

# 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,  $^{210}\text{Pb}$  (half-life 22.3 y) and  $^{137}\text{Cs}$  (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  $^{14}\text{C}$  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<sup>2</sup>.

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<sup>2</sup>) 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	
<b>Supporting services</b>				
Nutrient cycling	Weathering	Geochemistry	(39)	
		Stable isotopes	(40)	
Photosynthesis	Biogeochemical fluxes	Diatoms	(41)	
		Geochemistry	(42)	
Primary production	Aquatic	Carbon isotopes	(43)	
	Terrestrial biomass	Pollen microfossils	(44)	
Soil formation	Weathering	Genetic biomarkers	(45)	
		Fossil pigments	(46)	
Water cycling	Aquatic productivity	Fossil pigments	(46)	
	Hydrological state, groundwater	Geochemistry	(39)	
	Peat wetness	Testate amoebae	(47)	
		Peat humification	Colorimetry	(48)
	Stalagmite properties	Luminescence	(49)	
		Lake levels	Ostracods	(50)
		Stratigraphy/geochemistry	(51, 52)	
<b>Provisioning services</b>				
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)
Fiber	Fuel, wood	Fish fossils	(60)	
		Forest/scrub cover	Pollen microfossils	(53–55)
	Wood/charcoal burning	Organic macrofossils	(61)	
		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)
	Aquatic	Organic biomarkers	(69)	
			Geochemistry/stable isotopes	(70)
		DNA taxonomy	(71)	
			Algae	(72, 73)
Ornamental resources	Salinity	Zooplankton and zoobenthos	(74, 75)	
			DNA taxonomy	(76)
Fresh water	—	—	—	
		Diatoms	(77)	
		Chironomids	(78)	
<b>Regulating services</b>				
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)	
Climate regulation	Acidity	Diatoms	(86, 87)	
		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)
Pest regulation	Arboreal disease	Diatom microfossils	(107)
		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)
Water regulation	Dissolved oxygen/anoxia	Redox metals, biogenic silica	(116)
		Chironomid microfossils	(117)
	Surface water acidity	Diatom-inferred pH	(86, 87)
	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



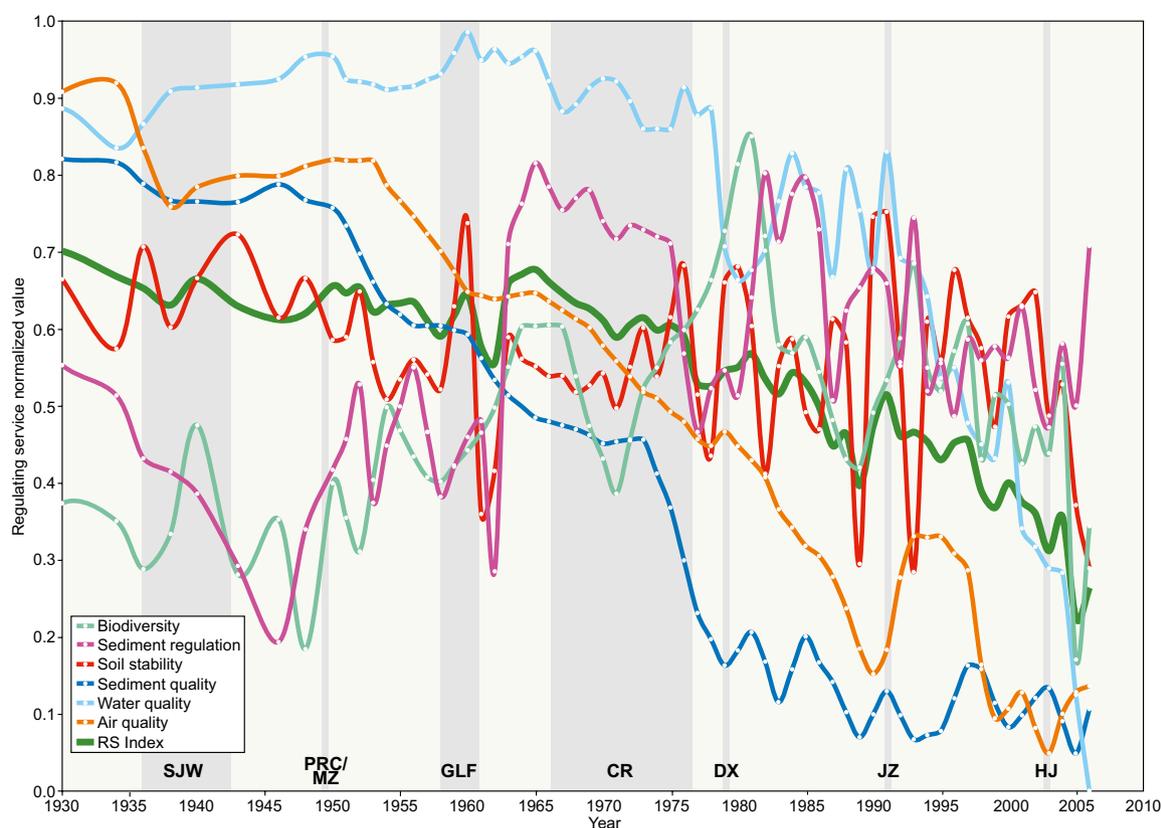
**Fig. 1.** Lower Yangtze basin showing the Chaohu and Taibai lake-catchment sites in the counties of Shucheng and Huangmei, the location of the Dabie mountains, and major regional cities.

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

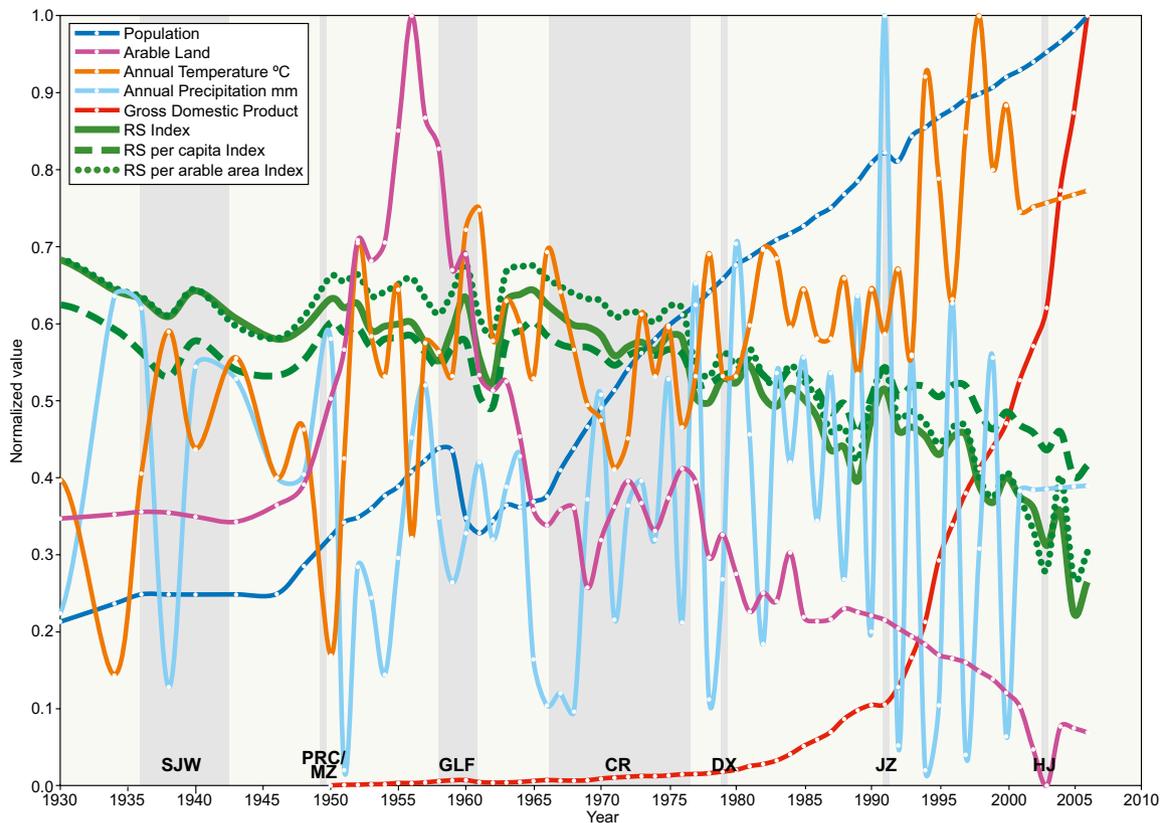
service time series were relatively high and stationary, suggesting sustainable land use.

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  $T$  ( $^{\circ}\text{C}$ ) 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.

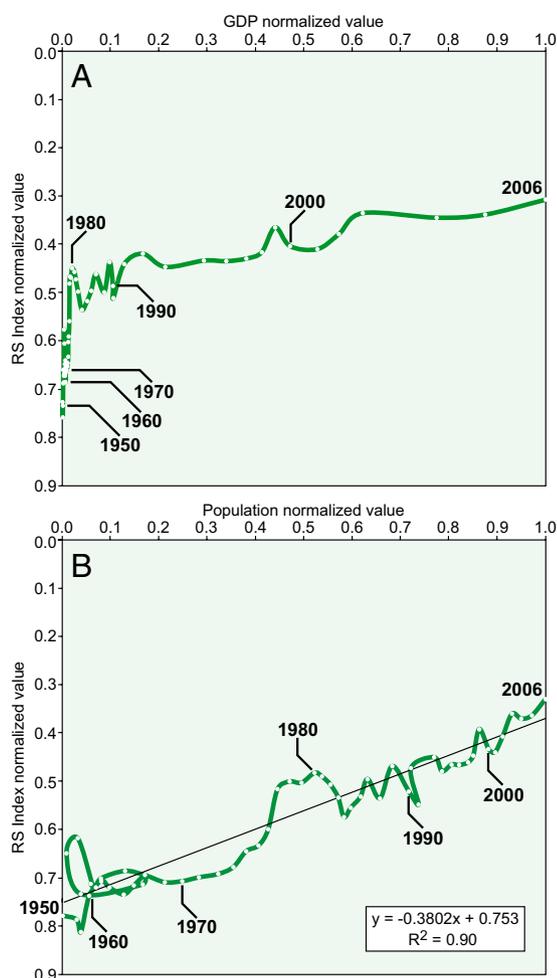
The timing of changes in the RS index suggests that the multidecadal decline in regulating services started after the main peak in arable land conversion in the 1960s and before the apparently changing climate of the 1990s. The post-1965 decline of the RS index that parallels both the population rise 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 sug-

gest 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. 4A) a positive but nonlinear relationship with a clear inflection  $\sim 1980$ . 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. 4B). 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 ~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  $^{210}\text{Pb}$  and  $^{137}\text{Cs}$  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  $\pm 5$  y, at  $1900 \pm 10$  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, ~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 $\times$  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 $\times$  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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