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Extending the timescale and range of ecosystem services through paleoenvironmental analyses, exemplified in the lower Yangtze basin

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In China, and elsewhere, long-term economic development and poverty alleviation need to be balanced against the likelihood of ecological failure. Here, we show how paleoenvironmental records can provide important multidecadal perspectives on ecosystem services (ES). More than 50 different paleoenvironmental proxy records can be mapped to a wide range of ES categories and subcategories. Lake sediments are particularly suitable for reconstructing records of regulating services, such as soil stability, sediment regulation, and water purification, which are often less well monitored. We demonstrate the approach using proxy records from two sets of lake sediment sequences in the lower Yangtze basin covering the period 1800–2006, combined with recent socioeconomic and climate records. We aggregate the proxy records into a regional regulating services index to show that rapid economic growth and population increases since the 1950s are strongly coupled to environmental degradation. Agricultural intensification from the 1980s onward has been the main driver for reducing rural poverty but has led to an accelerated loss of regulating services. In the case of water purification, there is strong evidence that a threshold has been transgressed within the last two decades. The current steep trajectory of the regulating services index implies that regional land management practices across a large agricultural tract of eastern China are critically unsustainable.

Over the past decade, ecosystem services (ES) have become central to discussions about the sustainable management of natural resources. A key review of the science for managing ES (1) highlighted the need for "networked, place-based and long-term social-ecological research" (ref. 1, p.1309). However, critical data needs include comprehensive time series information for major social and ecological states covering a range of appropriate timescales. Such views were already held by the Millennium Ecosystem Assessment (2), for example "the weakness in documentation and information on regional trends remains a serious handicap" (ref. 1, p. 837), and have recently been reiterated in the Council of Scientific Union (3) reports dealing with Earth System Science for Global Sustainability. The UK National Ecological Assessment (4) also highlights the gaps in information about trends that exist despite a science infrastructure that has supported the regular monitoring of many aspects of the UK environment.

Alternative sources of data for ecological change over the last few decades and centuries lie in natural archives, such as lake sediments. The paleoenvironmental community, comprising paleoecologists, paleolimnologists, and geomorphologists, has generated large amounts of proxy data that reconstruct different ecological and functional processes and services in many regions of the world. Over the past 50 y the ability to interpret sediment records as proxies for specific environmental processes has become increasingly refined, with the use of multivariate statistics and modern-day calibrations. Paleoenvironmental research has long been concerned with climate and human impacts on natural processes (5) but has yet to fully embrace the ecosystem service agenda (cf . refs. 6 and 7) that demands integration of social and ecological records. Despite several papers referring to how paleoenvironmental records may be used with respect to specific ecological issues, like biodiversity and conservation (e.g., refs. 8–10), there is no review of the scope and application of multiproxy records to the study of ES. In national/international reports dealing with ES (e.g., ref. 2), paleoenvironmental proxies are usually confined to reconstructing past climate. The aim of this paper is to rectify this situation with a case study using paleoenvironmental and socioeconomic records from the lower Yangtze basin, China.

Long Records of Ecosystem Services. The argument is often made (1, 2) that long records are needed to understand the dynamic behavior of coupled socioecological systems. We can categorize this need in greater detail (11, 12).

Fast and slow processes. Social and ecological processes and services operate over a wide range of timescales, with some longer than direct monitoring programs (12, 13). The relatively "slow" processes, like regional land use transformation, are strongly implicated in controlling resilience (14).

Trends and rates. Long trends in processes and system states allow comparison of directions and relative rates of change and help identify critical points of inflection, for example the Anthropocene (15), the Great Acceleration (16), or the Great Moderation (17).

Complex behavior. Extended timescales of modern processes may reveal the types of complex behavior and variability that are prevalent in the history of a specific process or system, for example alternate steady states, thresholds, and magnitude–frequency relationships (18, 19). Potentially they afford the means to analyze phase shift indicators (20).

Interactions. Reconstruction of how drivers and responses interact over different timescales can give insight into multiple-scale interactions (21), contingencies (22), path-dependency (23), and convergent trajectories (24). An integrated set of long-term records allows for a better understanding of how the modern system has

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evolved, for example with respect to trade-offs between provisioning and regulating services.

Modeling. Long timescales offer the scope for developing and testing socioecological models that can provide alternative future scenarios. These range from conceptual models like the adaptive cycle to systems- and agent-based simulation models (25).

Reference states. An ability to observe conditions before major environmental impact may provide a reference state against which to define restoration or management targets and give insight into the distance the modern process or service has moved from some background level (26–28).

How we choose to define the time period represented by "long records" depends on the processes involved and the history of the system. From existing studies of recent accelerating trends in global phenomena (16), we might argue that at least 60 y is a minimum timescale to observe the major developments in many modern socioecological systems. However, it is difficult to make generalizations about a maximum timescale without hindsight. At one end of the scale, significant impact on ecosystem processes in northeastern North America may date from just the beginnings of European agriculture, ~150 y ago. However, at the other end, some socioecological systems with long human histories may be currently exhibiting responses to impacts that are *to some degree* contingent on human actions stretching back millennia. For example, the pattern and frequency of river flooding and slope instability in European mountain areas partly reflect the impact of early deforestation (e.g., ref. 29). Additionally, some reconstructions of biophysical states, such as lake water pH, confirm timescales of natural, self-organized, change taking place over centuries and millennia (30, 31).

Paleoenvironmental Records of Ecosystem Services

Paleoenvironmental records are obtained from naturally occurring archives of material that record environmental signals (e.g., refs. 5, 32, and 33). Some archives comprise sediments that accumulate in aquatic and marine environments: bog, floodplain, lake, estuary, and ocean. Other sediments accumulate as wind-blown particles on terrestrial surfaces, like the Chinese loess plateau. Other records are contained in ice cores, tree rings, and cave deposits (speleothems). The properties of the sediments are identified by visual observations, imaging, microfossil investigation, and a variety of analytical techniques that include stable isotopes, geochemistry, and mineral magnetism (34–36). Absolute dating of lake sediments deposited over the last few decades is usually undertaken with radioisotope techniques, ^{210}Pb (half-life 22.3 y) and ^{137}Cs (hemispheric records of atmospheric bomb fallout), and spherical carbonaceous particles (regional records of industrial particulate pollution). In other settings, and over longer timescales, events of known age, like volcanic dust layers and annual laminations, or ^{14}C dating, provide age control (37, 38). There are numerous examples of dated proxy records for ecological processes and conditions (biotic and abiotic) stretching back over past centuries with a temporal resolution measured in decades, or finer, up to the present. These reconstructed records represent processes within the atmospheric, terrestrial, and aquatic components of bog, lake, river estuarine, and near-shore coastal ecosystems or catchments covering a wide range of spatial scales, from 10^1 to 10^4 km^2.

Following the Millennium Ecosystem Assessment Synthesis (2), we have mapped proxy records on to "supporting"", "provisioning", "regulating", and "cultural" ES categories (Table 1, column 1). For subcategories, we identify or define >50 representative processes or system states (Table 1, column 2) for which recognized types of paleoenvironmental proxy record exist (Table 1, column 3). For some processes and states there are several potential kinds of proxy records. For example, information for the regulating service, water purification, may be gained from lake sediments in several ways: (*i*) the flux or concentration of dissolved nutrients (e.g., phosphorus) deduced from changes in a range of aquatic microfossil/macrofossil groups calibrated against direct measurements of water chemistry, (*ii*) the flux or concentration of dissolved nutrients and organic matter deduced from inorganic and organic analyses, (*iii*) evidence for oxygen depletion or anoxia in a lake water column deduced from changes in microfossil groups (e.g., bottom water-dwelling insect larvae such as chironomids) and analyses of redox-sensitive metals (e.g., Fe and Mn), and (*iv*) surface water acidity deduced from diatom-inferred pH.

In practice, we should discriminate between direct and indirect proxy records of ES. Direct proxies signal the changing nature of ES states, for example where a high floristic richness index based on pollen counts is interpreted as representing high biodiversity. However, information about other ES, such as erosion regulation, relies on studying levels of degradation in the service, as expressed by soil erosion rates. Here we refer to these levels as indirect proxies: As recorded by a specific process they represent the inverse of an ES. With long records, preimpact or baseline levels of natural ES provision can be defined. Indirect proxies may then be interpreted as relative ES losses, deficits, or the inability of the natural system to provide service due to increasing system modifications by anthropogenic activities or climate.

New techniques for deriving proxies are continuously being developed and the interpretation of proxies in terms of quantitative reconstructions of processes continues to evolve. Thus, further entries in Table 1 for new processes/states and proxies can be expected. Nevertheless, there are several ES categories for which there are no obvious paleoenvironmental proxies, including the subcategories "biochemicals, natural medicines, and pharmaceuticals," "ornamental resources," and "pollination". It seems that the "regulating services" category may have the greatest number of potential paleoenvironmental proxy records. Importantly, these services are often the least well monitored, especially in remote areas and developing nations.

We demonstrate the scope and potential of using proxy records to study multidecadal changes in ES through the use of paleoenvironmental datasets obtained from the lower Yangtze basin for the period 1800–2006 in conjunction with modeled climate data and published statistics for land use, population, and economic development.

Case Study: Lower Yangtze Basin

Context. The lower Yangtze basin (LYB) occupies ~12% (220,000 km^2) of the total Yangtze basin. A diverse set of landscapes provides ES such as wildlife habitats, freshwater, food supply, water and erosion regulation for >300 million people. The current status of ES in the LYB owes much to the complex interactions between natural environmental change, human activities, and policies that stretch back several millennia. The timings of flooding and drought may be linked to the variability of the Asian monsoon and the El Niño-Southern Oscillation but the impact on the human population is often linked to land management practices. Deforestation has reduced forest cover from a natural level of ~80% total area to 16% in the mid-20th century (124). Recent land degradation is believed to have contributed to the destructive impacts of the major Yangtze flood in 1998 (125). The famines during the period 1958–1961 are now associated with agricultural collectivization during the time of the Great Leap Forward policies as well as drought (126). The dismantling of collective farming systems following the "opening-up" reforms in the early 1980s expanded the rural economy and led to rapid reductions in poverty (127). However, continued investments in fertilizers, pesticides, irrigation, land reclamation, effluent disposal, flood protection, farm mechanization, and crop intensification have led to widespread ecological degradation. There is already much evidence at the local scale for slope instability (128), higher flood frequency (129), and declining water quality (130, 131). A number of national programs to reduce ecosystem degradation have been deployed in the region, for example, the Sloping Land Conversion Program in the Dabie Mountains (132) and the National Wetland Action Plan for China (133) but these have not always produced positive ecological and socioeconomic outcomes (134, 135).

Table 1. Paleoenvironmental proxy records of ecosystem services based on categories used in ref. 2 (table 2.1, pp. 41–45)

Ecosystem service	Process/state	Proxy record	Publication example
Supporting services			
Nutrient cycling	Weathering	Geochemistry	(39)
		Stable isotopes	(40)
		Diatoms	(41)
	Biogeochemical fluxes	Geochemistry	(42)
Photosynthesis	Aquatic	Carbon isotopes	(43)
Primary production	Terrestrial biomass	Pollen microfossils	(44)
		Genetic biomarkers	(45)
	Aquatic productivity	Fossil pigments	(46)
Soil formation	Weathering	Geochemistry	(39)
Water cycling	Hydrological state, groundwater		
	Peat wetness	Testate amoebae	(47)
	Peat humification	Colorimetry	(48)
	Stalagmite properties	Luminescence	(49)
	Lake levels	Ostracods	(50)
		Stratigraphy/geochemistry	(51, 52)
Provisioning services			
Biochemicals, natural medicines and pharmaceuticals	—	—	—
Food	Cultivated/crop land	Pollen microfossils	(53–55)
		Phytoliths	(56)
	Pasture	Pollen microfossils	(57)
	Fish, salmon	Stable nitrogen isotopes	(58, 59)
	Fish, freshwater	Fish fossils	(60)
Fiber	Fuel, wood		
	Forest/scrub cover	Pollen microfossils	(53–55)
		Organic macrofossils	(61)
	Wood/charcoal burning	Charcoal	(62)
	Timber	Pollen microfossils	(63)
	Hemp	Pollen microfossils	(64)
Genetic resources	Biodiversity, invasive species and extinctions		
	Terrestrial	Pollen microfossils	(65–67)
		Plant macrofossils	(68)
		Organic biomarkers	(69)
		Geochemistry/stable isotopes	(70)
		DNA taxonomy	(71)
	Aquatic	Algae	(72, 73)
		Zooplankton and zoobenthos	(74, 75)
		DNA taxonomy	(76)
Ornamental resources	—	—	—
Fresh water	Salinity	Diatoms	(77)
		Chironomids	(78)
Regulating services			
Air quality regulation	Atmospheric particulates	Polycyclic aromatic hydrocarbons	(79)
		Other persistent organic pollutants	(80)
		Heavy metals	(81)
		Mercury	(82)
		Spherical carbonaceous particles	(83, 84)
		Magnetic spherules	(85)
	Acidity	Diatoms	(86, 87)
Climate regulation	Carbon sequestration		
	Lake sediment	Carbon accumulation	(88–90)
		Inorganic carbon accumulation	(91)
	Peatlands	Carbon accumulation	(92, 93)
	Land cover/land use	Pollen microfossils	(54, 55)
Disease regulation	—	—	—
Erosion regulation	Sediment flux/retention	Detrital accumulation rates	(94, 95)
	Sediment source	Geochemistry	(96, 97)
		Radioactive isotopes	(98)
		Biomarkers	(99)
		Magnetic minerals	(100, 101)

Table 1. Cont.

Ecosystem service	Process/state	Proxy record	Publication example
Natural hazard regulation	Landslides	Sediment stratigraphy	(102,103)
	Earthquakes	Sediment stratigraphy	(104)
	Storms	Stratigraphy, pollen microfossils, tree rings	(105)
	Tsunami	Sediment stratigraphy, tree rings	(106)
		Diatom microfossils	(107)
Pest regulation	Arboreal disease	Pollen microfossils	(108)
		Coleoptera fossils	(109)
Pollination	—	—	—
Water purification and waste treatment	Pesticide contamination	Organic compounds	(110)
	Nutrient fluxes/eutrophication	Diatom/cladocera microfossils	(74, 111)
		Organic carbon	(112)
		Nitrogen and carbon isotopes	(113)
		Biomarkers	(114)
		Plant macrofossils	(115)
	Dissolved oxygen/anoxia	Redox metals, biogenic silica	(116)
		Chironomid microfossils	(117)
	Surface water acidity	Diatom-inferred pH	(86, 87)
Water regulation	Flood discharge	Stratigraphy, particle size	(118–120)
	Drought/groundwater	Lake levels, tree rings	(121, 122)
Cultural services			
Aesthetic values	Water quality (see Water purification above) Biodiversity (see Genetic resources above)		
Cultural diversity	—	—	—
Cultural heritage values	Cultural landscapes	Pollen microfossils	(63, 123)
Education values	—	—	—
Inspiration	—	—	—
Knowledge systems	—	—	—
Recreation and ecotourism	Water quality (see Water purification above) Biodiversity (see Biodiversity above)		
Sense of place	—	—	—
Social relations	—	—	—
Spiritual/religious values	—	—	—

The publications shown are selected to exemplify applications, showing original and review papers where available, but do not represent an exhaustive list. The symbol "—" in the table body refers to the apparent absence of proxy records.

To assess how this highly interconnected and complex socio-ecological system may be managed more effectively it is important to understand how the drivers of change (both human and physical) have impacted ES over the decades leading up to the present. Key questions to address include the following:

Which regulating services are most degraded?
How have ES responded to external drivers?
How have different social and ecological elements interacted over time, particularly in terms of driving abrupt change caused by threshold transgressions?
Are there long-term convergent trends in socioecological drivers and ES responses?
Does the past offer guidelines on natural variability, limits, or reference points for management targets?
Can we model the regional relationships and trade-offs between economic development, population growth, and ES?

Proxy Records of Ecosystem Services. Proxy records for the categories of regulating services erosion regulation, water purification, and air quality regulation and for the provisioning service genetic resources (defined in ref. 2) were generated for the period 1800–2006 for two large lake-catchment sites, Chaohu and Taibai, both situated north of the Yangtze river some 240 km apart and draining the Dabie mountain range (Fig. 1 and Table S1). Pairs of curves for equivalent proxy records from the two lakes show some differences attributable to local variations in landscape and the history of human activities (Fig. S1). However, the long-term trends are sufficiently similar to justify averaging the data from the two lakes into six regional curves for *biodiversity*, *sediment regulation*, *soil stability*, *sediment quality*, *water quality*, and *air quality* (these terms refer to regulating service proxies shown in Figs. S2, 2, and 3) (see Table S2 for definitions). Aggregating the curves into an index of regulating services [*Regulating services (RS) index*] provides a useful measure of the changing state of regulating services across the region (Fig. S2).

Frequencies and trends. Changes in biodiversity, sediment regulation, and soil stability since 1800 show curves fluctuating over multidecadal periods with no clear trends (Fig. S3). Low levels of biodiversity are recorded in the mid-19th century, in the 1920s–1940s, and at the present time. Levels of sediment regulation remain high until the beginning of the 20th century, also reaching low levels in the late 1940s just before the start of the People's Republic of China. Levels of soil stability rise from low values in the mid-19th century to reach peak values in the 1920s before declining and, to some extent, stabilizing. In contrast, curves for

Fig. 1. Lower Yangtze basin showing the Chaohu and Taibai lake-catchment sites in the counties of Shucheng and Huangmei, the location of the Dabie mountains, and major regional cities.

sediment quality, water quality, and air quality are relatively stationary before the 1930s but all show strongly declining trends starting in the modern era: sediment quality, 1950; air quality, mid-1950s; and water quality, 1980. This set of sharply turning curves suggests that regional ecological thresholds may have been transgressed. The RS index shows the long-term trend declining from ~1920 and steepening after 1965. The late 19th century represents the last period when all of the regulating service time series were relatively high and stationary, suggesting sustainable land use.

A close-up of the period 1930–2006 (Fig. 2) shows fluctuating curves for biodiversity and sediment regulation with weak positive trends up to the 1980s and limited downward trends up to 2006. It seems that a recovery of sediment regulation from 1945 to 1980 may in part be due to the growth in the number of small irrigation and check dams. Biodiversity declined sharply after 1965 as a result of deforestation associated with agricultural collectivization. The relatively stable values for biodiversity, sediment regulation, and soil stability after 1990 are evidence of successful environmental regulation (e.g., reforestation) since the 1980s, although the rapid loss of biodiversity and soil stability in 2005 may show the effects of accelerating urban growth on previously farmed land. In contrast, the high rates of change and relative losses of sediment quality, water quality, and air quality indicate the most degraded regulating services. Sediment quality and air quality appear to have stabilized after 2000 but the downward trend in water quality has accelerated after 1980 with the most rapid deterioration taking place since 2000. On this evidence, the status of water quality may be moving through a critical transition before reaching an alternate steady state (18). In general, the RS index has dropped from ~0.67 in the mid-1960s to ~0.24 in the mid-2000s.

Socioenvironmental drivers. Normalized curves for regional land use (*arable land*), climate (*annual T* and *annual P*), *population*, and gross domestic product (*GDP*) for Anhui Province allow assessment of socioeconomic drivers (Fig. 3). Additional indexes were calculated for *RS per capita* and *RS per arable area* (Fig. 3) to assess the effects of changing population and land use on regulating services, respectively. The amount of arable land conversion rose

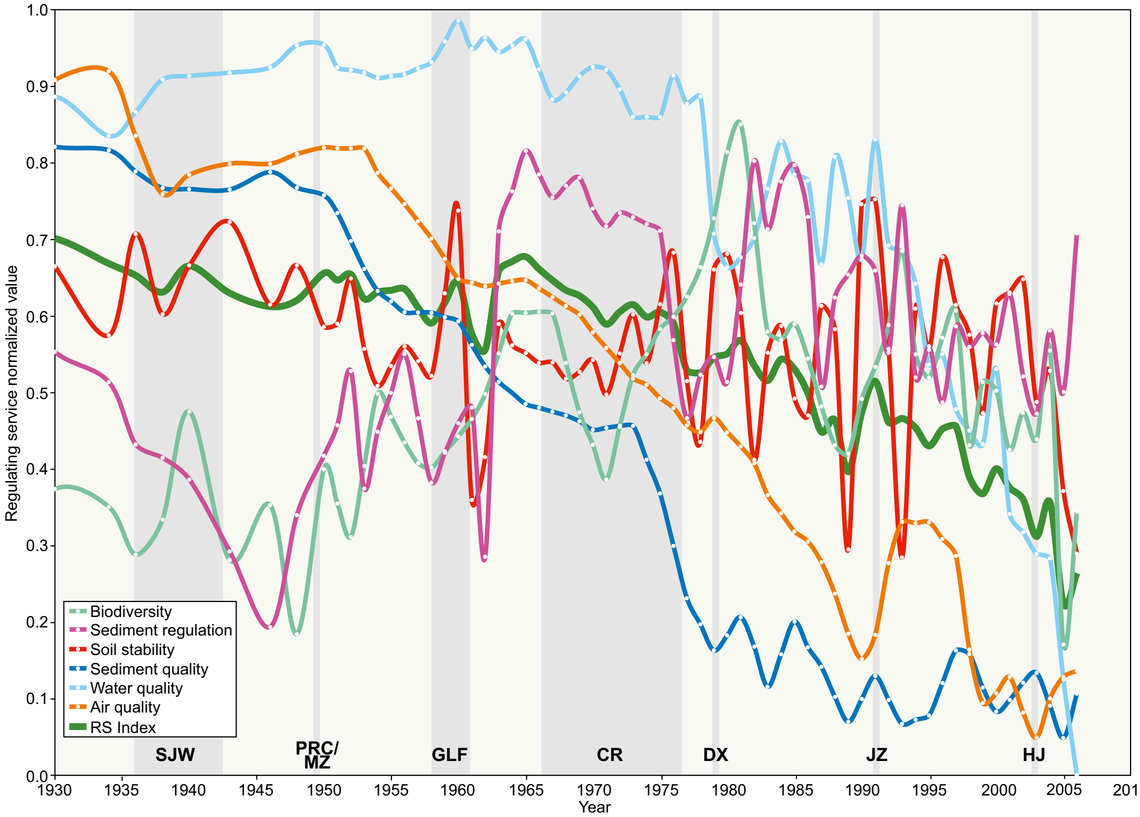

Fig. 2. Lower Yangtze basin, 1930–2006: normalized regulating service proxy records biodiversity, sediment regulation, soil stability, sediment quality, water quality, air quality, and RS index. Vertical bars show major 20th–21st century political events (from left to right): People's Republic of China founded by Mao Zedong, 1949; Great Leap Forward, 1958–1961; Cultural Revolution, 1966–1976; Deng Xiaoping's economic reforms from late 1970s to early 1980s; leadership of Jiang Zemin from 1989; and leadership of Hu Jintao from 2003.

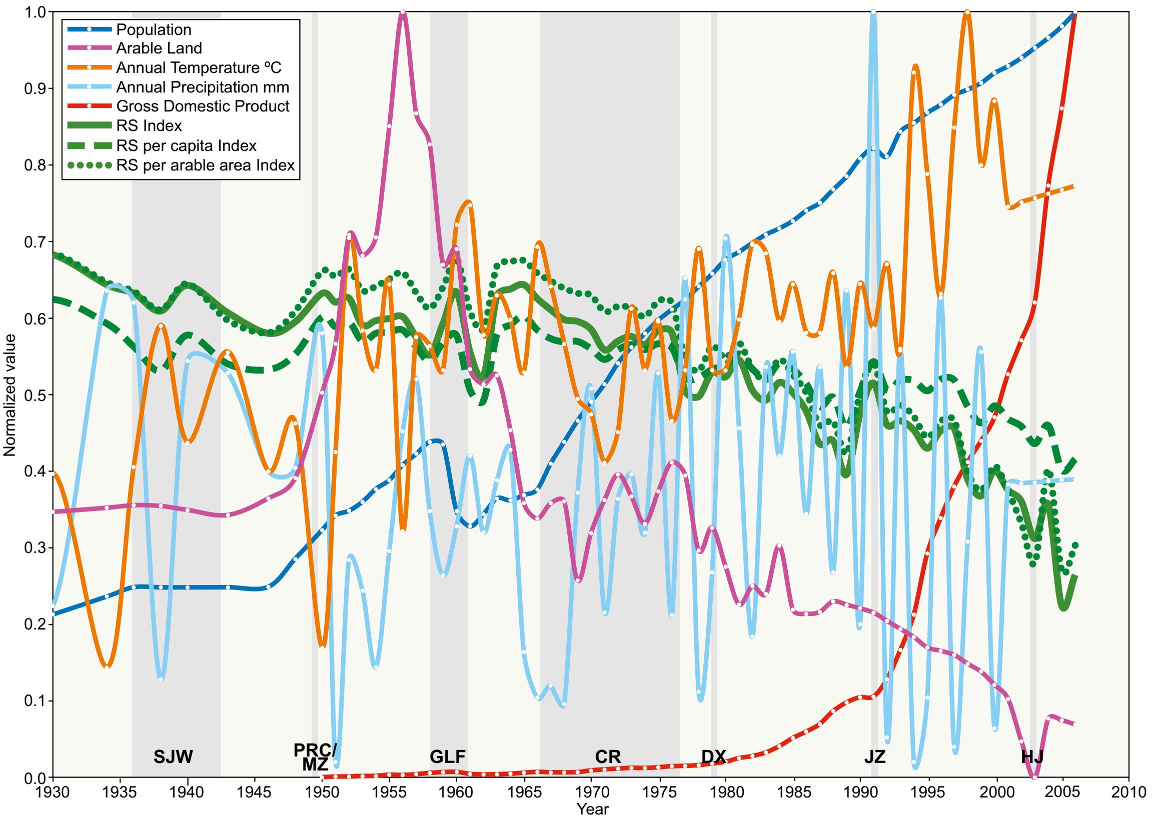

Fig. 3. Lower Yangtze basin, 1930–2006: normalized records for GDP (1950–2000), population, arable land (Chinese unit mu), annual T (°C) and annual P (mm) with normalized RS index (Fig. 3), and RS per capita and RS per arable land area indexes. Vertical bars show major 20th–21st century political events (from left to right): People's Republic of China founded by Mao Zedong, 1949; Great Leap Forward, 1958–1961; Cultural Revolution, 1966–1976; Deng Xiaoping's economic reforms late 1970s to early 1980s; leadership of Jiang Zemin from 1989; and leadership of Hu Jintao from 2003.

dramatically at the start of the People's Republic of China before declining rapidly through the 1960s as converted marginal land often failed to provide sustainable farming. Arable land has continued to decline, reaching lowest levels in 2003, as a result of the increased spread of urban land. Population numbers accelerated after 1945 and fell back after the Great Leap Forward in the late 1960s and 1970s, before continuing to rise to the present day. Annual T shows rising values in the late 20th century, particularly after the 1990s. Annual P shows no distinct trend but the envelope of variability appears to have increased in the early 1990s.

The timing of changes in the RS index suggests that the multidecadal decline in regulating services started after the main peak in arable land conversion in the 1960s and before the apparently changing climate of the 1990s. The post-1965 decline of the RS index that parallels both the population rise and the decline in arable land points strongly to agricultural intensification and industrial development as the main drivers of regulating service losses. RS per capita and RS per arable land area show similar curves to that of the RS index, with the exception of a less steeply declining curve for RS per capita since 1990. Economic development and an increase in regional wealth are clear trade-offs for the decline in regulating services over four decades. The GDP curve (data only from 1950) rose relatively slowly under the leadership of Mao Zedong and began to accelerate under the opening-up reforms of Deng Xiaoping, before rising faster under Jiang Zemin and faster still under Hu Jintao. These four political phases of economic development are closely tracked by the successively steepening stages in the curve of declining RS index.

Development and degradation. Previous analyses of relationships between environmental degradation and income, for example Kuznets curves (cf. ref. 140), at the Chinese provincial level suggest that only a few high-income areas have reached the stage of environmental improvement (141). The relationship between economic development (GDP) and environmental degradation (the reversed RS index) over five and a half decades for the LYB data set suggests (Fig. 4*A*) a positive but nonlinear relationship with a clear inflection ∼1980. This relationship mainly represents the shift from early agricultural land transformation to agricultural intensification through productivity growth in smallholder agriculture (127). Although these changes have helped to alleviate extreme poverty levels in rural communities (127), there is no evidence to argue that environmental degradation is lessening at the present time (although data after 2006 are needed to test opposing claims) (142).

Despite a one-child policy since 1978, the regional population has roughly doubled since 1950. Since 1990 this rate has exceeded the loss of regulating services as shown by the divergence of RS index and RS per capita index curves (Fig. 3), meaning that the regulating service deficit per person has actually reduced. The important finding, however, is the highly linear and positive trend in the relationship between population and environmental degradation (Fig. 4*B*). The statistically significant relationship ($r^2 = 0.90$ for the whole dataset) breaks down only during the early 1960s when the RS index reverses in the aftermath of the Great Chinese Famine of 1958–1961.

The available data support a Perfect Storm metaphor for the convergence of socioenvironmental drivers and ecosystem stresses driving the socioecological systems toward unsustainable conditions and threshold transgression (24): Past success in poverty alleviation must be tempered against the possibility of future ecological failure. The data presented here can be used to create hypotheses that are testable through further analysis and dynamical modeling:

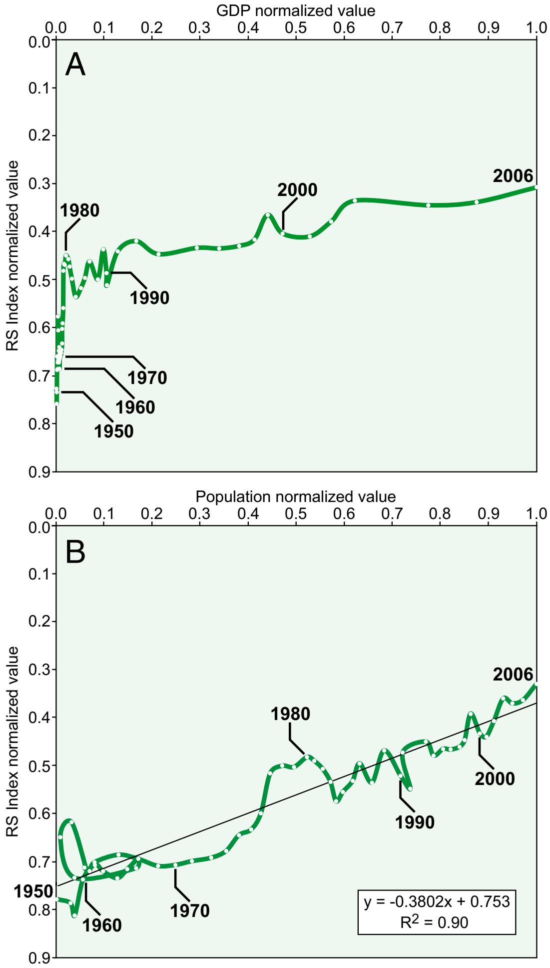

Fig. 4. Lower Yangtze basin, 1950–2006: (*A*) environmental degradation (reversed RS index) vs. economic development (GDP); (*B*) environmental degradation (reversed RS index) vs. population. (All normalizations are based on data from 1950 to 2006.)

Since 1950, the effect of population growth on regulating services has shifted from direct agricultural impacts to indirect industrial impacts.

Agricultural intensification continues to be the main multidecadal driver of losses in regulating services.

Improved environmental policies and regulation after the late 1980s have helped to stabilize losses of biodiversity and erosion regulating services.

Regional water purification services have already crossed thresholds.

The region has yet to reach a stage where economic development and ecological degradation are decoupled.

Similar reconstructions of regulating services and drivers across China (and elsewhere) would provide a unique basis on which to both make regional comparisons of ES status and develop appropriate management and adaptation strategies.

Discussion

The LYB case study underlines the power of paleoenvironmental records to provide multidecadal perspectives on changing ecological states and services. Even a relatively limited number of proxy records can provide an insightful audit for a landscape, generating useful hypotheses about the drivers of specific ES, the rates of service loss, the type of complex behavior, and potential reference points for restoration or management goals. Importantly, the complex interactions and dynamics revealed strongly warrant against the use of linear modeling techniques either as the appropriate tools for future projections or as the means to understand past relationships. There are, however, several caveats to note.

Accuracy and Precision. Paleoenvironmental proxy records vary from qualitative, semiquantitative to fully quantitative measures but only rarely are they calibrated to give the accuracy and precision of the equivalent monitored or surveyed data. Transfer functions based on modern-day relationships between a proxy, such as the distribution of diatoms, and an environmental variable, such as aquatic P concentration, are common techniques used to produce quantitative estimates of past changes. However, care is needed to exclude or disentangle the effects of strongly correlating variables on the response function (115, 143, 144).

Time Series. Proxy records cannot always be treated as time series for the purpose of statistical analyses. Some records, for example from tree rings and annually resolved laminated sediments (e.g., ref. 145), show equal time increments but, normally, changing sedimentation rates determine that time intervals between samples are irregular. Nevertheless, innovative spectral analysis and statistical modeling, for example variance partitioning (146, 147) and additive models (148), mean that the effect of a driver on a response can often be quantified with estimates of uncertainty. There may also be a temporal lag in an ecological response to some drivers and pressures, so that a cause and effect relationship may not occur on the same timeline (149).

Spatial Inference. Whereas some lake and river sediment records express a signal that potentially represents the whole bounded catchment, the spatial representation of others is less clear. For example, proxy records of vegetation derive mainly from the wind transport of pollen grains with an unbounded source. Thus, pollen records are increasingly processed using mathematical models that calibrate distributions of pollen grains in terms of spatial estimates of land cover (e.g., refs. 54 and 55).

Availability of Records. Regions with rich lake and bog records tend to exist in temperate glaciated mountains (e.g., English Lake District), large river systems with complex floodplains (e.g., Yangtze River), and tectonically active zones (e.g., East African Rift Valley). Some proxies listed in Table 1 are site specific, in the sense that the sediment properties exclusively depend on certain local features. For example, speleothems are linked only to limestone geology, and pollen-based reconstructions of vegetation are often difficult in the tropics where insect pollination dominates. Nevertheless, most regions have some natural archives that can be analyzed for proxy records and the reconstruction of ES. In this sense, the "provision of scientific records" as an ES demands more attention be given to the conservation of natural archives for scientific study.

Despite these caveats, the message is clear. As global concerns turn strongly toward impacts and adaptation within regions, it is time to use more effectively the wealth of information produced by paleoenvironmental reconstruction methods. Regional and global reconstructions of multidecadal trends for temperature and precipitation have been used to test hypotheses about the drivers of climate and to test outputs from global circulation models (150). The same approaches with respect to the future of ecosystem processes and services can be applied to regions throughout the world. Compiling, scrutinizing, integrating, and modeling multidecadal paleoenvironmental records should now be viewed as a major international science priority.

Materials and Methods

Normalized mean values of paleoenvironmental data representing six ES proxies (Table S3) from the two lakes were used to represent the region as a whole. These values were supplemented with official statistical data

(Table S4) for changes in population and gross domestic product (151, 152), land use (153, 154), and regional climate model outputs (155).

A sediment core $\sim$100 cm long was taken in the deepest area in each of the two lakes with a piston corer in 2006. Core sediments were subsampled at a 0.5-cm resolution for 0–50 cm and 1-cm resolution below 50 cm. Sediment samples were dated using ^{210}Pb and ^{137}Cs by nondestructive gamma spectrometry. Given the complexity and heavily impacted nature of the hydrological system in Yangtze shallow lakes, a constant rate of supply (CRS) model was used to calculate a chronology and depth–age curves for each core (156). Paleoenvironmental data from both lakes were converted from depth to age using depth–age models back to 1840. Before 1840 the records were linearly extrapolated with derived average sediment rates. Typical 2 SD errors at 1950 are ± 5 y, at 1900 ± 10 y, and at 1800 $\pm$ 30 y. To allow calculation of mean values from records in different lakes and generation of *x-y* plots, all paleoenvironmental data were matched to dates corresponding to dates in official statistical records, using linear interpolation between dated samples.

Sediment Regulation Proxy. Dry mass sediment accumulation rates were calculated from dry density data and wet accumulation rates.

Biodiversity Proxy. For pollen analysis, $\sim$2 g wet sediment of each subsample was treated with a modified acetolysis procedure (157), including HCl, NaOH, HF, and acetolysis. The concentrate was mounted in glycerol gel. Each pollen sample was counted under a light microscope at 400× magnification in regularly spaced traverses. For each sample, total count was >400 grains and a total terrestrial pollen sum (excluding spores) was used for pollen percentages. Rarefaction indexes for floristic taxon richness were calculated following ref. 65.

Soil Stability Proxy. Freeze-dried subsamples were packed into prescreened 10-mL polystyrene sample pots and analyzed using a dual-frequency Bartington Instruments MS2 sensor. Frequency-dependent magnetic susceptibility was calculated on a mass-specific basis as the difference between values at the two frequencies divided by sample mass (101).

Air Quality and Sediment Quality Proxies. Pb, P, and other metals were measured by inductively coupled plasma-atomic emission spectrometry. The accuracy of analytical determinations was established using the reference material GSD-9 (supplied by the Chinese Academy of Geological Sciences) and analytical accuracy for all elements was >95%.

Water Quality Proxy. Sedimentary diatom samples were prepared using standard techniques (158). All samples were mounted on microscope slides using Naphrax and were observed under a light microscope at 1,000× magnification. Diatom taxonomy mainly followed Krammer and Lange-Bertalot (159) and diatom data were presented as relative abundances. The reconstructions of the lake water total phosphorus (TP) concentration were based on the diatom–TP transfer functions established from 45 modern lakes in the middle and lower reaches of the Yangtze River (137).

Scaling and Indexes. For this study all raw data (Tables S3 and S4) were normalized (0–1) so that trends could be easily compared and aggregated. The formula used for scaling the data series $(x_1{:}x_n)$ to (0:1) is $x_1 - (\min x_1{:}x_n)/[(\max x_1{:}x_n) - (\min x_1{:}x_n)]$, where min and max are minimum and maximum values within the data range. In the case of biodiversity, values of 1 and 0 equate to highest and lowest levels of ES. For all other proxy records, values in the range 1–0 were inverted so that values of 1 and 0 equate to highest and lowest levels of ES, respectively. Raw data were also expressed on per capita and per arable land use bases by dividing through by population numbers and arable area, respectively. These data were scaled and averaged with equal weighting to produce curves per capita and per arable land use. Composite indexes were produced to compress a large amount of data into a simple measure, as recently produced by the International Geosphere–Biosphere Program (160) for global climate change. The scaled curves were combined additively to produce three regional indexes: regulating services index (cf. ref. 161), regulating services per arable land area index, and regulating services per capita index.

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1. Carpenter SR, et al. (2009) Science for managing ecosystem services: Beyond the Millennium Ecosystem Assessment. *Proc Natl Acad Sci USA* 106:1305–1312.
2. Millennium Ecosystem Assessment (2005) *Ecosystems and Human Well-Being: Synthesis* (Island Press, Washington, DC).
3. International Council for Science (2010) *Earth System Science for Global Sustainability: The Grand Challenges* (International Council of Science, Paris).
4. UK National Ecosystem Assessment (2011) *The UK National Ecosystem Assessment: Technical Report* (United Nations Environment Programme-World Conservation Monitoring Centre, Cambridge, UK).
5. Smol JP (2008) *Pollution of Lakes and Rivers: A Paleoenvironmental Perspective* (Wiley-Blackwell, Oxford), 2nd Ed.
6. Pederson GT, Gray ST, Fagre DB, Graumlich LJ (2006) Long-duration drought variability and impacts on ecosystem services: A case study from Glacier National Park, Montana. *Earth Interact* 10(4):1–28.
7. O'Reilly CM, Alin SR, Plisnier P-D, Cohen AS, McKee BA (2003) Climate change decreases aquatic ecosystem productivity of Lake Tanganyika, Africa. *Nature* 424:766–768.
8. Froyd CA, Willis KJ (2008) Emerging issues in biodiversity and conservation management: The need for a palaeoecological perspective. *Quat Sci Rev* 27:1723–1732.
9. Willis KJ, Bailey RM, Bhagwat SA, Birks HJB (2010) Biodiversity baselines, thresholds and resilience: Testing predictions and assumptions using palaeoecological data. *Trends Ecol Evol* 25:583–591.
10. Bunting MJ, Whitehouse NJ (2008) Adding time to the conservation toolkit: Palaeoecology and long term wetland function dynamics. *Biodivers Conserv* 17:2051–2054.
11. Dearing JA, Battarbee RW, Dikau R, Larocque I, Oldfield F (2006) Human-environment interactions: Learning from the past. *Reg Environ Change* 6:1–16.
12. Dearing JA, Braimoh AK, Reenberg A, Turner BL, II, van der Leeuw SE (2010) Complex land systems: The need for long time perspectives in order to assess their future. *Ecol Soc* 15(4):21. Available at http://www.ecologyandsociety.org/vol15/iss4/art21/.
13. Oldfield F (1983) Man's impact on the environment: Some recent perspectives. *Geography* 68:245–256.
14. Holling CS (1986) *Sustainable Development of the Biosphere*, eds Clark WC, Munn RE (Cambridge Univ Press, Cambridge, UK), pp 292–317.
15. Crutzen PJ (2002) Geology of mankind. *Nature* 415:23.
16. Steffen W, et al. (2004) *Global Change and the Earth System: A Planet Under Pressure* (Springer, Berlin).
17. Stock JH, Watson MW (2003) Has the business cycle changed? *Proceedings, Federal Reserve Bank of Kansas City*, pp 9–56. Available at http://www.kc.frb.org/publications/research/escp/escp-2003.cfm.
18. Scheffer M, Carpenter S, Foley JA, Folke C, Walker B (2001) Catastrophic shifts in ecosystems. *Nature* 413:591–596.
19. Dearing JA (2008) Landscape change and resilience theory: A palaeoenvironmental assessment from Yunnan, SW China. *Holocene* 18:117–127.
20. Scheffer M, et al. (2009) Early-warning signals for critical transitions. *Nature* 461:53–59.
21. Peterson GD (2000) Scaling ecological dynamics: Self-organization, hierarchical structures and ecological resilience. *Clim Change* 44:291–309.
22. Foster DR (2003) The importance of land-use legacies to ecology and conservation. *Bioscience* 53(7):77–88.
23. Stafford Smith DM, et al. (2007) Learning from episodes of degradation and recovery in variable Australian rangelands. *Proc Natl Acad Sci USA* 104:20690–20695.
24. Dearing JA, et al. (2012) Navigating the perfect storm: Research strategies for social-ecological systems in a rapidly evolving world. *Environ Manage*, 10.1007/s00267-012-9833-6.
25. Welsh KE, Dearing JA, Chiverrell RC, Coulthard TJ (2009) Testing a cellular modelling approach to simulating late Holocene sediment and water transfer from catchment to lake in the French Alps since 1826. *Holocene* 19:785–798.
26. Bennion H, Fluin J, Simpson GL (2004) Assessing eutrophication and reference conditions for Scottish freshwater lochs using subfossil diatoms. *J Appl Ecol* 41:124–138.
27. Willis KJ, Birks HJB (2006) What is natural? The need for a long-term perspective in biodiversity conservation. *Science* 314:1261–1265.
28. Jackson ST, Hobbs RJ (2009) Ecological restoration in the light of ecological history. *Science* 325:567–569.
29. Macklin MG, Lewin J (2003) River sediments, great floods and centennial-scale Holocene climate change. *J Quat Sci* 18:101–105.
30. Renberg I (1990) A 12600 year perspective of the acidification of Lilla Oresjön, southwest Sweden. *Philos Trans R Soc Lond B Biol Sci* 327:357–361.
31. Engstrom DR, Fritz SC, Almendinger JE, Juggins S (2000) Chemical and biological trends during lake evolution in recently deglaciated terrain. *Nature* 408:161–166.

32. Berglund BE, Ralska-Jasiewiczowa M (1986) *Handbook of Holocene Palaeoecology and Palaeohydrology* (Wiley, Chichester, UK).
33. Bell M, Walker MJ (2005) *Late Quaternary Environmental Change: Physical and Human Perspectives* (Pearson, Harlow, UK).
34. Last WM, Smol JP, eds (2001) *Tracking Environmental Change Using Lake Sediments. Physical and Geochemical Methods* (Kluwer Academic, Dordrecht, The Netherlands), Vol 2.
35. Smol JP, Birks HJB, Last WM, eds (2001) *Tracking Environmental Change Using Lake Sediments. Terrestrial, Algal, and Siliceous Indicators.* (Kluwer Academic, Dordrecht, The Netherlands), Vol 3.
36. Smol JP, Birks HJB, Last WM, eds (2001) *Tracking Environmental Change Using Lake Sediments. Zoological Indicators.* (Kluwer Academic, Dordrecht, The Netherlands), Vol 4.
37. Last WM, Smol JP (2001) *Tracking Environmental Change Using Lake Sediments. Basin Analysis, Coring, and Chronological Techniques* (Kluwer Academic, Dordrecht, The Netherlands), Vol 1.
38. Lowe JJ, Walker MJC (1997) *Reconstructing Quaternary Environments* (Prentice Hall, Harlow, UK).
39. Boyle JF (2007) Loss of apatite caused irreversible early-Holocene lake acidification. *Holocene* 17:543–547.
40. Kober B, Schwalb A, Schettler G, Wessels M (2007) Constraints on paleowater dissolved loads and on catchment weathering over the past 16 ka from ^{87}Sr/^{86}Sr ratios and Ca/Mg/Sr chemistry of freshwater Ostracode tests in sediments of Lake Constance, Central Europe. *Chem Geol* 240:361–376.
41. Hall RI, Smol JP (2010) *The Diatoms: Applications for the Environmental and Earth Sciences*, eds Smol JP, Stoermer EF (Cambridge Univ Press, Cambridge, UK), 2nd Ed, pp 122–151.
42. Martens CS, Klump JV (1990) Biogeochemical cycling in an organic-rich coastal marine basin—I. Methane sediment-water exchange processes. *Geochim Cosmochim Acta* 44:471–490.
43. Hollander DJ, McKenzie JA (1991) CO$_2$ control on carbon-isotope fractionation during aqueous photosynthesis: A paleo-pCO$_2$ barometer. *Geology* 19:929–932.
44. Seppä H, et al. (2009) Calibrated pollen accumulation rates as a basis for quantitative tree biomass reconstructions. *Holocene* 19:209–220.
45. Castañeda IS, Werne JP, Johnson TC, Powers LA (2010) Organic geochemical records from Lake Malawi (East Africa) of the last 700 years, part II: Biomarker evidence for recent changes in primary productivity. *Palaeogeogr Palaeoclimatol Palaeoecol* 303: 140–154.
46. McGowan S (2007) *Encyclopedia of Quaternary Sciences*, ed Elias SA (Elsevier, Amsterdam).
47. Charman DJ, Blundell A, Chiverrell RC, Hendon D, Langdon PG (2006) Compilation of non-annually resolved Holocene proxy climate records: Stacked records of Holocene peatland palaeo-water table reconstructions from northern Britain. *Quat Sci Rev* 25: 336–350.
48. Chambers FM, Barber KE, Maddy D, Brew J (1997) A 5500-year proxy-climate and vegetation record from blanket mire at Talla Moss, Borders, Scotland. *Holocene* 7: 391–400.
49. Baker A, et al. (1999) Stalagmite luminescence and peat humification records of palaeomoisture for the last 2500 years. *Earth Planet Sci Lett* 165:157–162.
50. Alin SR, Cohen AS (2003) Lake-level history of Lake Tanganyika, East Africa, for the past 2500 years based on ostracode-inferred water-depth reconstruction. *Palaeogeogr Palaeoclimatol Palaeoecol* 199:31–49.
51. Baioumy HM, Kayanne H, Tada R (2010) Reconstruction of lake-level and climate changes in Lake Qarun, Egypt, during the last 7000 years. *J Great Lakes Res* 36: 318–327.
52. Jones RT, Jordan J (2007) *Encyclopedia of Quaternary Sciences*, ed Elias SA (Elsevier, Amsterdam).
53. Gaillard M-J, Birks HJB, Emanuelsson U, Berglund BE (1992) Modern pollen/land-use relationships as an aid in the reconstruction of past land-uses and cultural landscapes: An example from south Sweden. *Veg Hist Archaeobot* 1:3–17.
54. Sugita S (2007) Theory of quantitative reconstruction of vegetation I: Pollen from large sites REVEALS regional vegetation. *Holocene* 17:229–241.
55. Sugita S (2007) Theory of quantitative reconstruction of vegetation II: All you need is LOVE. *Holocene* 17:243–257.
56. Piperno DR (2006) *Phytoliths: A Comprehensive Guide for Archaeologists and Paleoecologists* (AltaMira, Lanham, MD).
57. Mazier F, et al. (2009) Multidisciplinary approach to reconstructing local pastoral activities: An example from the Pyrenean Mountains (Pays Basque). *Holocene* 19: 171–188.
58. Finney BP, Gregory-Eaves I, Sweetman J, Douglas MSV, Smol JP (2000) Impacts of climatic change and fishing on Pacific salmon abundance over the past 300 years. *Science* 290:795–799.
59. Holtham AJ, et al. (2004) The influence of flushing rates, terrestrial input and low salmon escapement densities on paleolimnological reconstructions of sockeye salmon (*Oncorhynchus nerka*) nutrient dynamics in Alaska and British Columbia. *J Paleolimnol* 32:255–271.
60. Davidson TA, Sayer CD, Perrow MR, Tomlinson ML (2003) Representation of fish communities by scale sub-fossils in shallow lakes: Implications for inferring cyprinid-percid shifts. *J Paleolimnol* 30:441–449.
61. Binney HA, et al. (2009) The distribution of late-Quaternary woody taxa in northern Eurasia: Evidence from a new macrofossil database. *Quat Sci Rev* 28:2445–2464.
62. Whitlock C, Larsen C (2001) *Tracking Environmental Change Using Lake Sediments*, eds Smol JP, Birks HJB, Last WM (Kluwer Academic, Dordrecht, The Netherlands), Vol 3, pp 75–97.
63. Grant MJ, Edwards ME (2008) Conserving idealized landscapes: Past history, public perception and future management in the New Forest (UK). *Veg Hist Archaeobot* 17: 551–562.
64. Schofield JE, Waller MP (2005) A pollen analytical record for hemp retting from Dungeness Foreland, UK. *J Archaeol Sci* 32:715–726.
65. Birks HJB, Line JM (1992) The use of rarefaction analysis for estimating palynological richness from Quaternary pollen-analytical data. *Holocene* 2:1–10.
66. Odgaard BV (1999) Fossil pollen as a record of past biodiversity. *J Biogeogr* 26:7–17.
67. Brown AG (1999) Biodiversity and pollen analysis: Modern pollen studies and the recent history of a floodplain woodland in S.W. Ireland. *J Biogeogr* 26:19–32.
68. Barber KE (1993) Peatlands as scientific archives of past biodiversity. *Biodivers Conserv* 2:474–489.
69. Meyers PA, Teranes JL (2001) *Tracking Environmental Change Using Lake Sediments*, eds Last WM, Smol JP (Kluwer Academic, Dordrecht, The Netherlands), Vol 2, pp 239–270.
70. Hu FS, Hedges JI, Gordon ES, Brubaker LB (1999) Lignin biomarkers and pollen in postglacial sediments of an Alaskan lake. *Geochim Cosmochim Acta* 63:1421–1430.
71. Sønstebø JH, et al. (2010) Using next-generation sequencing for molecular reconstruction of past Arctic vegetation and climate. *Mol Ecol Resour* 10:1009–1018.
72. Sayer C, Roberts N, Sadler J, David C, Wade PM (1999) Biodiversity changes in a shallow lake ecosystem: A multi-proxy palaeolimnological analysis. *J Biogeogr* 26: 97–114.
73. Alin SR, et al. (2002) Effects of land-use change on aquatic biodiversity: A view from the paleorecord at Lake Tanganyika. *East Africa Geology* 30:1143–1146.
74. Jeppesen E, Leavitt P, De Meester L, Jensen JP (2001) Functional ecology and palaeolimnology: Using cladoceran remains to reconstruct anthropogenic impact. *Trends Ecol Evol* 16:191–198.
75. Whitehouse N, Langdon PG, Bustin R, Galsworthy S (2008) Sub-fossil insects and ecosystem dynamics in wetlands; implications for biodiversity and conservation. *Biodivers Conserv* 17:2055–2078.
76. Coolen MJL, et al. (2004) Combined DNA and lipid analyses of sediments reveal changes in Holocene haptophyte and diatom populations in an Antarctic lake. *Earth Planet Sci Lett* 223:225–239.
77. Fritz SC, Cumming BF, Gasse F, Laird KR (2010) *The Diatoms: Applications for the Environmental and Earth Sciences*, eds Smol JP, Stoermer EF (Cambridge Univ Press, Cambridge, UK), 2nd Ed, pp 186–208.
78. Heinrichs ML, Walker IR (2006) Fossil midges and palaeosalinity: Potential as indicators of hydrological balance and sea-level change. *Quat Sci Rev* 25:1948–1965.
79. Müller G, Grimmer G, Böhnke H (1977) Sedimentary record of heavy metals and polycyclic aromatic hydrocarbons in Lake Constance. *Naturwissenschaften* 64: 427–431.
80. Blais JM, Muir DCG (2001) *Tracking Environmental Change Using Lake Sediments*, eds Last WM, Smol JP (Kluwer Academic Publishers, Dordrecht, The Netherlands), Vol 2, pp 271–298.
81. Renberg I (1986) Concentration and annual accumulation values of heavy metals in lake sediments: Their significance in studies of the history of heavy metal pollution. *Hydrobiologia* 143:1379–1385.
82. Lockhart WL, et al. (2000) Tests of the fidelity of lake sediment core records of mercury deposition to known histories of mercury contamination. *Sci Total Environ* 260:171–180.
83. Renberg I, Wik M (1985) Carbonaceous particles in lake sediments: Pollutants from fossil fuel combustion. *Ambio* 14:161–163.
84. Rose N (2001) *Tracking Environmental Change Using Lake Sediments*, eds Last WM, Smol JP (Kluwer Academic, Dordrecht, The Netherlands), Vol 2, pp 319–349.
85. McLean D (1991) Magnetic spherules in recent lake sediments. *Hydrobiologia* 214: 91–97.
86. Birks HJB, Line JM, Juggins S, Stevenson AC, Ter Braak CJF (1990) Diatoms and pH reconstruction. *Philos Trans R Soc Lond Ser B* 327:263–278.
87. Battarbee RW, Charles DF, Bigler C, Cumming BF, Renberg I (2010) *The Diatoms: Applications for the Environmental and Earth Sciences*, eds Smol JP, Stoermer EF (Cambridge Univ Press, Cambridge, UK), 2nd Ed, pp 98–121.
88. Dean WE, Gorham E (1998) Magnitude and significance of carbon burial in lakes, reservoirs, and peatlands. *Geology* 26:535–538.
89. Rosén P (2005) Total organic carbon (TOC) of lake water during the Holocene inferred from lake sediments and near-infrared spectroscopy (NIRS) in eight lakes from Northern Sweden. *Biogeochemistry* 76:503–516.
90. Anderson NJ, D'Andrea W, Fritz SC (2009) Holocene carbon burial by lakes in SW Greenland. *Glob Change Biol* 15:2590–2598.
91. Noël H, et al. (2001) Human impact and soil erosion during the last 5000 yrs as recorded in lacustrine sedimentary organic matter at Lac d'Annecy, the French Alps. *J Paleolimnol* 25:229–244.
92. Clymo RS, Turunen J, Tolonen K (1998) Carbon accumulation in peatland. *Oikos* 81: 368–388.
93. Billett MF, et al. (2010) Carbon balance of UK peatlands: Current state of knowledge and future research challenges. *Clim Res* 45:13–29.
94. Davis MB (1976) Erosion rates and land-use history in southern Michigan. *Environ Conserv* 3:139–148.
95. Gälman V, Petterson G, Renberg I (2006) A comparison of sediment varves (1950-2003 AD) in two adjacent lakes in northern Sweden. *J Paleolimnol* 35:837–853.
96. Hilton J, Davison W, Ochsenbein U (1985) A mathematical model for analysis of sediment core data: Implications for enrichment factor calculations and trace-metal transport mechanisms. *Chem Geol* 48:1281–1291.
97. Collins AL, Walling DE, Leeks GJL (1997) Use of the geochemical record preserved in floodplain deposits to reconstruct recent changes in river basin sediment sources. *Geomorphology* 19:151–167.

98. Ritchie JC, McHenry JR (1990) Application of radioactive fallout Cesium-137 for measuring soil erosion and sediment accumulation rates and patterns: A review. *J Environ Qual* 19:215–233.
99. Meyers PA, Ishiwatari R (1993) Lacustrine organic geochemistry—An overview of indicators of organic matter sources and diagenesis in lake sediments. *Org Geochem* 20:867–900.
100. Thompson R, Battarbee RW, O'Sullivan PE, Oldfield F (1975) Magnetic susceptibility of lake sediments. *Limnol Oceanogr* 20:687–698.
101. Dearing JA, et al. (1996) Frequency-dependent susceptibility measurements of environmental samples. *Geophys J Int* 124:228–240.
102. Page MJ, Trustrum NA, DeRose RC (1994) A high resolution record of storm-induced erosion from lake sediments, New Zealand. *J Paleolimnol* 11:333–348.
103. Karlin RE, Holmes M, Abella SEB, Sylwester R (2004) Holocene landslides and a 3500-year record of Pacific Northwest earthquakes from sediments in Lake Washington. *Geol Soc Am Bull* 116:94–108.
104. Doig R (1990) 2300 yr history of seismicity from silting events, in Lake Tadoussac, Charlevoix, Quebec. *Geology* 18:820–823.
105. Liu K-B, Fearn ML (1993) Lake-sediment record of late Holocene hurricane activities from coastal Alabama. *Geology* 21:793–796.
106. Kelsey HM, Nelson AR, Hemphill-Haley E, Witter RC (2005) Tsunami history of an Oregon coastal lake reveals a 4600 yr record of great earthquakes on the Cascadia subduction zone. *Geol Soc Am Bull* 117:1009–1032.
107. Horton BP, Sawai Y (2010) *The Diatoms: Applications for the Environmental and Earth Sciences*, eds Smol JP, Stoermer EF (Cambridge Univ Press, Cambridge, UK), 2nd Ed, pp 357–372.
108. Bradshaw RHW, Miller NG (1988) Recent successional processes investigated by pollen analysis of closed canopy forest sites. *Plant Ecol* 76:45–54.
109. Clark SHE, Edwards KJ (2004) Elm bark beetle in Holocene peat deposits and the northwest European elm decline. *J Quat Sci* 19:525–528.
110. Sayer CD, et al. (2006) TBT causes regime shift in shallow lakes. *Environ Sci Technol* 40:5269–5275.
111. Anderson NJ, Rippey B, Gibson CE (1993) A comparison of sedimentary and diatom-inferred phosphorus profiles: Implications for defining pre-disturbance nutrient conditions. *Hydrobiologia* 253:357–366.
112. Korsman T, Birks HJB (1996) Diatom-based water chemistry reconstructions from northern Sweden: A comparison of reconstruction techniques. *J Paleolimnol* 15: 65–77.
113. Hodell DA, Schelske CL (1998) Production, sedimentation, and isotopic composition of organic matter in Lake Ontario. *Limnol Oceanogr* 43:200–214.
114. Vane CH, et al. (2010) Sedimentary records of sewage pollution using faecal markers in contrasting peri-urban shallow lakes. *Sci Total Environ* 409:345–356.
115. Sayer CD, Davidson TA, Jones JI, Langdon PG (2010) Combining contemporary ecology and palaeolimnology to understand shallow lake ecosystem change. *Freshw Biol* 55:487–499.
116. Brandenberger JM, et al. (2008) *Reconstructing Trends in Hypoxia Using Multiple Paleoecological Indicators Recorded in Sediment Cores from Puget Sound, WA*. (National Oceanic and Atmospheric Administration, Pacific Northwest National Laboratory, Seattle), Report PNWD-4013.
117. Brodersen KP, Pedersen O, Walker IR, Jensen MT (2008) Respiration of midges (Diptera; Chironomidae) in British Columbian lakes: Oxy-regulation, temperature and their role as paleo-indicators. *Freshw Biol* 53:593–602.
118. Knox JC (2000) Sensitivity of modern and Holocene floods to climate change. *Quat Sci Rev* 19:439–457.
119. Bøe A-G, Dahl SO, Lie Ø, Nesje A (2006) Holocene river floods in the upper Glomma catchment, southern Norway: A high-resolution multiproxy record from lacustrine sediments. *Holocene* 16:445–455.
120. Foster GC, Chiverrell RC, Harvey AM, Dearing JA, Dunsford H (2008) Catchment hydro-geomorphological responses to environmental change in the Southern Uplands of Scotland. *Holocene* 18:935–950.
121. Fritz SC, Ito E, Yu Z, Laird KR, Engstrom DR (2000) Hydrologic variation in the Northern Great Plains during the last two millennia. *Quat Res* 53:175–184.
122. Shapley MD, Johnson WC, Engstrom DR, Osterkamp WR (2005) Late-Holocene flooding and drought in the Northern Great Plains, USA, reconstructed from tree rings, lake sediments and ancient shorelines. *Holocene* 15:29–41.
123. Berglund BE (1991) *The Cultural Landscape During 6000 Years in Southern Sweden–The Ystad Project* (Munksgaard, Copenhagen).
124. World Wildlife Fund (2009) *Summary of the First-Ever Yangtze River Basin Climate Change Vulnerability and Adaptation Report*. Available at www.wwfchina.org/english/downloads/WWF_YangtzeVA.pdf. Accessed March 29, 2012.
125. United Nations Development Program (2003) *Human Development Report 2003; Millennium Development Goals: A Compact Among Nations to End Human Poverty* (Oxford Univ Press, New York).
126. Yang DT (2008) China's agricultural crisis and famine of 1959–1961: A survey and comparison to Soviet famines. *Comp Econ Stud* 50:1–29.
127. Ravallion M (2009) Are there lessons for Africa from China's success against poverty? *World Dev* 37:303–313.
128. Dai X, et al. (2009) The recent history of hydro-geomorphic processes in the upper Hangbu river system, Anhui Province, China. *Geomorphology* 106:363–375.
129. Yang GS, Wen LD, Li LF (2009) *Yangtze Conservation and Development Report* (Changjiang, Wuhan, China) (in Chinese).
130. Jin XC (2003) Analysis of eutrophication state and trend for lakes in China. *J Limnol* 62:60–66.
131. Zhang E, et al. (2010) A 150-year record of recent changes in human activity and eutrophication of Lake Wushan from the middle reach of the Yangtze River, China. *J Limnol* 69:235–241.
132. Zhang B, Zhuang JY, Zhang JC, Wang RJ (2010) Evaluation of the function of reforestation on soil loss control in the Dabie Mountains, China. *Bioinformatics and Biomedical Engineering, 4th International Conference Proceedings*, pp 1–4, 10.1109/ICBBE.2010.5515947.
133. Chen KL (2005) Possible solution on management and construction of wetlands park. *Wetland Sci* 3:298–301.
134. Liu JG, Li SX, Ouyang Z, Tam C, Chen XD (2008) Ecological and socioeconomic effects of China's policies for ecosystem services. *Proc Natl Acad Sci USA* 105:9477–9482.
135. Yin RS, Yin GP, Li LY (2010) Assessing China's ecological restoration programs: What's been done and what remains to be done? *Environ Manage* 45:442–453.
136. Liu Q, Yang XD, Anderson NJ, Liu EF, Dong X (2011) Ecological regime shifts in response to both natural and anthropogenic forcing of a shallow lake on the Yangtze Floodplain, SE China. *Ecohydrology*, 10.1002/eco.222.
137. Yang XD, Anderson NJ, Dong XH, Shen J (2008) Surface sedimentdiatom assemblages and epilimnetic total phosphorus in large, shallow lakes of the Yangtze floodplain: Their relationships and implications for assessing long-term eutrophication. *Freshw Biol* 53:1273–1290.
138. Chen X, Yang X, Dong X, Liu Q (2011) Nutrient dynamics linked to hydrological condition and anthropogenic nutrient loading in Chaohu Lake (southeast China). *Hydrobiologia* 66:223–234.
139. Nicholson E (2009) Priority research areas for ecosystem services in a changing world. *J Appl Ecol* 46:1139–1144.
140. Grossman GM, Krueger AB (1995) Economic growth and the environment. *Q J Econ* 110:353–377.
141. Song T, Zheng T, Tong L (2008) An empirical test of the environmental Kuznets curve in China: A panel cointegration approach. *China Econ Rev* 19:381–392.
142. Hayward SF (2005) *The China Syndrome and the Environmental Kuznets curve* (American Enterprise Institute for Public Policy Research, Washington, DC), Report Nov–Dec 2005. Available at http://www.aei.org/article/energy-and-the-environment/the-china-syndrome-and-the-environmental-kuznets-curve/. Accessed March 29, 2012.
143. Sayer CD (2001) Problems with the application of diatom-total phosphorus transfer functions: Examples from a shallow English Lake. *Freshw Biol* 46:743–757.
144. Brodersen KP, Anderson NJ (2002) Distribution of chironomids (Diptera) in low arctic West Greenland lakes: Trophic conditions, temperature and environmental reconstruction. *Freshw Biol* 47:1137–1157.
145. Cottingham KL, Rusak JA, Leavitt PR (2000) Increased ecosystem variability and reduced predictability following fertilisation: Evidence from palaeolimnology. *Ecol Lett* 3:340–348.
146. Borcard D, Legendre P, Drapeau P (1992) Partialling out the spatial component of ecological variation. *Ecology* 73:1045–1055.
147. Lotter AF, Birks HJB (1997) The separation of the influence of nutrients and climate on the varve time-series of Baldeggersee, Switzerland. *Aquat Sci* 59:362–375.
148. Simpson GL, Anderson NJ (2009) Deciphering the effect of climate change and separating the influence of confounding factors in sediment core records using additive models. *Limnol Oceanogr* 54:2529–2541.
149. Dawson TP, Rounsevell MDA, Kluvánková-Oravská T, Chobotová V, Stirling A (2010) Dynamic properties of complex adaptive ecosystems: Implications for the sustainability of service provision. *Biodivers Conserv* 19:2843–2853.
150. Intergovernmental Panel on Climate Change (2007) *4th Assessment Report. Synthesis Report Summary for Policymakers and Working Group II Report Impacts, Adaptation and Vulnerability Summary for Policymakers*. Available at http://www.ipcc.ch/publications_and_data/ar4/wg2/en/spm.html. Accessed March 29, 2012.
151. Statistical Bureau of Anhui Province (1950-2006) *Annual Census of Anhui Province* (Provincial Government of Anhui, Hefei, China) (in Chinese).
152. Statistical Bureau of Wuxue City (1950-2006) *Annual Census of Wuxue City* (City council of Wuxue, Hubei, China) (in Chinese).
153. Statistical Bureau of Anhui Province (1949-2006) *Agricultural Statistics Summary of Anhui Province* (Provincial government of Anhui, Hefei, China) (in Chinese).
154. Statistical Bureau of Wuxue City (1949-2006) *Agricultural Statistics Summary of Wuxue City* (City Council of Wuxue, Hubei, China) (in Chinese).
155. Liu J, et al. (2005) Simulated and reconstructed winter temperature in the eastern China during the last millennium. *Chin Sci Bull* 50:2872–2877.
156. Appleby PG, Oldfield F (1978) The calculation of Pb-210 dates assuming a constant rate of supply of unsupported Pb-210 to the sediment. *Catena* 5:1–8.
157. Faegri K, Iversen J (1989) *Textbook of Pollen Analysis*, revised by Faegri K, Kaland PE, Krzywinski K (Wiley, Chichester, UK), 4th Ed.
158. Smol JP (2010) *The Diatoms: Applications for the Environmental and Earth Sciences*, ed Stoermer EF (Cambridge Univ Press, Cambridge, UK), 2nd Ed.
159. Krammer K, Lange-Bertalot H (1986–1991) *Süβwasserflora von Mitteleuropa* [Freshwater flora of Central Europe], *Bacillariophyceae. – 2/1 Naviculaceae; 2/2 Bacillariaceae, Epithemiaceae, Surirellaceae; 2/3 Centrales, Fragilariaceae, Eunotiaceae; 2/4 Achnanthaceae* (Gustav Fisher, Stuttgart).
160. International Geosphere-Biosphere Programme Climate Change Index (2009) Available at http://www.igbp.net/4.1b8ae20512db692f2a680001647.html. Accessed March 29, 2012.
161. Banzhaf S, Boyd J (2005) *The Architecture and Measurement of an Ecosystem Services Index* (Resources for the Future, Washington, DC), Discussion Paper RFF DP-05-22.

Supporting Information

Dearing et al. 10.1073/pnas.1118263109

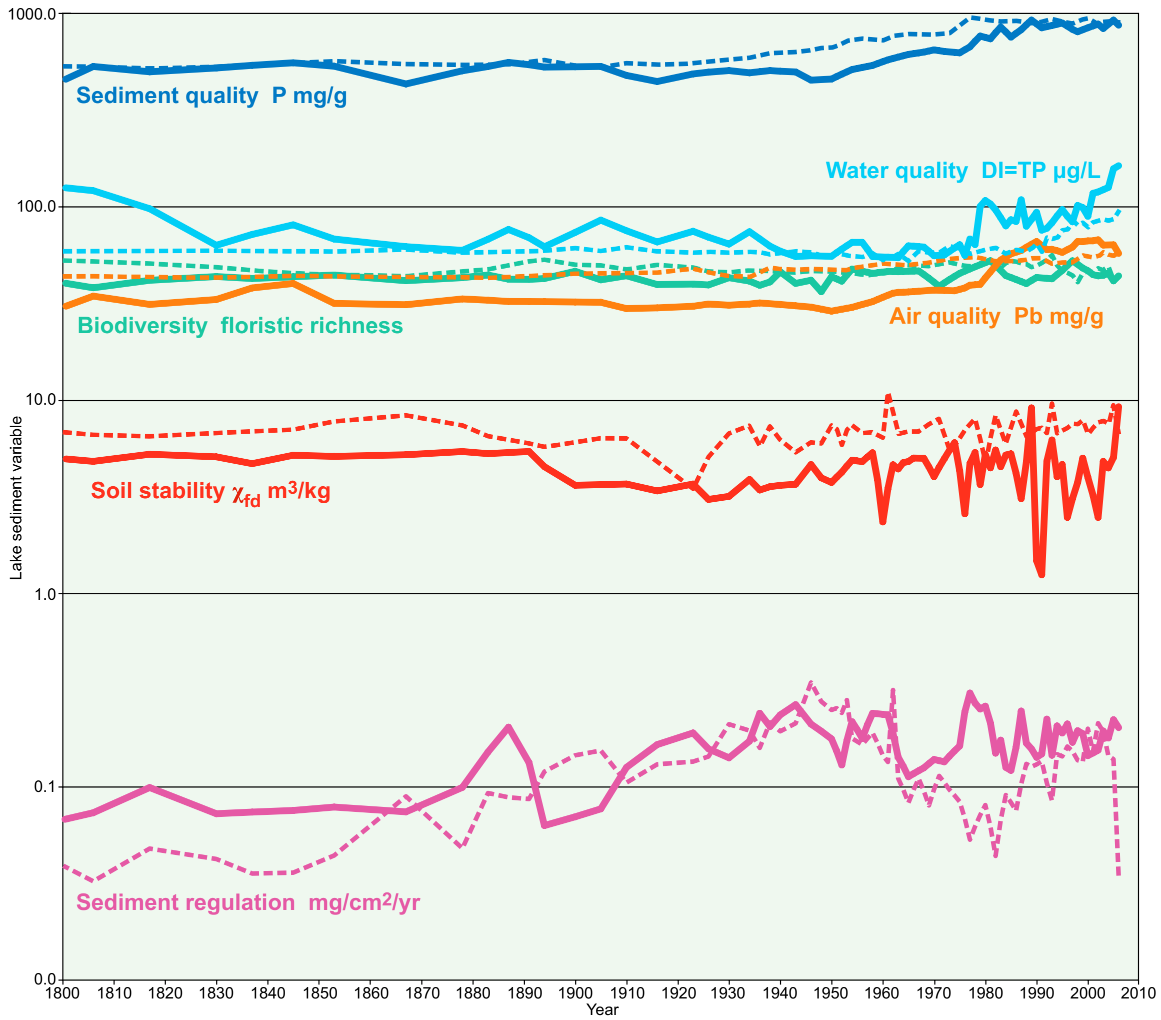

Fig. S1. Time series of sediment analytical data 1800–2006 for Chaohu Lake (solid lines) and Taibai Lake (dashed lines), showing pairs of proxies for sediment quality, water quality, sediment regulation, soil stability, air quality, and biodiversity (vertical axis shows values from Table S1 on logarithmic scale).

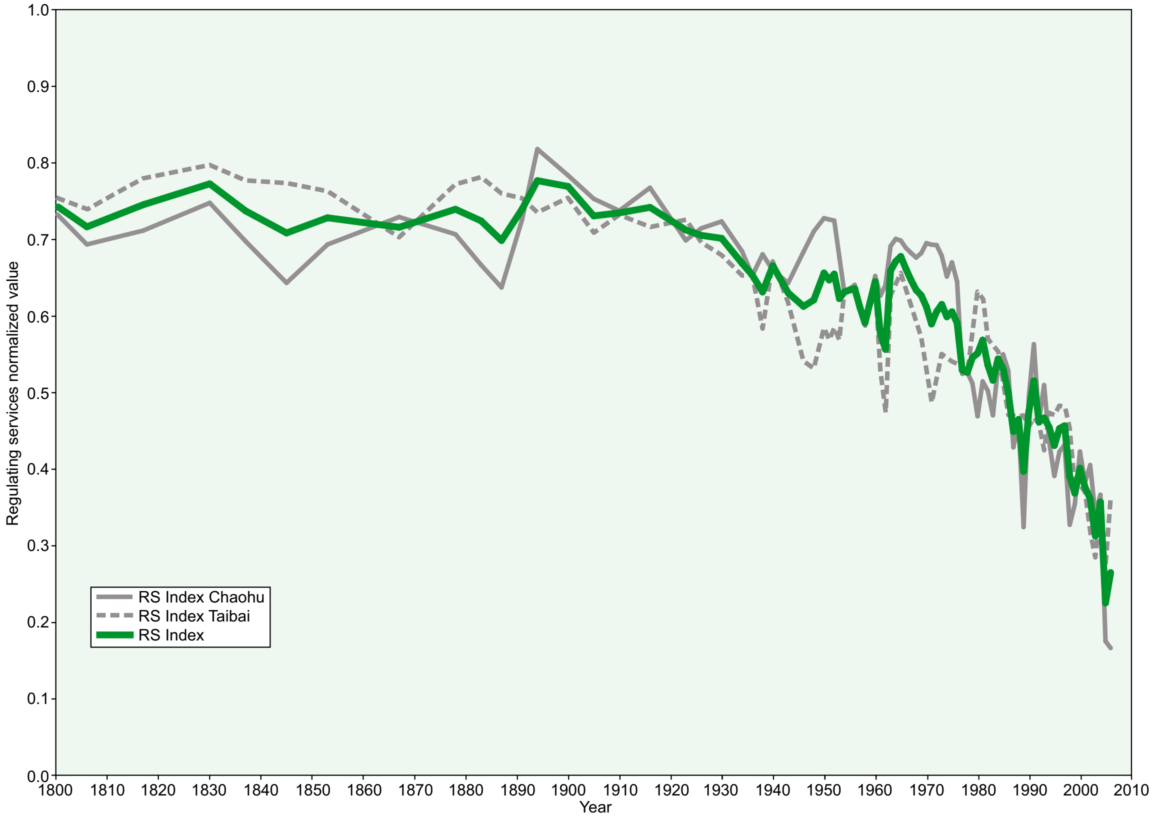

Fig. S2. Calculated normalized indexes for regulating services based on each lake dataset (RS index Chaohu and RS index Taibai) and for the combined lake dataset (RS index).

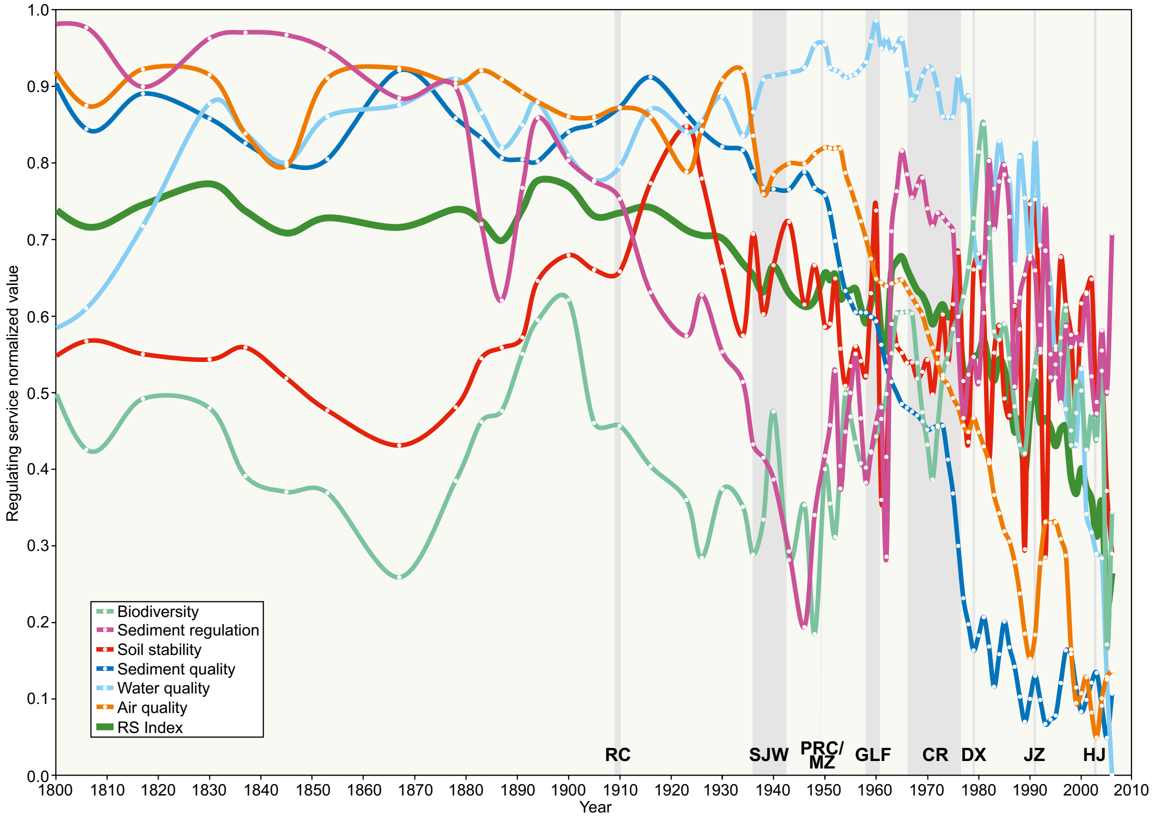

Fig. S3. Lower Yangtze basin 1800–2006: normalized regulating service proxy records for biodiversity, sediment regulation, soil stability, sediment quality, water quality, air quality, and RS index. Vertical bars show major 20th–21st century political events (from left to right): Republic of China, 1912; Sino-Japanese War, 1937–1945; People's Republic of China founded by Mao Zedong, 1949; Great Leap Forward, 1958–1961; Cultural Revolution, 1966–1976; Deng Xiaoping's economic reforms from late 1970s to early 1980s; leadership of Jiang Zemin from 1989; and leadership of Hu Jintao from 2003.

Table S1. Lower Yangtze basin: Lake-catchment characteristics (after refs. 136–138)

Taibai Lake, Huangmei County, Hubei Province	
Longtitude/latitude	29.933°–30.017° N, 115.767°–115.833° E
Lake area	25.1 km^2
Catchment area	960 km^2
Lake altitude	13.8 m above sea level
Maximum catchment altitude	1,223 m
Mean lake depth	3.2 m
Land use ~50% cultivated land in lowlands, oak forest and secondary pine forest in mountains	
Lake water quality	Hypereutrophic
Lake core location/depth	29.995° N, 115.808° E /1.5 m
Regional annual mean temperature	15.7–17.1 °C
Regional annual mean rainfall	1,273 mm
Chaohu Lake, Shucheng County, Anhui Province	
Longtitude/latiutude	31.417°–30.717° N, 117.267°–117.85° E
Lake area	770 km^2
Catchment area	13,349 km^2
Lake altitude	5 m above sea level
Maximum catchment altitude	1,760 m
Mean lake depth	3.1 m
Land use ~50% cultivated land in lowlands, oak forest and secondary pine forest in mountains	
Lake water quality	Hypereutrophic
Lake core location/depth	31.596° N, 117.399° E/3.2 m
Regional annual mean temperature	14.5–16.1 °C
Regional annual mean rainfall	1,120 mm

Table S2. Lower Yangtze basin: Regulating ecosystem services, proxy name/record, and proxy interpretation

Ecosystem service	Proxy name	Proxy record	Interpretation
Provisioning services: genetic resources	Biodiversity*	Lake sediment pollen records statistically analyzed by rarefaction for floristic taxa richness	Rarefaction indexes of floristic taxa richness approximate the diversity of land plants (main tree, shrub, and herb typesand associated ecological communities): relatively high values equate to an ability of land system to provide genetic resources and biodiversity.
Regulating services: erosion regulation	Sediment regulation	Lake sediment mass accumulation rates based on ^{210}Pb and ^{137}Cs radionuclide dating	River-borne sediment loads reflect the balance between soil/sediment erosion and catchment sediment storage: high values equate to loss of, or inability of hydro-geomorphic system to provide, erosion regulation.[†]
Regulating services: erosion regulation	Soil stability	Lake sediment frequency-dependent magnetic susceptibility	Frequency-dependent magnetic susceptibility measures secondary ferrimagnetic iron oxide particles that form in topsoil horizons, thus providing a proxy for eroded topsoil-derived material: high values equate to loss of, or inability of soil-vegetation system to provide, erosion regulation.
Regulating services: water purification	Sediment quality	Lake sediment phosphorus (P) concentrations derived from geochemical analyses	In well-mixed shallow lakes with little or no anoxia in surface sediments, sediment-associated phosphorus can be linked to surface soil erosion of fine particles from intensively cultivated areas: high values equate to loss of, or inability of natural soil system to provide, water purification.
Regulating services: water purification	Water quality	Lake sediment diatom-inferred records of total phosphorus in surface water (epilimnion)	Diatom assemblages calibrated to modern dissolved phosphate concentrations provide a proxy for dissolved phosphorus associated (in this context) with effluent and fertilizer application and runoff: high values equate to relative loss of, or inability of hydrological system to provide, water purification.
Regulating services: air quality	Air quality	Lake sediment lead (Pb) concentrations	Pb is a major component of the heavy metal loading in the region. Sediment Pb is linked to atmospheric emissions of heavy metals, direct (from stacks) and indirect (washed deposits from surfaces) from coal/oil burning, smelting, and vehicles: high values equate to loss of, or inability of land–atmosphere system to provide, air quality regulation.

*The Millennium Ecosystem Assessment places biodiversity in the provisioning services category. Here, biodiversity is included in the basket of regulating services because of its greater importance in the lower Yangtze basin in maintaining ecosystem function (e.g., ref. 139), and hence supporting and regulating services, than in maintaining provisioning services.

[†] In these catchments, erosion regulation provides natural sediment regulation in rivers that is a positive service because loss of service leads to channel infilling and raised flood risk. In other areas, or at other spatial scales (e.g., the whole Yangtze catchment), increased regulation either naturally (e.g., forest expansion) or artificially (e.g., dam construction) can have negative effects, such as starving coastal islands and shorelines of protective beach material.

Table S3. Complete analytical dataset for dated sediment samples from Chaohu and Taibai lake sediment cores

	Chaohu						Taibai					
Year	P mg/g, sediment quality	DI-TP g/mg, water quality	mg/y, sediment regulation	Xfd m^3/kg, soil stability	Pb mg/g, air quality	Pollen richness, biodiversity	P mg/g, sediment quality	DI-TP g/mg, water quality	mg/y, sediment regulation	Xfd m^3/kg, soil stability	Pb mg/g, air quality	Pollen richness, biodiversity
2006	875.2	164.0	0.2	9.3	57.7	44.4	908.6	94.6	0.0	6.7	58.2	44.1
2005	929.7	158.2	0.2	5.1	63.9	41.4	915.4	86.3	0.1	9.4	56.1	41.6
2004	885.6	126.6	0.2	4.5	63.8	49.5	914.0	85.1	0.1	7.6	57.0	45.6
2003	841.6	123.2	0.2	4.8	63.7	47.1	911.7	85.9	0.2	7.9	58.6	44.4
2002	886.7	120.1	0.2	2.5	67.9	48.4	886.9	84.8	0.2	7.7	56.1	44.2
2001	867.7	118.0	0.2	3.2	67.0	46.3	921.6	83.5	0.2	7.2	54.9	44.8
2000	848.7	89.8	0.1	4.0	67.0	46.6	950.0	78.5	0.2	6.7	55.6	46.9
1999	829.1	99.6	0.2	5.0	66.3	45.5	938.4	83.0	0.1	7.9	56.2	48.5
1998	809.4	102.2	0.2	3.8	66.5	40.9	915.9	80.5	0.1	7.5	54.0	50.7
1997	832.5	84.1	0.2	3.1	62.2	44.2	893.4	85.1	0.2	7.6	51.8	52.9
1996	865.3	89.8	0.2	2.5	60.3	45.9	904.3	76.8	0.2	7.2	51.8	50.0
1995	898.1	97.2	0.2	4.7	58.4	47.0	915.1	75.1	0.1	7.0	51.9	47.1
1994	885.1	90.2	0.2	4.0	59.6	50.1	930.2	68.9	0.1	6.8	51.5	44.9
1993	872.1	83.1	0.1	6.3	60.5	56.4	945.3	68.1	0.1	9.6	51.1	42.6
1992	860.3	77.8	0.2	4.8	60.3	53.2	927.5	69.5	0.1	6.8	52.8	42.9
1991	848.5	76.1	0.1	1.3	63.4	51.3	909.7	58.5	0.1	7.2	54.6	43.1
1990	889.1	94.1	0.1	1.5	66.5	49.7	903.4	64.7	0.1	7.1	54.4	43.3
1989	929.7	86.5	0.2	9.2	64.3	49.0	897.2	60.9	0.1	6.7	54.2	41.8
1988	879.5	79.8	0.2	4.8	62.1	50.8	908.7	59.0	0.1	6.5	53.4	40.3
1987	829.2	109.3	0.2	3.1	59.7	51.4	914.5	59.4	0.1	7.6	53.0	41.3
1986	794.1	84.4	0.2	4.2	58.6	52.4	920.3	59.8	0.1	8.7	52.6	42.3
1985	759.0	86.2	0.1	5.3	57.4	52.8	919.0	58.5	0.1	7.4	52.6	43.3
1984	807.3	80.1	0.1	5.2	55.4	51.2	917.7	57.2	0.1	6.0	52.7	44.3
1983	855.5	88.3	0.2	4.5	53.3	48.8	916.4	59.2	0.1	7.2	52.7	47.2
1982	799.8	97.0	0.1	5.5	49.8	50.5	915.1	61.3	0.0	8.3	52.7	50.0
1981	744.1	104.0	0.2	4.5	46.3	51.8	925.9	60.7	0.1	6.4	53.3	52.9
1980	756.4	108.3	0.3	5.3	43.1	51.8	936.7	60.1	0.1	4.5	54.0	51.7
1979	768.8	101.0	0.3	3.7	39.9	50.3	943.9	59.3	0.1	6.3	54.6	50.4
1978	722.5	64.1	0.3	5.4	39.7	49.5	951.1	58.4	0.1	8.1	55.2	49.2
1977	676.2	68.5	0.3	4.7	39.5	49.5	958.3	57.5	0.1	7.6	55.0	48.0
1976	652.9	56.3	0.2	2.6	38.2	49.8	917.3	59.1	0.1	7.0	54.8	46.7
1975	629.6	64.0	0.2	4.3	37.6	50.5	876.2	60.7	0.1	6.4	54.7	45.5
1974	633.1	61.5	0.2	6.0	37.0	51.0	835.1	61.6	0.1	6.0	54.4	43.9
1973	636.5	59.1	0.1	5.5	37.0	51.7	794.0	62.6	0.1	5.5	54.1	42.2
1972	640.0	56.6	0.1	5.0	37.1	51.2	791.4	60.5	0.1	6.8	53.4	40.6
1971	646.1	56.4	0.1	4.5	37.2	50.6	788.7	58.4	0.1	8.0	52.8	39.0
1970	652.1	56.1	0.1	4.0	37.3	50.1	786.0	58.3	0.1	7.8	52.1	40.9
1969	643.6	59.2	0.1	4.5	37.1	49.6	783.3	58.1	0.1	7.6	51.5	42.9
1968	635.0	62.3	0.1	5.0	36.9	49.7	783.5	58.7	0.1	7.2	51.2	44.9
1967	629.3	62.6	0.1	5.0	36.8	49.8	783.7	59.3	0.1	6.9	50.9	46.8
1966	623.5	62.9	0.1	5.0	36.6	50.0	783.8	55.9	0.1	6.9	50.6	46.7
1965	617.8	63.2	0.1	4.8	36.5	50.1	784.0	52.5	0.1	6.9	50.3	46.6
1964	608.1	59.0	0.1	4.8	36.3	50.2	779.1	54.8	0.1	6.8	50.4	46.5
1963	598.4	54.8	0.1	4.4	36.3	48.7	774.3	57.1	0.1	6.7	50.5	46.4
1962	588.7	55.0	0.2	4.7	35.9	47.0	764.5	55.5	0.3	9.1	50.7	46.5
1961	579.0	55.2	0.2	3.5	35.1	45.9	747.7	56.6	0.1	11.0	50.9	46.5
1960	566.6	55.3	0.2	2.4	34.2	45.5	730.8	53.5	0.1	6.4	51.1	46.2
1959	554.2	55.4	0.2	3.9	33.3	45.2	735.8	55.7	0.2	6.6	50.6	45.8
1958	541.8	55.6	0.2	5.4	32.5	44.9	740.7	57.9	0.2	6.8	50.1	45.5
1957	535.3	60.7	0.2	5.1	31.9	44.5	745.6	56.6	0.2	6.8	49.6	46.1
1956	528.8	65.8	0.2	4.8	31.4	44.8	750.5	55.3	0.2	6.8	49.1	46.7
1955	522.3	65.8	0.2	4.9	30.9	45.3	743.6	55.5	0.2	7.1	48.7	47.3
1954	515.8	65.8	0.2	4.9	30.3	45.6	736.6	55.7	0.2	7.5	48.2	47.9
1953	502.0	63.2	0.2	4.6	30.0	45.8	722.6	56.1	0.3	7.0	47.4	44.7
1952	488.2	60.7	0.1	4.3	29.7	45.9	701.8	56.8	0.2	6.0	47.5	41.5
1951	474.4	58.2	0.2	4.0	29.3	46.2	680.9	57.5	0.3	7.1	47.6	42.6
1950	460.6	55.7	0.2	3.8	29.0	46.5	672.0	56.0	0.3	7.4	47.7	43.7
1948	457.7	55.9	0.2	4.0	29.7	46.6	665.6	55.9	0.3	6.0	47.7	36.6
1946	454.8	56.1	0.2	4.7	30.4	46.8	650.1	58.3	0.3	6.1	47.8	41.9

Table S3. Cont.

	Chaohu						Taibai					
Year	P mg/g, sediment quality	DI-TP g/mg, water quality	mg/y, sediment regulation	Xfd m^3/kg, soil stability	Pb mg/g, air quality	Pollen richness, biodiversity	P mg/g, sediment quality	DI-TP g/mg, water quality	mg/y, sediment regulation	Xfd m^3/kg, soil stability	Pb mg/g, air quality	Pollen richness, biodiversity
1943	501.4	55.6	0.3	3.7	30.9	46.0	632.9	59.1	0.2	5.4	47.6	40.3
1940	505.5	59.2	0.2	3.6	31.4	46.3	629.2	58.0	0.2	6.3	47.9	46.4
1938	509.7	62.9	0.2	3.6	31.7	47.0	624.6	57.0	0.2	7.3	48.6	41.1
1936	502.9	68.6	0.2	3.4	32.0	47.1	611.1	58.4	0.2	5.9	46.1	39.5
1934	496.2	74.7	0.2	3.9	31.6	47.1	592.3	58.7	0.2	7.4	43.6	41.5
1930	509.6	64.5	0.1	3.2	31.1	46.2	577.8	58.3	0.2	6.7	44.1	43.2
1926	500.0	70.0	0.2	3.1	31.6	46.8	567.8	58.8	0.1	5.1	46.0	39.6
1923	489.7	75.1	0.2	3.7	30.7	48.7	556.6	58.1	0.1	3.5	48.0	40.0
1916	447.3	66.1	0.2	3.4	30.2	50.3	548.2	59.0	0.1	4.9	46.0	39.8
1910	481.1	75.6	0.1	3.7	29.9	47.8	555.6	61.7	0.1	6.4	45.7	44.2
1905	535.3	85.8	0.1	3.7	32.2	49.9	531.9	59.3	0.2	6.3	45.3	42.1
1900	533.3	74.1	0.1	3.6	32.3	50.6	542.4	61.0	0.1	6.1	45.2	46.6
1894	531.3	62.4	0.1	4.5	32.5	53.4	577.1	59.7	0.1	5.7	44.5	42.8
1891	546.5	69.6	0.1	5.4	32.5	52.5	563.1	59.4	0.1	6.0	44.1	42.3
1887	561.7	76.8	0.2	5.4	32.5	50.1	549.2	59.2	0.1	6.3	43.6	42.4
1883	535.0	68.3	0.2	5.3	33.0	47.6	547.8	58.6	0.1	6.6	43.0	44.6
1878	508.3	59.8	0.1	5.4	33.5	46.5	546.4	58.1	0.0	7.4	43.4	43.2
1867	434.5	62.5	0.1	5.2	31.3	44.1	550.8	60.0	0.1	8.3	43.6	41.7
1853	536.8	68.4	0.1	5.1	31.8	44.7	570.3	59.0	0.0	7.7	43.8	44.6
1845	559.1	81.1	0.1	5.2	40.3	45.6	559.0	59.1	0.0	7.0	44.2	43.7
1837	542.3	72.3	0.1	4.7	38.2	47.1	547.7	59.3	0.0	6.9	43.6	42.8
1830	525.5	63.6	0.1	5.1	33.3	48.9	533.1	59.4	0.0	6.8	43.1	43.8
1817	502.2	98.3	0.1	5.3	31.4	51.1	523.4	59.5	0.0	6.5	43.6	41.9
1806	535.1	121.8	0.1	4.8	34.7	52.4	537.7	59.5	0.0	6.7	43.9	38.3
1794	382.5	131.4	0.1	5.2	26.5	53.9	534.0	59.5	0.0	7.1	43.6	42.6

P, phosphorus; DI-TP, diatom-inferred total phosphorus; Xfd, frequency-dependent magnetic susceptibility; Pb, lead.

Table S4. Socioeconomic data for GDP (Anhui Province, Renmimbi), population (mean of lake-catchment counties), arable land area (mean of lake-catchment counties), and modeled mean annual regional temperature and rainfall (sources: refs. 151–155)

Year	Gross domestic product: Anhui, RMB × 10^8	Mean population	Arable land (mu)	Mean annual temperature, T °C	Mean annual rainfall, mm/d
2006	6,148.73	4,667,219	3,441,653	16.3	3.64
2005	5,375.84	4,600,008	3,450,638	16.3	3.64
2004	4,759.3	4,546,044	3,454,253	16.3	3.64
2003	3,823.1	4,499,712	3,327,678	16.3	3.63
2002	3,519.72	4,452,971	3,405,314	16.3	3.63
2001	3,246.71	4,414,202	3,496,878	16.2	3.62
2000	2,902.09	4,382,235	3,527,257	16.7	2.83
1999	2,712.34	4,335,610	3,555,400	16.4	4.06
1998	2,542.96	4,305,283	3,572,845	17.1	3.44
1997	2,347.32	4,279,339	3,591,696	16.6	2.77
1996	2,093.3	4,234,291	3,600,616	15.8	4.25
1995	1,810.66	4,196,371	3,607,800	16.4	2.93
1994	1,320.43	4,148,185	3,630,398	16.9	2.72
1993	1,037.14	4,108,590	3,647,708	15.6	4.07
1992	801.16	3,992,072	3,665,321	16.0	2.80
1991	663.6	4,030,854	3,683,007	16.0	5.17
1990	658.02	3,981,574	3,692,406	15.9	3.17
1989	616.25	3,898,650	3,700,076	15.5	4.26
1988	546.94	3,837,051	3,707,206	15.9	3.34
1987	442.35	3,774,678	3,684,575	15.7	4.01
1986	382.76	3,739,080	3,680,693	15.7	3.53
1985	331.24	3,690,763	3,689,662	15.9	4.06
1984	265.74	3,656,222	3,827,241	15.7	3.72
1983	215.68	3,627,205	3,723,706	16.0	4.01
1982	187.02	3,587,977	3,740,530	16.1	3.13
1981	170.51	3,546,375	3,700,885	15.7	3.81
1980	140.88	3,509,082	3,782,602	15.5	4.43
1979	127.31	3,443,268	3,866,462	15.5	3.34
1978	113.96	3,383,684	3,817,259	16.1	2.95
1977	108.01	3,322,976	3,979,530	15.5	4.30
1976	105.77	3,276,238	4,007,834	15.3	3.20
1975	97.01	3,227,452	3,944,996	15.7	3.99
1974	91.44	3,165,123	3,875,150	15.5	3.47
1973	92.18	3,100,620	3,933,748	15.8	3.66
1972	85.88	3,025,268	3,981,319	15.2	3.58
1971	79.99	2,927,524	3,926,281	15.1	3.21
1970	71.79	2,844,869	3,855,327	15.3	3.94
1969	58.09	2,757,096	3,752,249	15.4	3.60
1968	56.09	2,658,055	3,923,243	15.6	2.91
1967	56.88	2,557,064	3,919,254	15.9	2.97
1966	59.82	2,436,149	3,885,978	16.1	2.93
1965	52.75	2,409,735	3,919,522	15.5	3.08
1964	44.97	2,384,779	4,077,038	15.7	3.74
1963	40.81	2,394,296	4,194,893	15.8	3.64
1962	39.47	2,319,538	4,175,577	15.7	3.47
1961	43.65	2,263,666	4,209,034	16.3	3.72
1960	59.76	2,335,700	4,467,981	16.2	3.49
1959	57.97	2,645,932	4,434,017	15.5	3.33
1958	51.31	2,657,543	4,693,872	15.6	3.54
1957	41.37	2,601,733	4,760,084	15.7	3.97
1956	35.27	2,550,547	4,979,452	14.8	3.80
1955	37.15	2,479,520	4,732,867	15.9	3.41
1954	27.76	2,438,169	4,493,172	15.5	3.03
1953	26.99	2,377,928	4,453,268	15.7	3.28
1952	22.88	2,336,177	4,497,722	16.1	3.38
1951	22.52	2,314,447	4,263,230	15.1	2.72
1950	17.32	2,245,101	4,157,830	14.2	4.12