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Poverty alleviation strategies in eastern China lead to critical ecological dynamics

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HIGHLIGHTS

- Lower Yangtze ecological and economic records reveal long-term system dynamics.
- Resilience in the regional social–ecological system declined from 1970s.
- Poverty alleviation led to losses of regulating ecosystem services.
- Modern regional system is in transient phase moving towards new steady state.
- Economic growth and ecological degradation are still coupled.

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ABSTRACT

Poverty alleviation linked to agricultural intensification has been achieved in many regions but there is often only limited understanding of the impacts on ecological dynamics. A central need is to observe long term changes in regulating and supporting services as the basis for assessing the likelihood of sustainable agriculture or ecological collapse. We show how the analyses of 55 time-series of social, economic and ecological conditions can provide an evolutionary perspective for the modern Lower Yangtze River Basin region since the 1950s with powerful insights about the sustainability of modern ecosystem services. Increasing trends in provisioning ecosystem services within the region over the past 60 years reflect economic growth and successful poverty alleviation but are paralleled by steep losses in a range of regulating ecosystem services mainly since the 1980s. Increasing connectedness across the social and ecological domains after 1985 points to a greater uniformity in the drivers of the rural economy. Regime shifts and heightened levels of variability since the 1970s in local ecosystem services indicate progressive loss of resilience across the region. Of special concern are water quality services that have already passed critical transitions in several areas. Viewed collectively, our results suggest that the regional social–ecological system passed a tipping point in the late 1970s and is now in a transient phase heading towards a new steady state. However, the long-term relationship between economic growth and ecological degradation shows no sign of decoupling as demanded by the need to reverse an unsustainable trajectory.

1. Introduction

1.1. Agricultural social–ecological systems

Poverty alleviation through agricultural intensification that increases trade opportunities and rural incomes has been achieved in many regions, but there is often only limited understanding of the impacts on ecological dynamics. Agricultural intensification is also seen as an essential component of ensuring global food security over the coming decades (Royal Society, 2009; Tilman et al., 2002). However,

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the links between agricultural intensification, ecosystem services and the sustainability of social and ecological conditions, while known in general terms, are often difficult to gauge. For example, the apparent paradox between continued rises in wellbeing in the face of ecological degradation (Raudsepp-Hearne et al., 2010) is still not fully understood (Duraiappah, 2011; Nelson, 2011). While there is growing awareness that sustainable agriculture should be viewed from the perspective of adaptive and coupled social–ecological systems (Liu et al., 2007), the lack of long term data for regulating and supporting ecosystem services is also a major barrier to assessing the likelihood of sustainability or agricultural collapse (Costanza et al., 2007; Dearing et al., 2012a).

In a rapidly globalizing world, complexity theory suggests that agricultural intensification might be a process associated with increasing levels of connectedness across and between sub-systems, raising the chance of cascading failure and systemic collapse (Scheffer et al., 2012; Walker et al., 2009). Thus, a clearer understanding of how system network interactions are changing in rapidly developing agricultural systems would help to assess levels of resilience to external shocks and the likelihood of the tipping points that precede critical transitions (Biggs et al., 2012). The theory also indicates that a system may display early warning signals of impending instability and tipping points (Scheffer, 2009), potentially offering vital evidence for agricultural managers to modify strategy (Brock and Carpenter, 2006).

While there have been numerous calls to narrow the gap between complexity theory and its application to real world situations (e.g. Carpenter et al., 2009; Dearing et al., 2012a; Nicholson et al., 2009), progress has not advanced much beyond the implicit reference to system dynamics in frameworks for adaptive management (Dawson et al., 2010; Ostrom, 2009) and the development of more sophisticated social–ecological models (e.g. Lade et al., 2013). As a result, there are many calls for research that can quantify trade-offs between provisioning and regulating ecosystem services (e.g. UNEP, 2011), help anticipate tipping points and critical transitions (e.g. Carpenter et al., 2009), and provide an evidence base for policy-making based on complexity science principles. But there is little evidence for the successful application of complexity science in real world, regional, social–ecological systems to a level that provides new insight for sustainable management.

1.2. China as a case study

Spectacular economic growth over the past 30 years has made China the world's second largest economy, taking more than 600 million people out of poverty (World Bank, 2007). At the same time, environmental deterioration has become a major threat to China's future sustainable development (Liu and Diamond, 2005). With growing evidence for reduced crop yields (Guo et al., 2010; Ray et al., 2013), polluted water bodies (Gao and Zhang, 2010) and higher frequencies of extreme flood events (Dai and Lu, 2010) as unintended consequences of agricultural development, it seems that a conventional approach to environmental management in China is failing. As a result, the Chinese government has implemented environmental laws and policy (Wang, 2010), launched conservation and ecological engineering projects (Zhang and Wen, 2008), and driven institutional innovations (Liu and Diamond, 2008). Despite these measures, environment degradation cost around 3.8% of gross domestic product (GDP) in 2011, and the rate of growth in environmental costs exceeded the rate of GDP growth in 2009 (Chinese Academy, 2009). The main problem with these traditional policy responses is that they are essentially static measures lacking essential adaptive mechanisms that might weaken or dampen the positive feedbacks in the system that could lead to instability. A key question facing managers of rapidly changing social–ecological systems in China and elsewhere is how to develop a deeper, holistic understanding of system dynamical behavior that can underpin successful adaptive management strategies.

1.3. Study aims

A previous study of social–ecological change in the Lower Yangtze River Basin (LYB) region over the past 60 years, using lake sediment records (Dearing et al., 2012b), provided insight into the sustainability of the modern land use through analysis of ecosystem services (MEA, 2005). Here, we add new reconstructions and analyses of time-series for individual and aggregated (indexed) ecosystem services over the past decades for three rural counties (Huangmei, Shucheng and Wujiang) and the Yangtze tidal zone (Chongming), upscaled to represent the whole LYB: a total of 55 annually resolved time series representing the main trends in social, economic and ecological conditions since 1950, including representative trends for both provisioning and regulating services. Our aim is to develop an empirical, evolutionary approach to the study of the nonlinear dynamics of a rapidly changing region in eastern China that includes the rapidly growing cities of Shanghai and Nanjing. In doing so, we aim to quantify the long term trajectories of change, the levels of resilience and instability across the region, and the presence of tipping points at local through to the regional scales for input into management plans.

1.4. Locational context

For the purposes of the study we define the LYB as the area in the Yangtze River watershed lying east of Jiujiang City (29°41′37″ N, 116° 00′ 30″ E) within Hubei, Anhui, Jiangxi, Jiangsu, Zhejiang and Shanghai Provinces (Fig. 1). This river watershed area is ~122,000 km^2 with a main channel river length of ~940 km. The modern LYB represents 7% of total farmland in China with 10% of national crop production. Huangmei, Shucheng, Wujiang and Chongming Counties are located in the Hubei, Anhui, Jiangsu, and Shanghai Provinces respectively. Each county covers an area of ~1200 km^2 with ~1 M population.

Remote sensing data (Gu et al., 2009; Ning et al., 2010; Li et al., 2009; Yin et al., 2011: Zhu et al., 2007) from the past decades show increased areas of built-on land (45–198%) in all counties and relative losses of farmland (3–31%) in three of the counties (Tables A.1 and A.2). Agricultural intensification started in the 1980s with affordable fertilizers, herbicides and pesticides. Nitrogenous fertilizers have caused the acidification of soils leading to declines in wet paddy rice yields (Guo et al., 2010). The accelerated nutrient loading from fertilizers and dairy farm effluent to water courses, ponds and lakes is causing anoxia, recycling of phosphorus from sediments, eutrophication and lower fish yields (Gao and Zhang, 2010). Increased sediment delivery from soil erosion is reducing river channel volume, causing more destructive floods and more sediment delivery from bank erosion (Dai and Lu, 2010).

2. Materials and methods

2.1. Approach

It is conventional to reason (e.g. Costanza et al., 2007) that given a history of environmental degradation, regional social–ecological systems may gradually lose resilience and become vulnerable to either external events, like climate, or changes to internal dynamics that make regime shift more probable. What is not so clear in the literature is how to quantify the losses of resilience and changes in dynamics: what symptoms would a modern, vulnerable, regional social–ecological system be expected to show if it was close to a tipping point or had already passed a tipping point into a transient phase? Here, we identify lines of evidence for a number of systemic changes that together would provide a strong basis for considering the state of the modern system. These are: 1) evidence for long term trends in the degradation of supporting or regulating ecosystem services up to the present with known links to environmental management; 2) evidence for changes in the linkages or connections between system elements that are

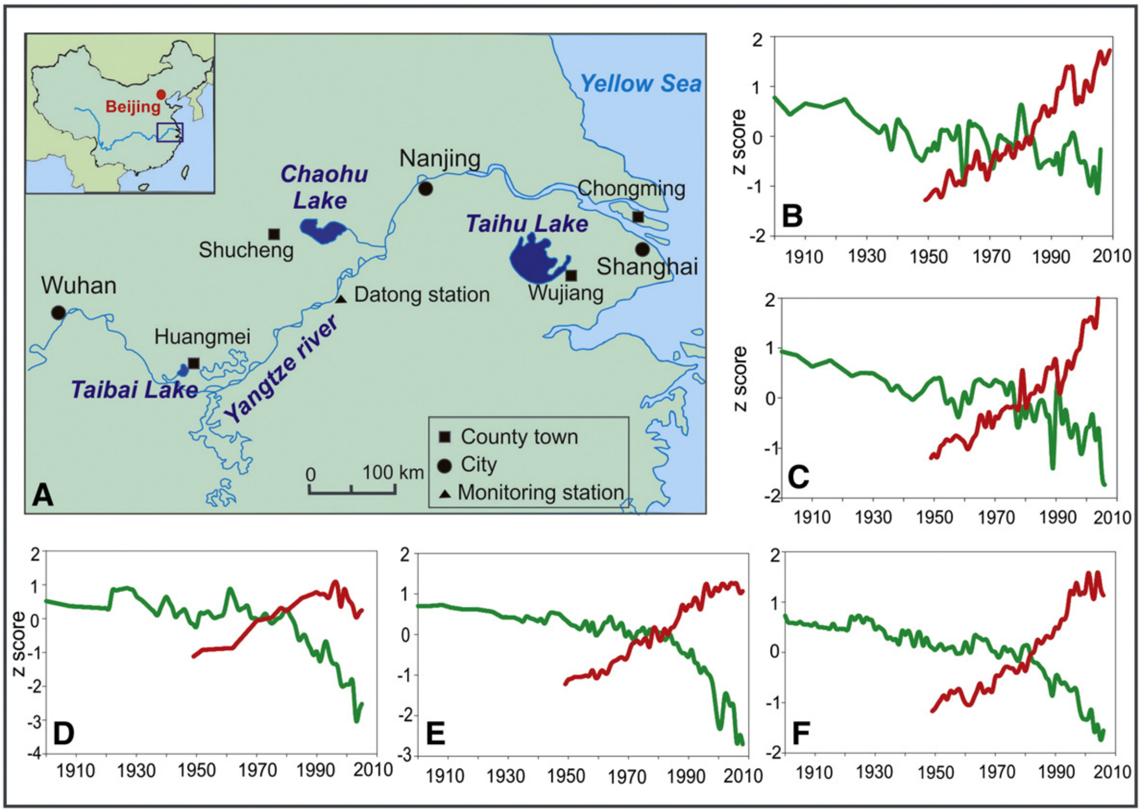

Fig. 1. Long term trends of provisioning services and regulating services in the LYB during the period 1900–2006. A) Map showing study site and locations with names. B–F) Indices of provisioning (red) and regulating (green) services based on aggregated and scaled data from official statistics, monitoring records and lake sediments for Huangmei (B), Shucheng (C), Wujiang (D), Yangtze tidal zone (E) and the LYB (F) respectively. Statistically significant breakpoints for the aggregated regulating service curves (Table S6) are dated 1985 (Huangmei), 1977 (Shucheng), 1983 (Wujiang), 1985 (the Yangtze tidal zone), and 1983 (LYB).

theoretically associated with declining resilience; 3) evidence for increased sensitivity to drivers in ecosystem service responses that might serve as an early warning signal for local regime shifts, or observations of actual local tipping points already crossed; 4) evidence for the continuation of policy that maintains the long term relationship between environmental drivers and responses. Thus our methodology uses time-series data for environmental drivers, provisioning and regulating services, and a number of statistical analyses to infer multivariate relationships, levels of connectivity, breakpoints, regime shifts and early warning signals, and environmental Kuznets curves.

2.2. Data collection

Data for provisioning services (Table A.3), area of arable land and climate (mean monthly temperature and precipitation) were collected from the Statistical Bureau in each of the four studied counties (Shucheng, Huangmei, Wujiang, Chongming) for the period 1950–2006. Provincial GDP and population data were accessed from the China Compendium of Statistics (1949–2008) published by the National Bureau of Statistics of China (http://www.stats.gov.cn/). For the whole LYB, data were drawn from all the counties in Hubei, Anhui, Jiangxi, Jiangsu, Zhejiang and Shanghai Provinces lying within the LYB watershed (Fig. 1). Most of the data obtained were annual: missing data were interpolated from data for adjacent years. As most of the county data for GDP were only recorded after 1980 we used provincial GDP per capita data to represent the county GDP per capita.

Data for regulating services (Table A.4) were obtained as ecosystem proxies over the period 1900–2006 reconstructed (Dearing et al., 2012b) from dated bottom sediments in large lakes adjacent to three of the counties: lake Chaohu–Shucheng, lake Taibai–Huangmei and lake Taihu–Wujiang. The fourth county, Chongming, is the largest island in the Yangtze estuary with no lake, so sediment data were taken from local estuarine marine sediments. We also used tidal river data from the Datong monitoring station on the Yangtze River (Fig. 1). Together these sources of information are taken to represent the 'Yangtze tidal zone'. The representation of county-level watershed ecosystem services in lake records is reasonable for the three inland counties but it is likely that the marine sediment records represent a larger upstream area than the estuary area and should be used cautiously as proxies for the LYB. We upscaled the data to represent the whole LYB by averaging the regulating service data from the three inland counties to give an aggregated regulating service curve. With specific reference to reconstruction of water quality, criticisms of transfer functions (Brodersen and Anderson, 2002) cast doubt on the accuracy of calculated total phosphorus (TP) levels. Here we use TP data to investigate trends and variability in water quality rather than to compare absolute values.

2.3. Data analysis

All the time-series were standardized (z scores) before analysis. Aggregated indices for individual counties and the basin were calculated from average standardized values. Simple linear relationships between ecosystem services and potential drivers were examined using scatter plots and Detrended Correspondence Analysis (DCA) followed by Redundancy Analysis (RDA), as the length of the first DCA gradient was <2 in all cases (Lepš and Šmilauer, 2003).

2.3.1. Connectivity analysis

Network theory suggests that system resilience is partly dependent upon the degree of connectedness between key variables (Ash and Newth, 2007; Scheffer et al., 2012). In this sense, sequential Principal Components Analysis (PCA) is widely used for capturing correlation dynamics among indexes of different economic sectors, in order to investigate the risk of system failure (Billio et al., 2010; Kritzman et al., 2011; Zheng et al., 2012). The risk rises when the largest eigenvalue increase explains the most variation in the data. We applied this approach to time-series indices representing social, ecological and economic sectors across the LYB region for the period 1950–2006. We calculated the covariance using a 10, 20 and 30 year moving window PCA for provisioning services, regulating services, provisioning and regulating services together, and regulating, provisioning, population, land use and GDP together. Only the results from the 20 year window are shown because the different window sizes give similar results. PCA axis 1 values are >0.5 for provisioning services, ≤0.5 for regulating services and ~0.5 for the combined datasets. PCA 1 + PCA 2 values are >0.5 for all datasets and these are preferred for the analysis of connectivity.

2.3.2. Breakpoints and regime shifts

Significant breakpoints in time-series were identified from a sequential analysis of mean values using Student's t-test (Rodionov, 2004) and F-statistics (Andersen et al., 2009) set to detect significant ($p \leq 0.01$) transitions over the periods 1900–2006 and 1950–2006. For the sequential Student's t-test, different cut-off lengths ($l = 10, 20, 30$) were used in order to assess the significance of the breakpoint. If the breakpoint is present in both F-statistics and Student t-test within different cut-off lengths, we mark this point as a potential regime shift or critical transition. We tested the null hypothesis that a breakpoint was an inherent feature of the time-series, predictable from a linear autoregressive model. We fitted a suite of autoregressive integrated moving average [ARIMA (p,d,q)] models where p is the autoregressive (AR) order, q is the moving average (MA) order and d is the differencing part to the time series for the period 1900 up until the point of the hypothesized critical transition using R (http://www.r-project.org/). We selected the optimum model for each time series based on the lowest Akaike Information Criterion (AIC) to predict the evolution of the time-series after the transition (Wang et al., 2012).

2.3.3. Early warning signals and instability

The most robust signal for system instability generally, and early warning signals prior to a fold bifurcation transition based on critical slowing down or flickering theories, is increased variance (Dakos et al., 2008; Kefi et al., 2012). We followed previous studies (Dakos et al., 2012), analyzing residuals from detrended annual time series of ecosystem services and drivers using a Gaussian kernel smoothing function. Standard deviations of sliding windows representing half the length of the time-series were plotted starting at the mid-point of each series. Variance in potential driver signals was assessed on individual time-series and a PCA axis 1 proxy of all driving controls.

2.3.4. Kuznets curve analysis

The environmental Kuznets curve theory (Dinda, 2004) predicts that the degree of coupling between economic growth and environmental degradation remains strong until a point is reached where wealth leads to investment into cleaner industrial processes. In the LYB, Kuznets curves for each region over the period 1950–2006 were derived from plots of regulating service indices (inverted) against county GDP per capita.

3. Results

3.1. Long term trends

Our results for indexed regulating services in the LYB since 1900 (Fig. 1, Fig. A.1) provide empirical evidence of long term environmental degradation, with declines in air quality regulation, soil stability, sediment regulation, biodiversity and water purification, which is particularly notable after 1980. The decline in regulating services has been greater in the relatively wealthy Wujiang and the LYB as a whole, than in the poorer rural Shucheng and Huangmei to the west. In contrast, the same period shows rising levels of provisioning services (Fig. 1, Fig. A2) in terms of crop production and agricultural goods. Bivariate plots of provisioning against regulating services (Fig. A.3) show that the nature of the relationship in the eastern locations (Chongming, Wujiang) and the whole LYB changed after the mid-1990s with regulating services continuing to decline while provisioning services remained either stationary or in decline.

3.2. Drivers and ecosystem responses

The decadal trends in regulating and provisioning services broadly match the rise in regional population numbers and GDP per capita but are not significantly linked to regional changes in climate or land use over the same period. The RDA analyses show that the first two eigenvalues explain 62–85% of the total change observed in the four regions, but that the explanatory variables vary in type and sign (Table A.5). Population and GDP per capita are the most correlated with the ecosystem service changes, but some are negatively correlated and some are positively correlated. This suggests that over the whole period there is no single driver or pair of drivers that determines ecosystem service change across the four regions. Rather, the ecosystem services are shaped by the actions of interacting multiple drivers. Given the concerns about global warming, it is notable that the external climate drivers (precipitation and temperature) have not exerted obvious long-term influences on ecosystem service changes.

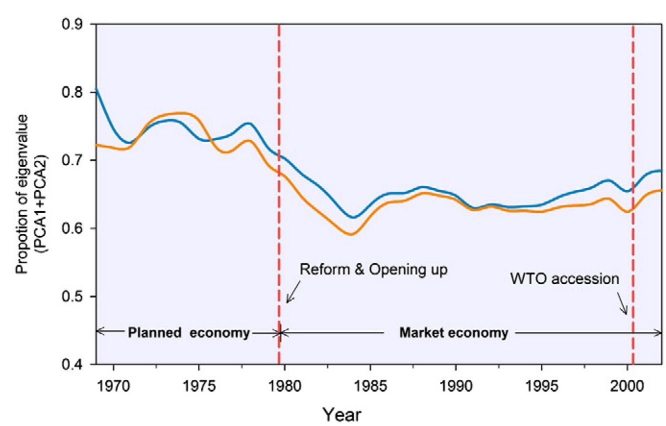

Fig. 2. Connectivity of the ecosystem service sectors and the whole social–ecological system within the LYB since 1970. The two curves represent the changing connectivity for regulating and provisioning service records alone (blue line) and for regulating and provisioning service records with data for population, GDP and arable land use (brown line) for combined areas of Huangmei, Shucheng, Wujiang and the Yangtze tidal zone. The curves are calculated as the proportion of variability (eigenvalues) for PCA axes 1 and 2 over a 20 year moving-window. The shift from high values to declining values in the late 1970s coincides with the change from a planned economy to the market economy brought about by the 'opening-up' reforms. The recent rise in the values coincides with China's accession to the World Trade Organisation (WTO) in 2001.

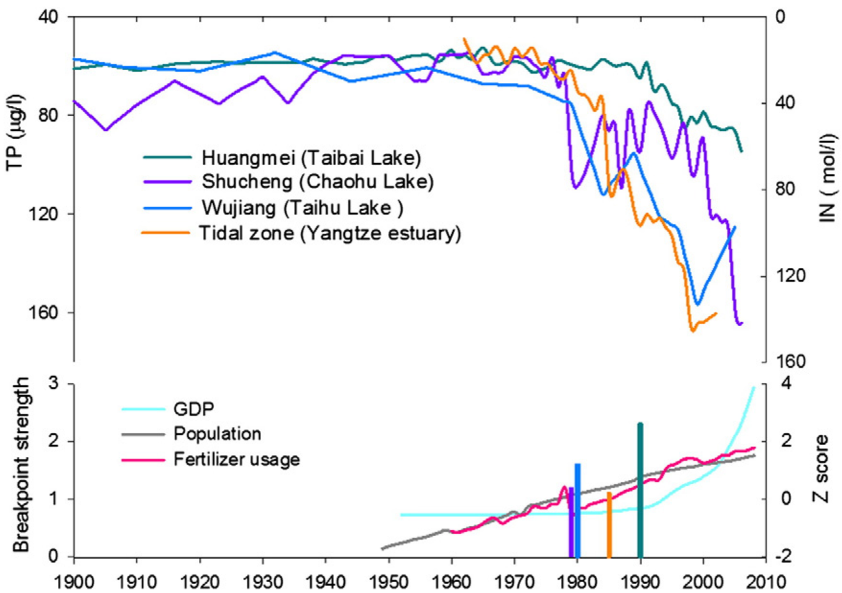

Fig. 3. Breakpoints and regime shifts in water quality records across the LYB 1900–2006. Reconstructed time series (upper panel) for total dissolved phosphorus (TP µg/l) in Huangmei, Shucheng and Wujiang and dissolved inorganic nitrogen (in mol/l) in the tidal Yangtze zone show rapid nutrient enrichment (note reversed left and right axes) after the 1970s. The timings and relative strength of statistically significant breakpoints (Table S2) are shown as vertical bars in the lower panel and are dated as Huangmei (1990), Shucheng (1979), Wujiang (1980), and the Yangtze tidal zone (1985). Normalized (z score) records of potential drivers of agricultural intensification (lower panel) show LYB-level changes for fertilizer usage, population and GDP. There are no strong linear links between the individual drivers of water quality and the water quality records.

3.3. System connectedness

Curves of PCA axis 1, or combined PCA axes 1 and 2, for the combined regulating and provisioning services (with or without population, GDP and arable land use changes included) since 1950 suggest high connectivity prior to the late 1970s, a rapid decline in connectivity through the early 1980s reaching a minimum ~1984, and a rising trend from the mid 1980s to 2006 (Fig. 2).

3.4. Breakpoints and regime shifts

For individual regulating services (Table A.6) both the F-statistics and Student's t-test results from the two timescales (1900–2006 and 1950–2006) show a large number of statistically significant breakpoints depending on the length of time series and cut-off length. A conservative analysis (Fig. 3) of the whole set of breakpoints ($p \leq 0.01$) suggests one highly significant cluster of dates for water quality across the LYB in the period 1979–1990. There are also some clusters of dates for individual regulating service records within each region, for example: soil stability (Wujiang 1979–80), sediment quality (Huangmei 1974, Shucheng 1977), and air quality (Wujiang 1983). Student's t-test analysis of aggregated regulating service records (Table A.7) for the period 1950–2006 suggests dominant break-points in the period 1977–1985. For the longer timescale 1900–2006, clusters of significant but weaker breakpoints occur in the years 1928–1930 (Huangmei), 1950–1951 (tidal Yangtze zone) and 1934 (LYB) reflecting earlier environmental changes. In contrast, the breakpoint values ($l = 30$) for aggregated provisioning service records (Table A.8) cluster in the periods 1968–1974 and 1990–1994. For the water quality time-series, which show the clearest breakpoints, the predicted ARIMA values diverge from the observed data within 95% probability levels (Fig. A.4) showing that the abrupt changes observed cannot be predicted from previous observations using a linear model. We therefore reject the null hypothesis and refer to these breakpoints as nonlinear transitions or regime shifts.

3.5. Early warning signals and instability

The Shucheng and Huangmei water quality records show increasing variability (Fig. A.4) starting in the 1950-60s that could be interpreted as early warning signals of critical transitions (Dakos et al., 2008), as postulated elsewhere in China (Wang et al., 2012). However, the majority of other regulating service records (Fig. A.5) and provisioning service records (Fig. A.6) also show rising variability, even where there is no evidence of a breakpoint, suggesting a consistent and cumulative sensitivity to forcings at multiple locations. In contrast to the ecosystem service records, there is no clear pattern of variance in individual or aggregated driving variables (PCA axis 1) across the region (Fig. A.7),

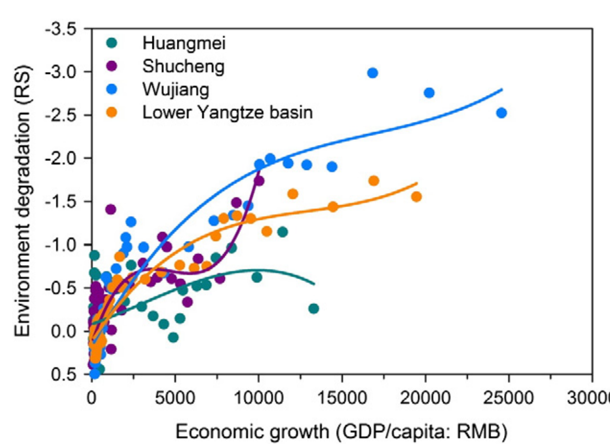

Fig. 4. Environmental Kuznets curve relationships between environmental degradation (regulating service indices: z scores) and economic growth (GDP/capita: RMB—renminbi) for Huangmei, Shucheng, Wujiang and the whole LYB over the period 1950–2006. Fitted polynomials show significant levels of explanation: Huangmei $r^2 = 0.26$, $p = 0.014$; Shucheng $r^2 = 0.65$, $p \leq 0.01$; LYB $r^2 = 0.91$, $p \leq 0.01$; Wujiang $r^2 = 0.89$, $p \leq 0.01$.

except for GDP/capita. The pattern of variance of aggregated drivers in each sub-region is also inconsistent, showing decreasing variance in Shucheng and Chongming, but increasing variance in Huangmei and Wujiang from 1990 (Fig. A.8). Therefore, it is unlikely that the widespread increasing variability in the majority of ecosystem service records is simply a reflection of variance in the drivers, unless GDP/capita has an overwhelmingly strong and disproportionate effect.

3.6. Environmental Kuznets curves

During the last 60 years, the four areas within the LYB display a rapid rise in environmental degradation associated with very low incomes followed by a less steep rise as incomes increase (Fig. 4). The 'poverty-stricken' Shucheng shows rapid environment deterioration when the annual GDP per capita was below 2000 yuan (US $320) and relative environmental stability between 2000 and 8000 yuan (US $1280), but a sharp environmental decline in recent years as GDP per capita exceeded 8000 yuan. In the wealthiest county, Wujiang, the curve describes continuing loss of regulating services even while its GDP per capita has exceeded 20,000 yuan (US $3200). Only Huangmai shows evidence for a recent turning point in the curve towards lower environmental degradation.

4. Discussion

4.1. Chinese agricultural dynamics

It took nearly 50 years after the birth of the People's Republic of China in 1949 to achieve food sufficiency, but the environmental cost was extensive (World Bank, 2007). During the late 1950s and 1960s, nearly 10% of China's forest was lost in the three years of the 'Great Leap Forward' (Shapiro, 2001) and numerous lakes, wetlands and coastal areas were reclaimed for crop production (Zhao and Woudstra, 2007). The contrasting trends in provisioning and regulating services (Fig. 1) in the LYB are thus consistent with the national focus on agricultural development and intensification (Ju et al., 2009). Tradeoffs occur when the quality or availability of one ecosystem service is reduced as a consequence of the increased exploitation of another (Rodriguez et al., 2006). Local farmers and environmental managers in the LYB are to a large extent aware of the environmental degradation (our unpublished interviews) but there is essentially an accepted tradeoff between rising agricultural production and environmental degradation. The question for the LYB is whether the tradeoff is acceptable in terms of the maintenance of provisioning ecosystem services now and in the future. In attempting to answer this question we can draw on several independent lines of evidence for the dynamical state of the regional system.

First, the results of the connectivity analysis (Fig. 2) are consistent with an early social–ecological regime (1970s) characterized by relatively homogenous rural communes that were, in terms of ecosystem services, highly connected due to the top-down control policies associated with the Maoist planned economy. The subsequent decline in connectivity marks the reforms brought about by Deng Xiaoping and the opening-up to a market economy. As communes were rejected in favor of family farms (the household responsibility system), agricultural diversity increased and the levels of connectivity between provisioning and regulating services declined for nearly a decade. After the mid-1980s, the gradually rising curves suggest rising levels of connectivity up to the present time. Unlike the 1970s, the recent connectivity implies increasing uniformity in the impact of driving variables linked to improving incomes, incremental urban expansion, increasing international trade and, most recently, government agricultural subsidies. These trends have strengthened with globalization during the 1990s and particularly since China's accession to the World Trade Organization in 2001. Comparison with other real world systems is not possible due to the lack of studies, so caution is required when interpreting the data. But from a theoretical standpoint, the accelerating trend in connectivity after 1999 could indicate a heightened system risk for the rapid cascade of local failure across the regional scale or possibly the harbinger of a new steady state.

Second, the increasing variability in ecosystem services and regime shifts can be viewed as a generic sign of decreasing system stability and loss of resilience (Dakos et al., 2008; Kefi et al., 2012). The evidence for widespread and increasing variability in regulating services from the 1950–1960s onwards (Fig. A.5) accords with other analyses that extreme events across the LYB, like the 1998 Yangtze mega flood and the 2007 algal bloom in Taihu lake (Guo, 2007; Yin and Li, 2001), are becoming more frequent. For individual regulating services, water quality records in all the studied locations show consistent evidence for regime shifts in the form of statistically significant breakpoints during the period 1979–1990 (Figs. 3 and A.4). Breakpoints in the aggregated regulating services index for the whole LYB also identify the 1980s as a key decade (Table A.7). Therefore, despite the early landscape transformations of the Maoist era, our data suggest that local regime shifts in a bundle of regulating services occurred later. Deng Xiaoping's opening-up market reforms from the late 1970s onwards set in motion new land use organizations and agricultural practices that had initial effects on local regulating services, like water quality, rather than provisioning services. In contrast, the processes of agricultural intensification and rural poverty alleviation since the mid 1980s have led to fewer transformations of landscapes but have driven much larger impacts on local and, ultimately, regional biogeochemical cycles. In system terms, the resilience of the regional ecosystems has continued to be undermined by the relatively 'slow' (chronic) and cumulative effects of social and economic drivers. Of these, the consistently rising variance in GDP per capita across the region since 1990 (Fig. A.7) argues for strong bi-directional coupling between rural wealth and environmental conditions affecting the stability of the regional social–ecological system.

Third, the lack of recent growth, and even decline (Fig. 1), in some provisioning services (per county) may reflect that maximum production capacities have been reached or that there are significant losses of farmland to other land uses (e.g. urbanization) in some areas (Tables A.1 and A.2). However, there is also growing evidence for deleterious impacts from agricultural intensification caused by the development of positive feedback loops. For example, farmers respond to declining rice yields (Guo et al., 2010), caused by the acidifying effects of nitrogenous fertilizers, by increasing fertilizer application rates even higher. Also, the long term nutrient enrichment of lakes and other surface waters is leading to bottom water anoxia and release of phosphorus from sediments causing accelerated eutrophication (Li et al., 2011; Wang et al., 2012).

Fourth, the criticisms of China for following a 'pollute first, clean up later' policy linked to the idea that progressive development can drive improved environmental conditions are upheld in the present study. The patterns of the environmental Kuznets curves reveal a long term weakening of the coupling between environmental degradation and economic growth but there is, importantly, no evidence for a regional-wide turning point towards improved environmental conditions. Given the evidence for declining resilience, conventional turning points may become increasingly unattainable as environmental degradation leads to lower agricultural outputs and rural incomes (Liu, 2012).

Such findings suggest that the Environmentalist's Paradox (Raudsepp-Hearne et al., 2010) is not explained by a decoupling of wellbeing from nature through technological advance; more likely they support the theory that time lags may lead to declines in wellbeing in the future. However, the globalized nature of agriculture means that deteriorating ecosystem services in the LYB might be compensated in the future by agricultural imports, a potential transfer of ecological degradation through telecoupling (Liu et al., 2013) between distant regions. Indeed, the original explanations examined for the Environmentalist's Paradox, and subsequent discussions of this phenomena (Ang and van Passel, 2012; Duraiappah, 2011; Nelson, 2011) fail to acknowledge the underlying mechanism leading to a 'Tragedy of the Commons' (Hardin, 1968). Essentially, individuals, acting in a rational manner, are motivated to exploit common pool natural resources beyond the capacity of those resources to deliver sustainably. For a period of time, even after the socially optimal point is reached, individuals will continue to gain in wealth or some other measure of wellbeing, as the benefit of continued or increased exploitation outweighs the environmental costs, which is shared by all. In this sense, 'individuals' may describe any group or collective in a larger society which acts independently according to self-interest, for example, national interest when the common pool resource is global. Hence, increased access to markets and demand through population growth, urbanization and globalization, as experienced by the LYB, will serve to increase individual benefits from over-exploitation of regulating services within the region, and increasingly from foreign ecosystems.

Therefore, the key questions are whether the evidence suggests that the regional system is heading for a new dynamical state, what it would look like, and how long would it take to reach. The combination of evidence for multi-decadal environmental degradation, increasing instability, local regime shifts, and strengthening (positive) feedback loops certainly indicates a transition of the LYB regional social–ecological system from one state to another (Scheffer, 2009). It is currently difficult to distinguish between the different types of transition – smooth, threshold or hysteretic (Hughes et al., 2012) – especially in a large, slowly responding system. But the presence of evidence for systemic instabilities plus the lack of evidence for an identifiable driver of the main trends suggests that the LYB is not following a smooth, deterministic transition. Thus, one interpretation of the evidence is a macro-scale shift between two regional regimes that started in the late-1970s at the time of maximum connectivity. At that time, the regional LYB social–ecological system passed a major threshold and now currently sits in a transient phase.

Transient phases of regime shifts are less predictable than stable phases, and can be associated with negative impacts (Folke et al., 2010) where ecological responses to stochastic drivers, like climate events, are likely to become less proportionate, less predictable and less manageable. These impacts are unlikely to result in abrupt transitions at the regional scale because large, complex systems may show relatively slow transitional response (Hughes et al., 2012). But the clear evidence for regime shifts in the highly sensitive, fast responding lake sub-systems suggests that some nested elements of the larger system have already shifted. With growing connectivity, we postulate that over the coming decades there will be an increasing likelihood for internally or externally driven disturbances (e.g. continuing water quality degradation or global commodity price fluctuations, respectively) to propagate new impacts between different sectors and across the region.

A critical issue for the management of the LYB in a transient phase is how to mitigate the inherent instabilities that have emerged, which are now effectively decoupled from the external conditions that originally led to the current system behavior. There even remains the possibility that hysteretic effects will render ineffective any standard management procedures designed to reverse the degradation trends. This presents a major challenge to effecting an appropriate management or policy response in terms of where (in the system) to intervene and in the timing of such interventions. To assess with any certainty how long the transition will take and what the final state will look like can probably only be ascertained through new research. In this sense, there are two priorities: (i) maintain and extend monitoring programs of ecosystem services to allow continuous appraisal of safe operating spaces for alternative land use and agricultural interventions (Dearing et al., 2014); and (ii) develop new regional-scale modeling approaches that can simulate nonlinear changes in ecosystem services over the next years and decades for given intervention. But however daunting a prospect, Chinese scientists, policy-makers and environmental managers should recognize that the current social–ecological trends will be easier to reverse before the new system states lock-in and stabilize (Hughes et al., 2012): especially important if the recent rise in connectivity heralds the termination of the current transient phase.

In November 2012, Hu Jintao's report to the 18th National Congress (Ecological Progress, 2012) stressed the need to keep the pace of China's development under control in order to maintain a balance between population, resources and the environment. This study shows that new policies for land management should take into account the vital information about nonlinear dynamics that comes from a multi-scale analysis of the social–ecological system. It provides a means for evaluating the impact of environmental degradation on human wellbeing. Failure to include this type of information in the implementation of the 12th Five Year Plan (Ecological Progress, 2012) across the LYB, and other regions, will not only risk failure in regional agricultural systems and fisheries but also jeopardize the continued success of poverty alleviation in rural areas, and the ability of those rural areas to support the ecosystem service demands of their rapidly expanding urban areas (Seitzinger et al., 2012).

5. Conclusions

We develop an evolutionary approach to study social–ecological systems based on analyses of multi-decadal time series from official county statistics and paleoecological records from lake sediments. In the LYB, these analyses provide multiple lines of evidence within counties to suggest that the long term dynamics of the regional social–ecological system have become less stable since the 1970s, and may show that the system has entered a transition phase between two steady states.

Evidence for growing trade-offs between provisioning and regulating services, increased variance in a range of social and ecological indicators, transgressed thresholds in lake systems and growing connectivity between social and ecological variables suggests declining regional resilience. Economic growth, poverty alleviation and ecological degradation do not appear to have de-coupled as required for long term sustainable use of the environment, especially with regards food security and access to clean water.

The study demonstrates how complexity science theories may be applied to real world social–ecological systems through empirical analyses of available time-series (http://www.complexity.soton.ac.uk). The findings support the need for evolutionary policy making (cf. Ostrom, 2009) based on an understanding of social and ecological interactions, ultimate biophysical constraints and inherent system dynamics.

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Appendix A

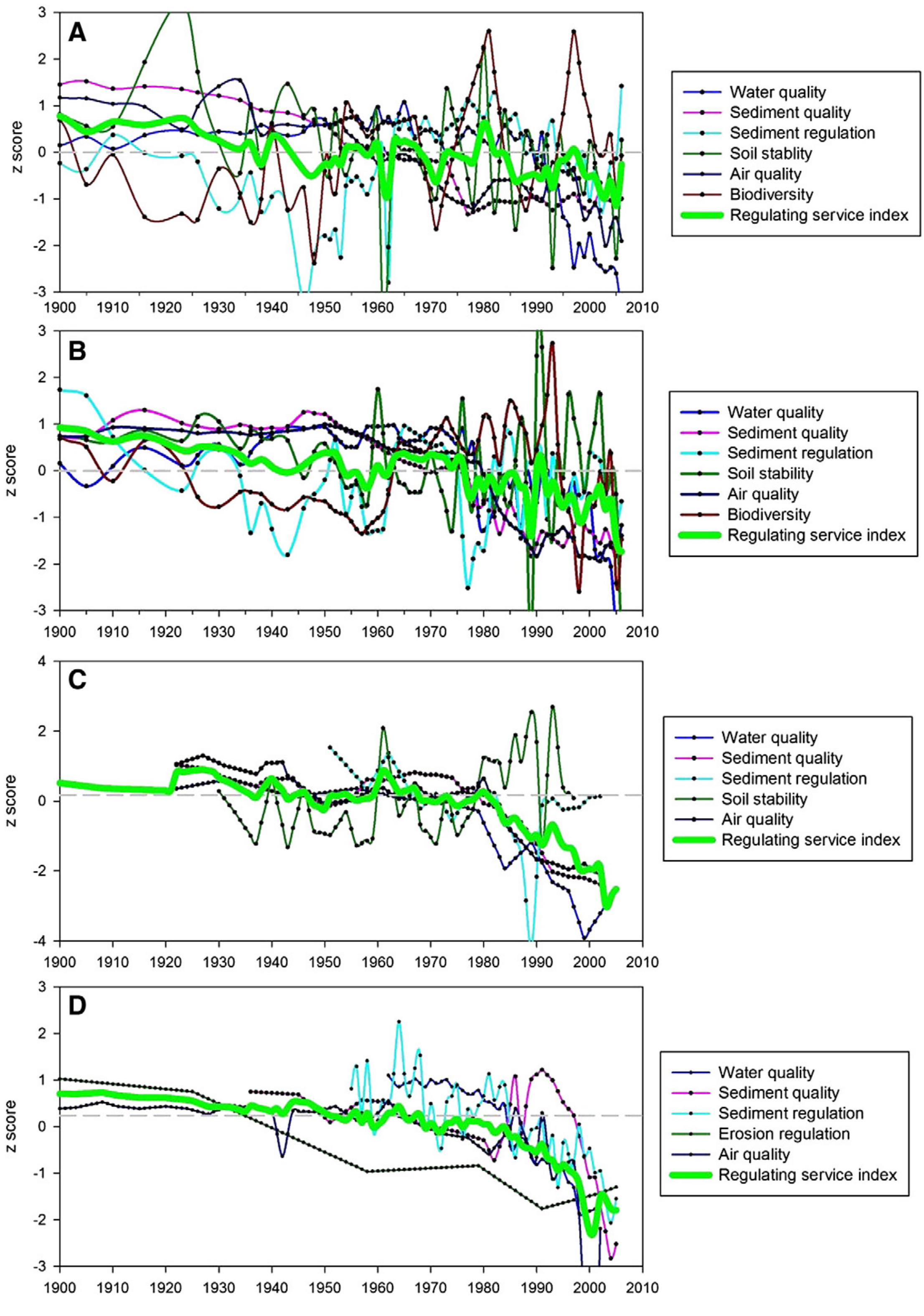

Fig. A.1. Regulating services in the lower Yangtze basin. A–D represent Huangmei, Shucheng, Wujiang, and Yangtze tidal zone (Chongming), respectively. Aggregated curve for whole LYB shown in Fig. 1F.

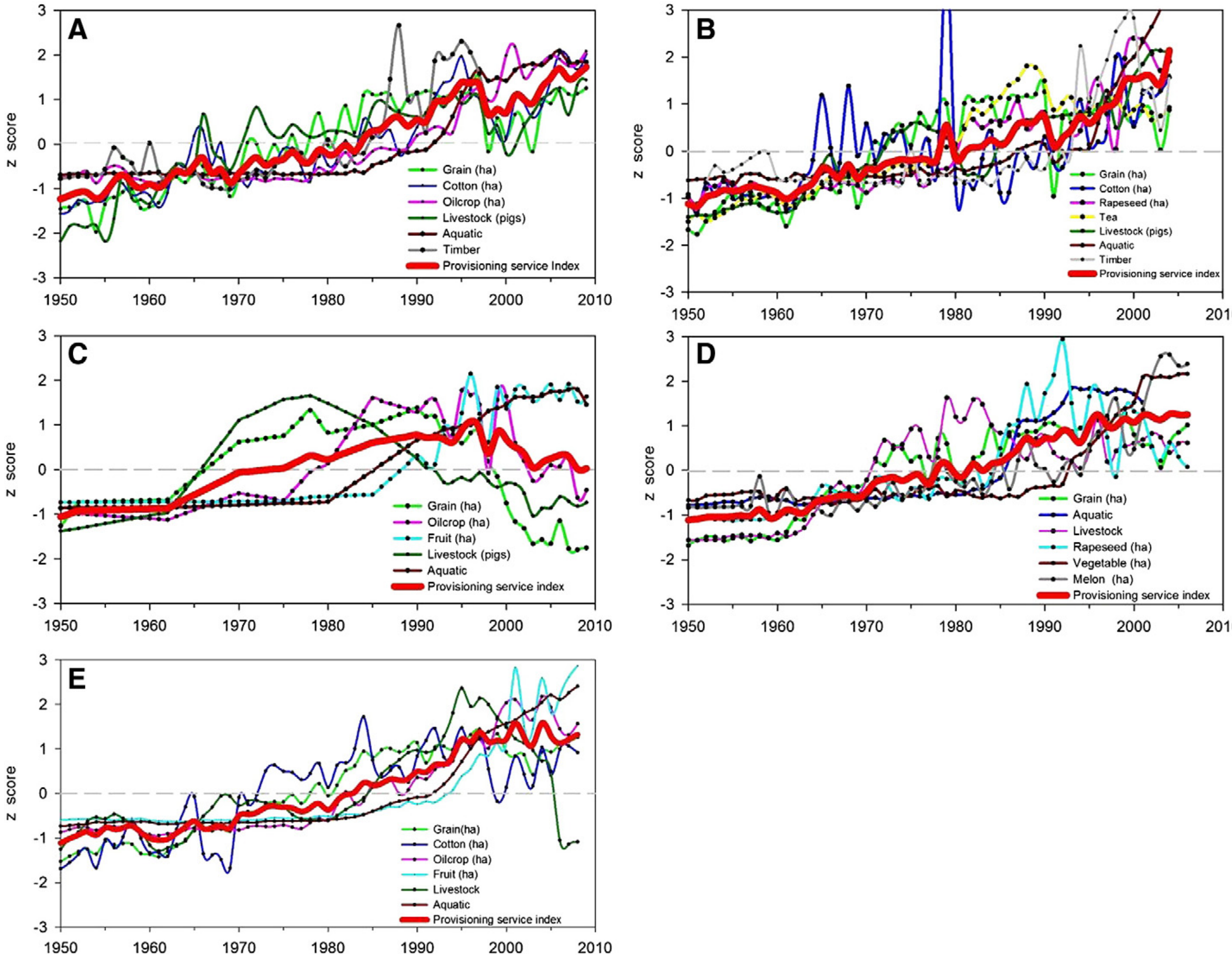

Fig. A.2. Provisioning services in the lower Yangtze basin. A–E represent Huangmei, Shucheng, Wujiang, Yangtze tidal zone (Chongming), and whole LYB, respectively.

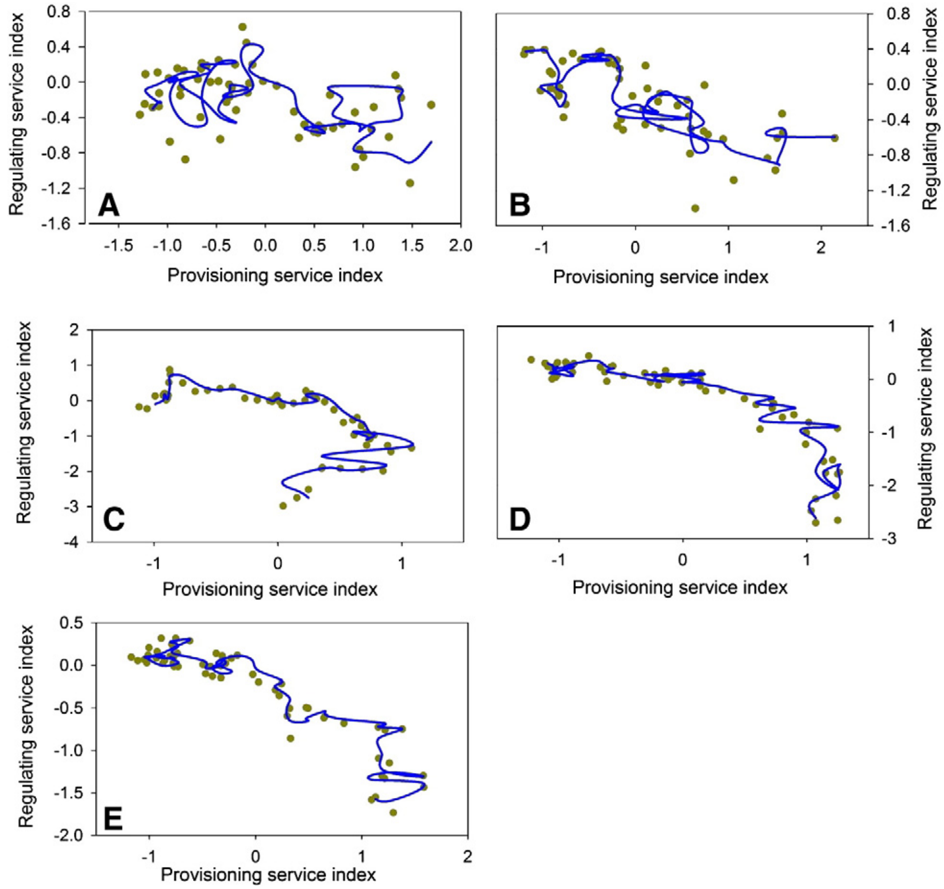

Fig. A.3. Bivariate phase plots of provisioning against regulating services with moving average curves: A–E represent Huangmei, Shucheng, Wujiang, Yangtze tidal zone (Chongming), and whole LYB, respectively. Note the recent shifts in trajectories away from relatively linear curves towards stationary (C, E) and reversed values (D) with respect to provisioning services.

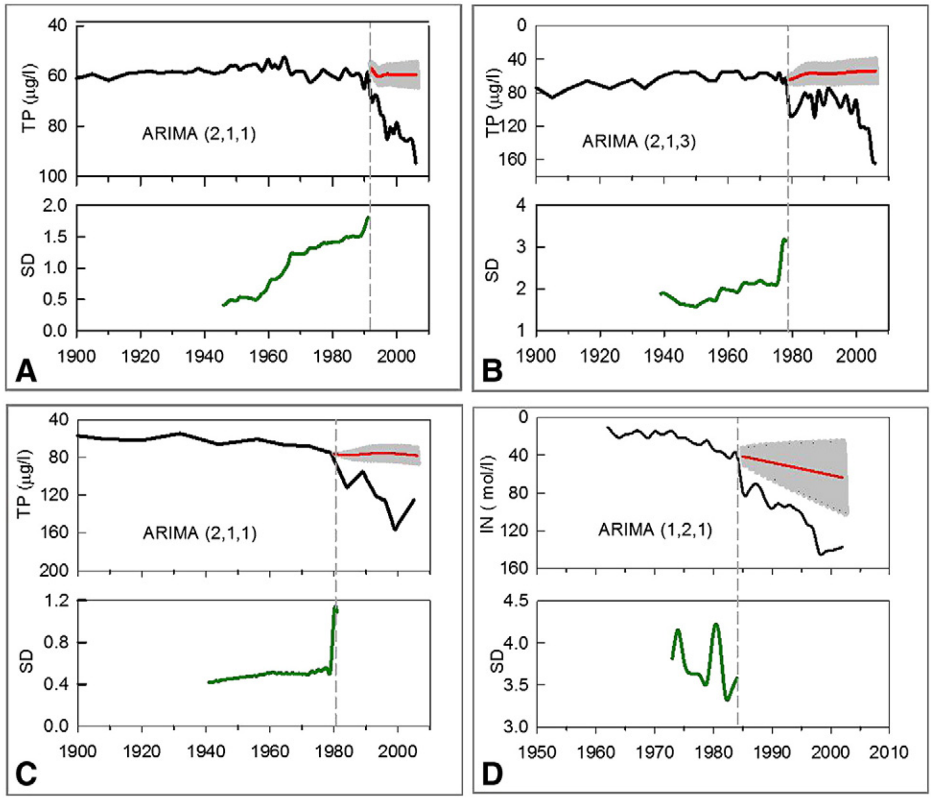

Fig. A.4. Rising variance and regime shift in water quality records across the LYB 1900–2006. A–D (upper panels) show optimized ARIMA model predictions (red lines) with error bars ($p < 0.01$) starting from each break-point (vertical dashed line) based on time-series before the break-point for Huangmei, Shucheng, Wujiang, and Yangtze tidal zone respectively. A–D (lower panels) show standard deviation of residuals after detrending, calculated for a moving window (half time-series), and plotted to the right. Analyses of interpolated data from dated lake sediments may induce a bias towards higher variance in the most recent sediments. But the presence of rising variance in advance of ~20 year old breakpoints in water quality suggests that this widespread phenomenon seen in the regulating service records (Fig. S5) is real.

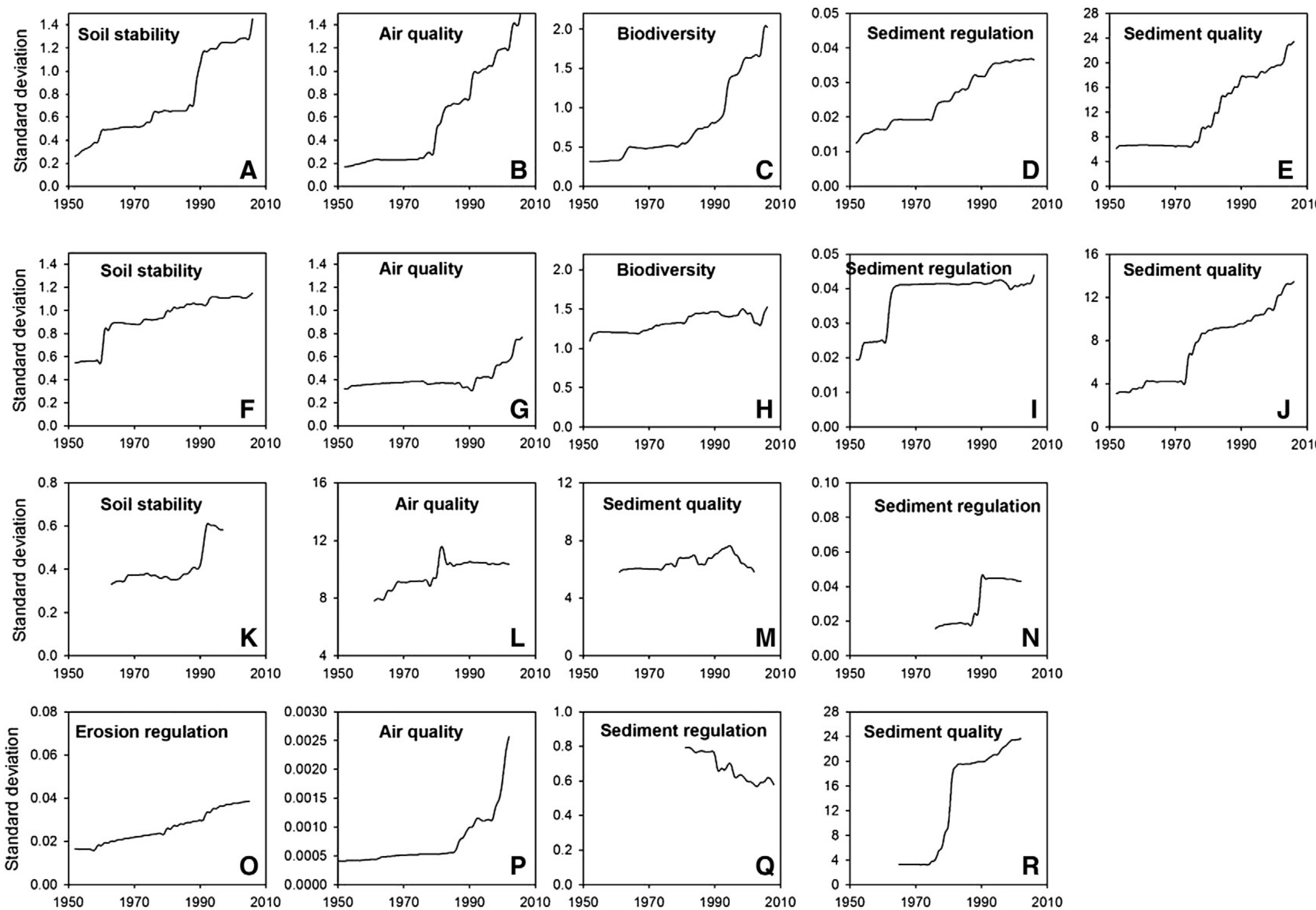

Fig. A.5. Rising variance (standard deviation) of regulating services (except water quality shown in Fig. S4) across the LYB since 1950 (some shorter records): A–E, Huangmei; F–J, Shucheng; K–N, Wujiang; and O–R, Yangtze tidal zone. The standard deviation is calculated for a moving window (half time series) of residuals after detrending the whole original dataset. Caution is needed in interpreting these data as analyses of interpolated data from dated lake sediments may induce a bias towards higher variance in the most recent sediments (see text for discussion).

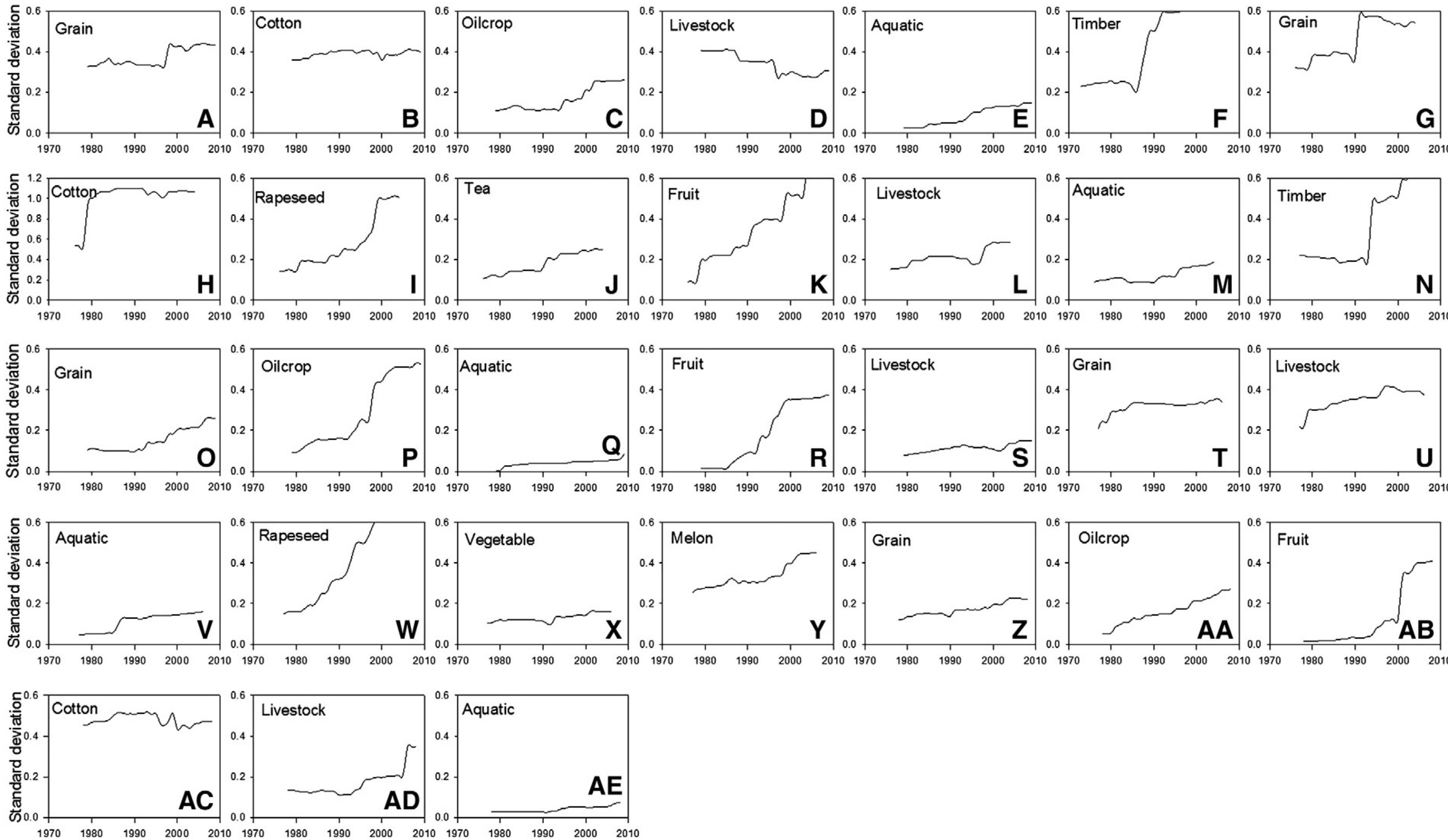

Fig. A.6. Rising variance (standard deviation) of individual provisioning service records across the LYB. A–F, Huangmei; G–N, Shucheng; O–S, Wujiang; T–Y, Yangtze tidal zone; and Z–AE, whole LYB. The standard deviation is calculated for a moving window (half time series) of residuals after detrending the original data. Unlike the regulating service records (Figs. S4 and S5), there is no potential bias in the calculation of variance caused by interpolation across unequal time increments.

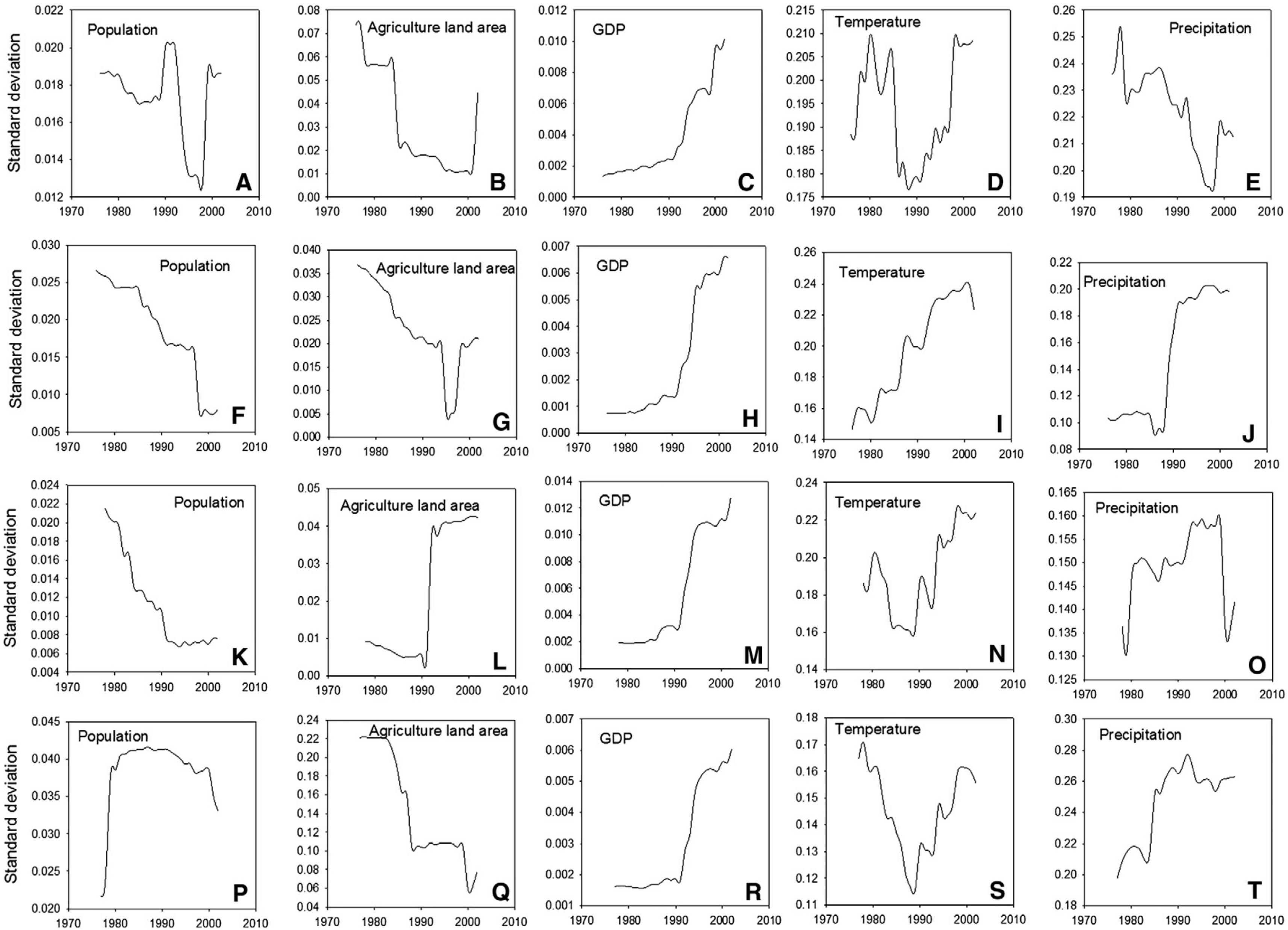

Fig. A.7. Variance (standard deviation) of possible individual drivers in each region: A–E, Huangmei; F–J, Shucheng; K–O, Wujiang; and P–T, Yangtze tidal zone. The standard deviation is calculated for a moving window (half time series) of residuals after detrending the original data.

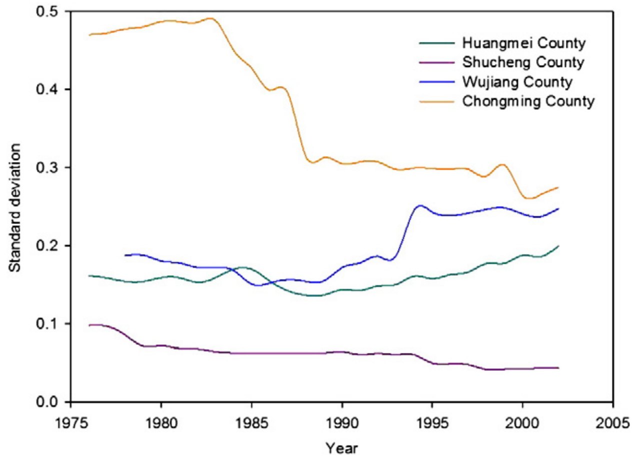

Fig. A.8. Variance (standard deviation) of PCA axis 1 of all drivers (temperature, precipitation, GDP per capita, population and arable land in each region. The standard deviation is calculated for a moving window (half time series) of residuals after detrending the original PCA axis 1 data.

Table A.1
Land use change across the LYB during the past 30 years.

	Shanghai metropolitan area (Yin et al., 2011)				
Year	1979	1990	2000	2009	Change rate (1979–2009)
Farmland (km^2)	5429	4984	4469	2894	−0.47
Built on land (km^2)	254.9	832.5	1529.4	2968.0	10.64
	Taihu catchment (Ning et al., 2010)				
Year	1980	1995	2000	2005	Change rate (1980–2005)
Farmland (km^2)	23,614	22,303	21,816	20,043	−0.15
Built on land (km^2)	3498	4707	5150	6543	0.87
	Chaohu catchment (Li et al., 2009)				
Year	1979	1995	2005	2008	Change rate (1979–2009)
Farmland (km^2)	9242	9272	9078	8971	−0.03
Built on land (km^2)	945	1101	1258	1375	0.45

Table A.2
Land use change during the recent 30 years at county level in the LYB.

	Chongming county (Zhu et al., 2007)			
Year	1988	1997	2005	Change rate (1988–2005)
Farmland (km^2)	249.1	284.8	292.7	0.17
Built on land (km^2)	15.7	27.0	46.7	1.98
	Wujiang county (Zhu et al., 2008)			
Year	1993	2000	2004	Change rate (1993–2004)
Farmland (km^2)	679.3	513.6	467.9	−0.31
Built on land (km^2)	221.1	294.1	350.3	0.58
	Shucheng county (Gu et al., 2009)			
Year	1952	1982	1992	Change rate (1952–1992)
Farmland (km^2)	509.3	490.3	444.0	−0.13
Built on land (km^2)	65.1	76.7	176.4	1.71

Table A.3
Proxies used for provisioning services in the LYB.

	Huangmei county	Shucheng county	Wujiang county	Chongming county	Lower Yangtze basin
Provisioning service	Grain Cotton Oilcrop Livestock Aquatic Timber	Grain Cotton Rapeseed Tea Livestock Aquatic Timber	Grain Oilcrop Fruit Livestock Aquatic	Grain Rapeseed Vegetable Melon Livestock Aquatic	Grain Cotton Oilcrop Fruit Livestock Aquatic

Table A.4
Proxies used for regulating services including terrestrial biodiversity in the LYB.

Region	Regulating services	Proxy	References
Huangmei Shucheng	Water quality	Diatom-inferred total phosphorus (DI-TP)	Dearing et al. (2012b)
	Sediment quality	Phosphorus (P) concentration	
	Sediment regulation	Mass accumulation rates	
	Soil stability	Frequency-dependent magnetic susceptibility	
	Air quality	Lead (Pb) concentration	
	Biodiversity	Pollen richness	
Wujiang	Water quality	Diatom-inferred total phosphorus (DI-TP)	Dong et al. (2008)
	Sediment quality	Phosphorus (P) concentration	Jin et al. (2010)
	Sediment regulation	Mass accumulation rates	Xue et al. (2010)
	Soil stability	Frequency-dependent magnetic susceptibility	Rose et al. (2004)
	Air quality	Lead (Pb) concentration	Jin et al. (2010)
Chongming (Yangtze tidal zone)	Water quality	Dissolved nitrogen (DIN) from Datong station	Dai et al. (2011)
	Sediment quality	Polycyclic aromatic hydrocarbons (PAHs)	Wang et al. (2011)
	Sediment regulation/soil stability	Suspended sediment discharge	Dai et al. (2011)
	Soil stability/sediment regulation	Water depth of Yangtze mouth from navigation charts	Dai et al. (2011)
	Air quality	Pb ratio	Hao et al. (2008)

Table A.5
Canonical coefficient of the first two RDA axes with population, arable land area, GDP, temperature and precipitation in the four regions from 1950 to 2002. The coefficients in bold front denote p < 0.05.

	Huangmei		Shucheng		Wujiang		Chongming	
	AX1	AX2	AX1	AX2	AX1	AX2	AX1	AX2
Population	**−0.9806**	−0.0574	**−0.9539**	0.0846	**0.8322**	**−0.4711**	**−0.6104**	**−0.6239**
Cultivated land area	**0.8943**	−0.1949	**0.8376**	0.0753	**−0.9098**	−0.1363	0.1541	**0.2925**
GDP	**−0.7224**	**0.2864**	**−0.5514**	0.06	**0.8037**	**0.2949**	**−0.6594**	**0.2917**
Temperature	**−0.4526**	**0.3023**	−0.0461	**−0.984**	**0.4985**	0.194	**−0.6679**	**0.4433**
Precipitation	−0.0818	0.2024	−0.1369	0.2019	−0.4617	**−0.3687**	−0.1145	0.2293

Table A.6
Statistically significant ($p \leq 0.01$) breakpoints for individual regulating services from sequential F statistic and Student's t-test (* represents no data covering 1900–1950 and / represents no breakpoint detected). The whole set of breakpoints ($p \leq 0.01$) suggests clusters of dates (date ±1 year in all calculations) for water quality in 1990 (Huangmei), 1979 (Shucheng), 1980 (Wujiang) and 1985 (Yangtze tidal zone). Clusters of dates for other regulating service records include: soil stability (Wujiang 1979–80), sediment quality (Huangmei 1974, Shucheng 1977), and air quality (Wujiang 1983).

Region	Proxy	1900–2006 (P < 0.01)				1950–2006 (p < 0.01)			
		F-statistics	t-Test (l = 10)	t-Test (l = 20)	t-Test (l = 30)	F-statistics	t-Test (l = 10)	t-Test (l = 20)	t-Test (l = 30)
Huangmei	Water quality	1994	1990 1996 2006	1992	1990	1994	1990	1958 1990	1990
	Sediment quality	1953	1932 1946 1953 1963 1974	1932 1948 1963 1975	1934 1953 1974	1974	1963 1974	1974	1974
	Sediment regulation	1962	1929 1944 1954 1963 1994 2006	1928 1954 1994	1928 1954 1994	1962	1963 1994 2006	1963 1994	1994
	Soil stability	1928	1916 1927	1930	1929 2002	/	/	/	/
	Air quality	1957	1937 1957 1970 1999	1937 1956 1971 1999	1937 1958 1998	1969	1959 1971 1999	1969 1999	1971 1999
	Biodiversity	1952	1953 1995 2005	1953 2005	1953 2005	/	/	/	/
Shucheng	Water quality	1978	1939 1979 2001	1938 1979 2001	1938 1979	1978	1979 2001	1979 2001	1979
	Sediment quality	1977	1910 1956 1965 1977 1987	1957 1977 2004	1958 1978	1977	1960 1977 1987	1965 1979 2005	1977 2005
	Sediment regulation	1911	1912 1936 1963 1976 1982	1915 1935 1963 2005	1935 1963 2005	/	1963 1976 1982	/	/
	Soil stability	1944	2006	1953 2006	1952 1996	/	2006	2006	2006
	Air quality	1981	1961 1980 1987 1998	1961 1980	1961 1981	1981	1962 1980 1988 2006	1980 1998	1980
	Biodiversity	1962	1926 1963 1995 2006	1925 1963 1995	1925 1963 1995	1962	1963 1995 2005	1964 1995	1970 1995
Wujiang	Water quality	1981	1974 1981 1992	1974 1991	1974 1993	1981	1980 1992	1980 1994	1980
	Sediment quality	1987	1946 1957 1979 1988 1996	1946 1980 1992	1979	1987	1958 1979 1988	1980 1992	1980
	Sediment regulation	*	*	*	*	1966	1985	1984	1984
	Soil stability	1978	1979	1979	1979	1978	1980	1979	1979
	Air quality	1983	1944 1983 1990	1944 1983 2002	1945 1983	1983	1983 1990	1983 2002	1983
Yangtze tidal zone	Water quality	*	*	*	*	1984	1983 1996	1985	1985
	Sediment quality	1993	1993 2001	1992	1992	1995	1993 2001	1993	1993
	Sediment regulation	*	*	*	*	1991	1986 2003	1985 2003	1985
	Air quality	/	1993 1999	1970 1993	1968 1993	1998	1998	1993	1993

Table A.7
Statistically significant ($p \leq 0.01$) breakpoints for regulating services aggregated by site using sequential Student's t-test with different cut-off lengths (l = 10, l = 20, l = 30). Selected breakpoint dates shown in bold. As l is increased from 10 to 30 there tends to be fewer significant break-points identified but those that are identified when l = 30 are also present in the other calculations for 1950–2006 (±1 year) and for 1900–2006 (±4 years). For 1950–2006, clusters are dated 1985 (Huangmei), 1977 (Shucheng), 1983 (Wujiang), 1985 (Yangtze tidal zone) and 1983 (LYB). For 1900–2006, clusters of significant but weaker breakpoints are dated 1928–1930 (Huangmei), 1950–1951 (Yangtze tidal zone) and 1934 (LYB).

Region	1900–2006 (p < 0.01)			1950–2006 (p < 0.01)		
	t-Test (l = 10)	t-Test (l = 20)	T-test (l = 30)	t-Test (l = 10)	t-Test (l = 20)	t-Test (l = 20)
Huangmei	1930 1945 **1986** 2000	1928 1945 **1985** 2002	1928 **1985**	**1986**	**1985** 2002	**1985**
Shucheng	1934 **1977** 1995 2006	1921 **1977** 1995	1922 **1977** 1995	**1977**	**1977** 1995	**1977** 1995
Wujiang	1922 1933 **1983** 1995 2003	1943 **1983** 1997	1943 **1983**	**1983** 1995 2003	**1983** 1998	**1983**
Yangtze tidal zone	1951 **1985** 1994 1999 2006	1950 **1985** 1998	1950 1982	**1985** 1994 1999 2006	**1985** 1998	**1985**
Lower Yangtze basin	1934 **1982** 1992 1998	1934 1969 **1985** 1998	1934 1969 1987	**1983** 1995 2003	**1983** 1998	**1983**

Table A.8
Statistically significant ($p \leq 0.01$) breakpoints for provisioning services aggregated by site using sequential Student's t-test. Breakpoint values in provisioning service series are less consistent than for regulating services (Table S7) as a result of more linear trends. The $l = 30$ calculations indicate some clustering in the periods 1968–1974 and 1990–1994. The negative breakpoint values (bold) in Wujiang for 2002 suggest a recent downturn but are very close to the end of the time-series and should be treated with caution.

Region	1950–2006 ($p < 0.01$)		
	t-Test ($l = 10$)	t-Test ($l = 20$)	t-Test ($l = 30$)
Huangmei	1963 1982 1992 2005	1971 1985 2004	1974 1992
Shucheng	1965 1979 1994 2004	1965 1983 1997	1972 1994
Wujiang	1964 1974 1984 **2002**	1965 1982 **2002**	1968
Yangtze tidal zone	1964 1971 1984 1995	1965 1978 1988 2001	1971 1990
Lower Yangtze basin	1970 1982 1992	1970 1984 1995	1973 1994

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