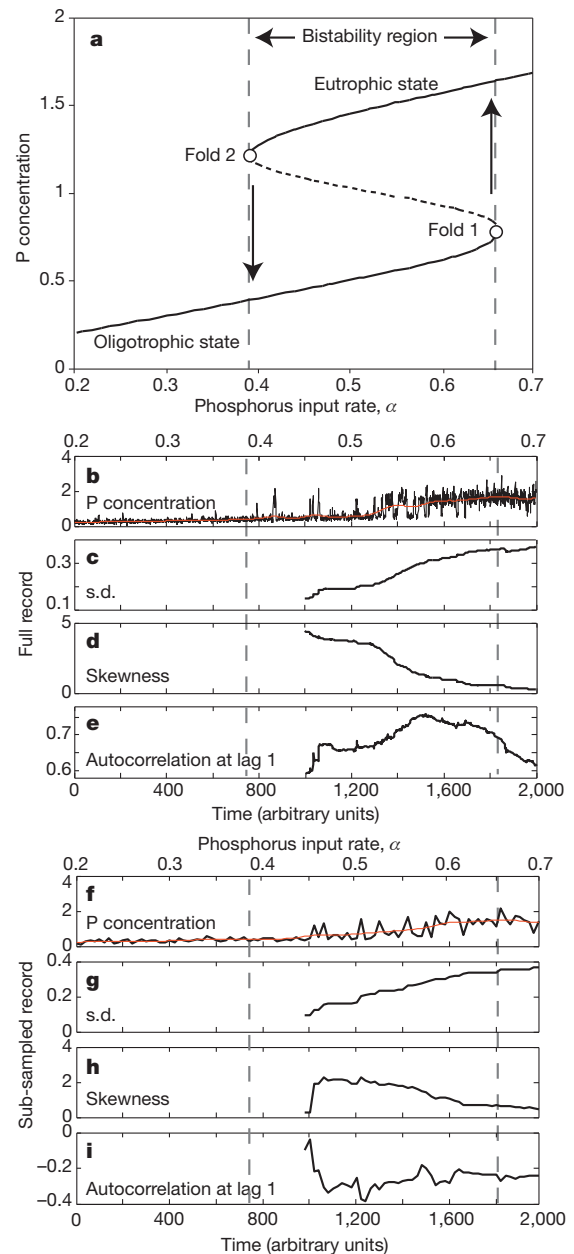

Figure 4 | Response of the lake model to increased phosphorus loading, and early warning signals. a, Equilibrium phosphorus concentration in the water as a function of the input rate. The middle section of the curve between the two bifurcation points, fold 1 and fold 2, consists of unstable saddle points that mark the border between the basins of attraction of the two stable branches of the hysteresis curve. **b**, Simulated response of the stochastically forced model to a gradual increase in phosphorus input rate over the same range covered by the axis in **a**. **c–e**, Early warning signals, s.d. (**c**), skewness (**d**) and lag 1 autocorrelation (**e**) for the full data, high-resolution, record (**b**). **f**, As for **b**, but sub-sampled (every 20 points) to give a coarse-resolution record. **g–i**, Early warning signals, s.d. (**g**), skewness (**h**) and lag 1 autocorrelation (**i**), for the coarse-resolution record (**f**). The vertical dashed lines mark the region of hysteresis in the non-stochastic model (**a**), corresponding to the parameter region with flickering in the stochastically forced model (**b**). Skewness, s.d. and autocorrelation were computed for a sliding window (a half time series) after removing a trend (red lines) using a Gaussian smoothing function and were plotted to the right of the window. All y-axis values are dimensionless.

Figure 3 | Potential early warning signals of the regime shift in the lake trophic state for DCA (blue) and HDI (orange) time series. a, Interpolated one-dimensional gradients for sediment diatom composition (derived from Fig. 1a). **b**, Positive and negative residuals from **a**, with grey horizontal lines showing zero values. **c**, Variance of **b** using s.d. **d**, Skewness of **b**. **e**, Lag 1 autocorrelation of **b**. (**c–e**, Plots were calculated using a 59-year (half time series) sliding window through the period 1883–2001 and are plotted to the right of the window.) The dashed vertical line denotes 2001.

dynamics over a range of parameter values are characterized by flickering between the alternative basins of attraction (Fig. 4b, f). This flickering results in bistability in the system before the system settles more permanently into an alternative state. Variance rises in both the original 'high-resolution' time series (Fig. 4c) and in a sub-sampled 'coarse-resolution' record (Fig. 4g). Skewness decreases to zero in both series (Fig. 4d, h). Autocorrelation rises in the high-resolution time series (Fig. 4e), until it drops in the last part of the record before the transition. But autocorrelation declines to zero or even negative values over the flickering region in the sub-sampled time series (Fig. 4i). Although published reports on systems with small fluctuations around equilibrium also show simultaneous increases in variance, autocorrelation and skewness[11], our results show that highly stochastic systems can produce contrasting patterns. The observed rise in variance, together with the simultaneous declines in autocorrelation and skewness, in the Lake Erhai records is thus in line with the findings expected for a flickering system sampled at relatively low time resolution.

Our findings have several implications for detecting transitions in real world systems. First, in systems in which exogenous drivers result in high levels of disturbance, flickering can be a more likely source of early warning signals than critical slowing down. Second, flickering will produce a rise in variance coupled to a decrease in skewness and autocorrelation at low time resolutions. Third, flickering can start before the stage at which the attractor of an alternative state becomes strong enough to capture the system from the noisy regime of forcing. Thus, a flickering signal in a modern system can be considered a direct warning that the system has left the 'safe operating space'[16]. Fourth, the potential advantages and ease of finding flickering signals suggests that every opportunity should be taken to study multi-decadal time series of modern social–ecological systems, even if the available data are of low resolution. Because monitored data do not always provide sufficiently long timescales of observations, especially for ecological variables, proxies such as the ones derived from sediment studies could be a useful resource in this respect[25,26].

1. Carpenter, S. R. *et al.* Science for managing ecosystem services: beyond the Millennium Ecosystem Assessment. *Proc. Natl Acad. Sci. USA* **106,** 1305–1312 (2009).
2. Nicholson, E. *et al.* Priority research areas for ecosystem services in a changing world. *J. Appl. Ecol.* **46,** 1139–1144 (2009).
3. Brock, W. A. & Carpenter, S. R. Variance as a leading indicator of regime shift in ecosystem services. *Ecol. Soc.* **11,** 9 (2006).
4. Biggs, R., Carpenter, S. R. & Brock, W. A. Turning back from the brink: detecting an impending regime shift in time to avert it. *Proc. Natl Acad. Sci. USA* **106,** 826–831 (2009).
5. Guttal, V. & Jayaprakash, C. Changing skewness: an early warning signal of regime shifts in ecosystems. *Ecol. Lett.* **11,** 450–460 (2008).
6. Carpenter, S. R. *et al.* Early warnings of regime shifts: a whole-ecosystem experiment. *Science* **332,** 1079–1082 (2011).
7. Drake, J. M. & Griffen, B. D. Early warning signals of extinction in deteriorating environments. *Nature* **467,** 456–459 (2010).
8. Veraart, A. J. *et al.* Recovery rates reflect distance to a tipping point in a living system. *Nature* **481,** 357–359 (2012).
9. Dai, L., Vorselen, D., Korolev, K. S. & Gore, J. Generic indicators for loss of resilience before a tipping point leading to population collapse. *Science* **336,** 1175–1177 (2012).
10. Scheffer, M. *et al.* Early-warning signals for critical transitions. *Nature* **461,** 53–59 (2009).
11. Scheffer, M. *Critical Transitions in Nature and Society* (Princeton Univ. Press, 2009).
12. Brock, W. A. & Carpenter, S. R. Interacting regime shifts in ecosystems: implication for early warnings. *Ecol. Monogr.* **80,** 353–367 (2010).
13. Beddington, J. Food security: contributions from science to a new and greener revolution. *Phil. Trans. R. Soc. B* **365,** 61–71 (2010).
14. International Council for Science. *ICSU Strategic Plan II* 2012–2017 (International Council for Science, 2011).
15. Lenton, T. M. *et al.* Tipping elements in the Earth's climate system. *Proc. Natl Acad. Sci. USA* **105,** 1786–1793 (2008).
16. Rockström, J. *et al.* A safe operating space for humanity. *Nature* **461,** 472–475 (2009).
17. Carpenter, S. R. & Brock, W. A. Rising variance: a leading indicator of ecological transition. *Ecol. Lett.* **9,** 311–318 (2006).
18. Dakos, V. *et al.* Slowing down as an early warning signal for abrupt climate change. *Proc. Natl Acad. Sci. USA* **105,** 14308–14312 (2008).
19. Ditlevsen, P. D. & Johnsen, S. J. Tipping points: early warning and wishful thinking. *Geophys. Res. Lett.* **37,** L19703 (2010).
20. Hastings, A. & Wysham, D. B. Regime shifts in ecological systems can occur with no warning. *Ecol. Lett.* **13,** 464–472 (2010).
21. Taylor, K. C. *et al.* The 'flickering switch' of late Pleistocene climate change. *Nature* **361,** 432–436 (1993).
22. Carpenter, S. R., Ludwig, D. & Brock, W. A. Management of eutrophication for lakes subject to potentially irreversible change. *Ecol. Appl.* **9,** 751–771 (1999).
23. Livina, V. N., Kwasniok, F. & Lenton, T. M. Potential analysis reveals changing number of climate states during the last 60 kyr. *Clim. Past* **6,** 77–82 (2010).
24. Hirota, M., Holmgren, M., Van Nes, E. H. & Scheffer, S. Global resilience of tropical forest and savanna to critical transitions. *Science* **334,** 232–235 (2011).
25. Dearing, J. A., Braimoh, A. K., Reenberg, A., Turner, B. L. & van der Leeuw, S. Complex land systems: the need for long time perspectives to assess their future. *Ecol. Soc.* **15,** 21 (2010).
26. Dearing, J. A. *et al.* Extending the timescale and range of ecosystem services through paleoenvironmental analyses: the example of the lower Yangtze basin. *Proc. Natl Acad. Sci. USA* **109,** E1111–E1120 (2012).
27. Little, J. L., Hall, R. I., Quinlan, R. & Smol, J. P. Past trophic status and hypolimnetic anoxia during eutrophicaton and remediation of Gravenhurst Bay, Ontario: comparison of diatoms, chironomids, and historical records. *Can. J. Fish. Aquat. Sci.* **57,** 333–341 (2000).

Author Contributions R.W. designed the research, undertook fieldwork, performed diatom and mathematical analyses, compiled historical data and wrote the paper. J.A.D. and P.G.L. designed and supervised the research and wrote the paper. E.Z. and X.Y. undertook fieldwork, performed and supervised other analyses, and commented on the manuscript. V.D. and M.S. carried out modelling experiments and wrote the paper. All authors discussed the results and commented on the final manuscript.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to J.A.D. (j.dearing@soton.ac.uk).