

## ECOLOGY

# Evolution and effects of the social-ecological system over a millennium in China's Loess Plateau

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Understanding the regime shifts of social-ecological systems (SES) and their local and spillover effects over a long time frame is important for future sustainability. We provide a perspective of processes unfolding over time to identify the regime shifts of a SES based on changes in the relationships between SES components while also addressing their drivers and local and spillover effects. The applicability of this approach has been demonstrated by analyzing the evolution over the past 1000 years of the SES in China's Loess Plateau (LP). Five evolutionary phases were identified: "fast expansion of cultivation," "slow expansion of cultivation," "landscape engineering for higher production," "transition from cultivation to ecological conservation," and "revegetation for environment." Our study establishes empirical links between the state (phase) of a SES to its drivers and effects. Lessons of single-goal driven and locally focused SES management in the LP, which did not consider these links, have important implications to long-term planning and policy formulation of SES.

## INTRODUCTION

Global sustainability challenges, such as maintaining multiple ecosystem services, are closely intertwined across space and time (1). Their solution often requires holistic approaches (1, 2), which can incorporate human and natural components simultaneously (3), reduce regional and cross-scale environmental impacts (4), and identify system-level management strategies and priorities (5). These approaches thus avoid uncoordinated and unintentional impacts on global sustainability (1).

A social-ecological system (SES) perspective provides an integrative framework that could lead to better understanding of the interactions between human and natural systems (6, 7). Regime shifts, i.e. large, abrupt, and persistent changes in system structure, function, and feedbacks, occur across a wide range of SES (8, 9). Identifying the evolutionary phases (regime shifts) of a SES and the drivers of regime shifts for a long time frame is critical to successful future system management (10). Sustainable development efforts should be directed at maintaining desirable regimes (e.g., those that underpin human well-being and maintain a well-balanced set of ecosystem services such as food and water provisioning, biodiversity, and climate regulation) and/or avoiding undesirable regimes, by managing the drivers that affect key feedback processes (10).

Identifying the regime shifts that have their foundations in intertwined social-ecological dynamics remains a scientific challenge and is an emerging frontier of SES research (10). There are an increasing number of studies analyzing the social or more ecological regime shifts. These studies use statistical methods—for example, the sequential *T* test and *F* test for the difference between two or more regimes (11)—or early warning signals, such as increasing variability, growing autocorrelation, and slower recovery rates from disturbance

(12). The SES regime shifts identified in these studies are mainly based on the change points of a single social and/or ecological component, with the interactions between them often being neglected. However, the critical dynamics of a SES crossing the system thresholds are often determined by the interaction between multiple variables (processes) (13, 14). Therefore, these methods may fail to capture some key regime shifts (15). In addition, through reciprocal processes, a SES can generate spillover effects beyond the system boundary (16). Thus, regime shifts in a SES may also affect the sustainability of distant systems (8). However, current regime shift studies focus mainly on the local effects, with spillover effects being ignored.

Here, we propose a framework for identifying the regime shifts of a SES based on the change of interactions between system components while also addressing their drivers and both local and spillover effects. We take the evolution of the SES in China's Loess Plateau (LP) over the past 1000 years as a case study to demonstrate the applicability of this framework. Because the past and present are inextricably bound to the future, it is expected that the findings of this study will assist in achieving an understanding of how SES problems emerged in the past, how they were dealt with, and their implications for future SES management.

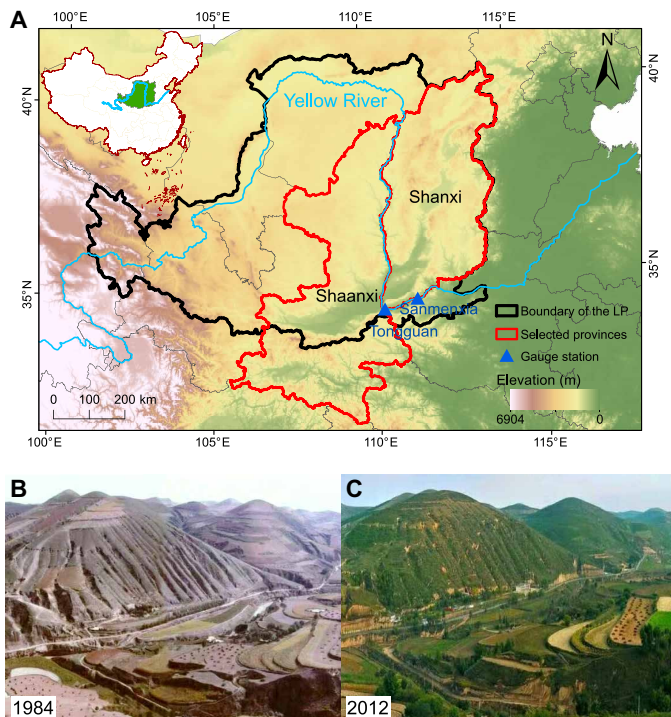
## Framework

The LP (Fig. 1A) is a well-recognized SES case suitable for understanding social-ecological interactions and their effects (17). Chinese culture originated in the LP and adjacent areas approximately 7000 years ago (17). The region was recognized for its fertile loess soil and was an early and long-lasting center of cultivation (18). The LP is located at the forest-steppe ecotone, which is suitable for both farming and grazing. The location of the farming-grazing boundary shifted southward in cold and dry periods or northward in warm and wet periods, with change of the balance of power between arable farmers and nomadic pastoralists (19). With increasing population pressure, especially in the past 1000 years, cultivation expanded rapidly throughout the loess areas and even into steeply sloping hills (18). This expansion of agriculture resulted in vegetation destruction and exacerbated the problem of soil erosion (20). These issues affected downstream areas by raising riverbed levels (21) and causing delta expansion (22) in the lower Yellow River (YR). The LP used to be the YR's largest source of sediment, providing nearly 90% of

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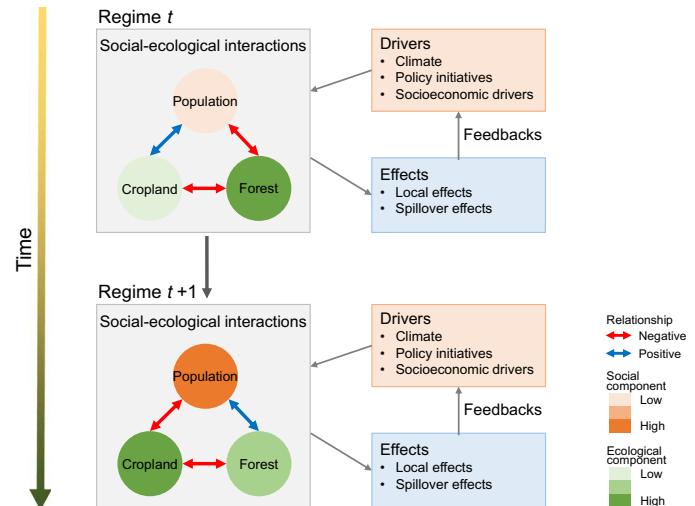
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**Fig. 1. Study area.** (A) Location of the LP and selected provinces. (B and C) Landscape on the LP before and after the GTGP, respectively. Photo credit: Y. Liang and Z. Wu, Office of the GTGP of Yan'an City.

the sediment load (23). For many years, severe erosion, sparse vegetation, high population, low agricultural productivity in the LP, and high sediment load in the YR were notorious (17). Since the 1960s, the Chinese government has implemented various strategies to address these challenges, with the Grain to Green Program (GTGP) from 1999 being one of the best known (Fig. 1, B and C) (24). Under the GTGP and numerous landscape engineering works such as terracing, check dams, and reservoir construction, the sediment load of the YR decreased (23) and the vegetation coverage of the LP nearly doubled (21). However, large-scale vegetation restoration led to soil desiccation and other adjoint problems in some areas of the LP (25); the downstream ecosystems of the YR and its delta were affected by substantial reductions in runoff and sediment load in the lower YR and an accompanying change in the water-sediment dynamics (22).

A framework for understanding the evolution of the SES in the LP was developed (Fig. 2). The relationships between SES components were used to represent the interactions between system components and their transition. We assumed that, in a stable evolutionary phase or regime of a SES, the interactions between the system components remain unchanged. Thus, the transition of any relationship from positive to negative, or vice versa, represents a SES move from one evolutionary phase to another. Drivers from human activities and climate change determine the social-ecological interactions and then generate both local effects and spillover effects in distant systems. By detecting the abrupt changes in the relationships between the system components based on piecewise linear regression (PLR; see Methods), we divided each relationship into several periods. By identifying the periods during which all the relationships remain unchanged, the evolutionary phases of the SES can be determined and the evolution of SES can be analyzed.



**Fig. 2. A framework for understanding the evolution of the SES in the LP.** Double-sided arrows represent the interactions between system components. The transition of any relationship from positive to negative, or vice versa, represents a SES move from one evolutionary phase to another.

Population and the accompanying food demand have been the core issue facing society in the LP throughout its long history. Population was therefore selected as the indicator for the social subsystem component. Forest coverage was selected as an indicator for the ecological subsystem component, because not only it can influence the local environment through the carbon cycle, regional hydrology (26), and soil erosion (27) but also, compared to other vegetation types, long-term historical data exist. Cropland area, as a link between social and ecological subsystems through land use, was also selected as an indicator for the ecological subsystem component, which plays an enormous role in food security. The competition for land use between forest and crop growth has existed for thousands of years (17). The interactions of these three indicators represent the relationship between the development of society (population growth) and its demand for both food supply and a sustainable environment.

To reflect the complexity of SES, we selected as many as possible the political, climatic, and socioeconomic drivers that might affect social-ecological interactions. Climate drivers include temperature anomalies (28), a proxy precipitation index for historical periods (29), recorded precipitation after 1949, and extreme drought and flood events (30). Socioeconomic drivers include the level of agricultural technology and management (reflected by grain production per hectare) (31), war frequency (32), and shift of the farming-grazing boundary on the LP (33). Policy initiatives such as policy priorities and reform of tax policy (34) were also qualitatively analyzed on the basis of the published literature.

To analyze the effects generated by social-ecological interactions in different regimes, we selected several indicators reflecting the local and spillover effects. Grain production in the LP was chosen to reflect the local food security. Considering that the LP is the largest sediment source and an important water source for the YR (17), the sediment load and natural runoff of the YR were selected to reflect both the conditions of soil erosion and water yield in the LP and their effects on downstream systems. Because sediment in the YR affects the downstream riverbed (21) and the YR delta (22), YR delta

area changes, and natural breaches of the lower YR were specified as the spillover effects of the LP on the downstream system.

We chose the past 1000 years as our study period. During this period, the LP experienced rapid population growth and cultivation expansion (18), environmental deterioration, and restoration (17). Although the LP covers seven provinces of China, our study area was focused on the Shaanxi and Shanxi provinces (Fig. 1A), primarily because these provinces cover most parts of the loess region in the LP (17). Because of the long study period, the datasets we used are combinations of historical records, reconstructed data for historical periods, and observational and statistical data after 1949 (see Methods and tables S1 and S2).

## RESULTS

### Evolutionary phases identified by the interactions between system components

On the basis of the changes of interactions between the system components (Figs. 3 and 4 and sections S1 and S2), five evolutionary phases of the SES in the LP were identified during the past 1000 years: I (1100 to 1750s), II (1750s to 1950s), III (1950s to 1970s), IV (1980s to 1990s), and V (2000s to the present; Fig. 3D).

The first phase (1100 to the 1750s) can be identified as “fast expansion of cultivation.” In this phase, population was positively correlated with cropland area but negatively correlated with forest coverage, while cropland area was negatively correlated with forest coverage. The population increased from 6 million in 1100 to 16 million in the 1750s, while cropland area increased from  $2.33 \times 10^6$  ha to  $8.57 \times 10^6$  ha and forest coverage decreased from 33 to 18%.

The second phase (the 1750s to the 1950s) can be characterized as “slow expansion of cultivation.” The relationship between population and cropland area became nonsignificant, and the negative regression slope between cropland area and forest increased. The population increased to 28 million in the 1850s but dropped to 19 million in the 1880s and then gradually increased to 27 million in the 1950s, while cropland area fluctuated around  $8.5 \times 10^6$  ha and forest coverage decreased from 18 to 9%.

The third phase from the 1950s to the 1970s can be described as “landscape engineering for higher production.” The relationship between population and cropland area became negative and that between population and forest coverage became positive. Numerous terraces and check dams were constructed in this phase to control soil erosion and improve production. The cropland area increased to about  $9 \times 10^6$  ha in the late 1950s and decreased to about  $8 \times 10^6$  ha in the 1970s, while population increased steadily to 53 million and forest coverage increased to 15%.

The phase from the 1980s to the 1990s can be identified as “transition from cultivation to ecological conservation.” The negative regression slope between population and cropland area decreased in this phase. The population increased steadily to 68 million, while cropland area decreased to about  $7 \times 10^6$  ha and forest coverage increased to about 20%.

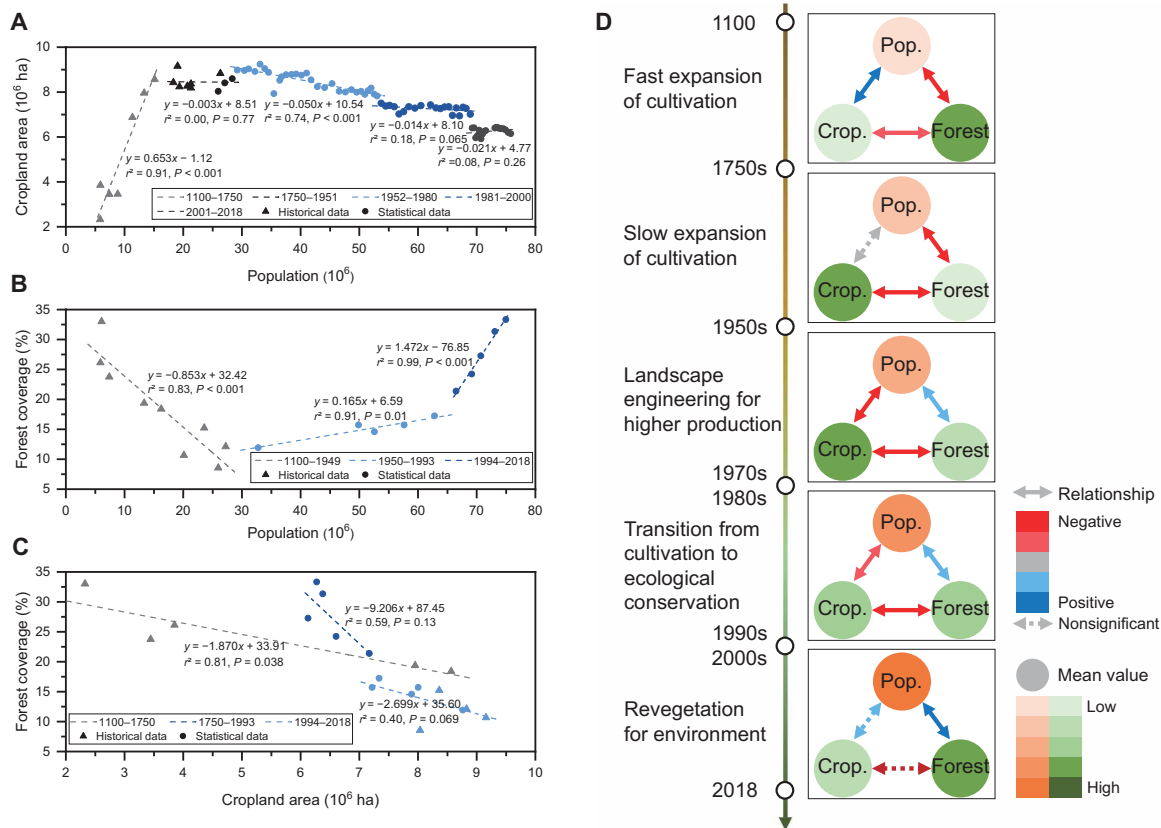
The final phase can be characterized as “revegetation for environment.” The relationship between population and cropland area and that between cropland and forest coverage became irrelevant, while the positive regression slope between population and forest coverage increased. The population increased to 76 million, while cropland decreased to about  $6 \times 10^6$  ha and forest coverage increased to 33%.

### Drivers of changes in social-ecological interactions

The changes in the chosen political, climatic, and socioeconomic drivers during the study period are shown in Fig. 5 and section S3. We found that there existed significant changes in some drivers during shifts of the evolutionary phases of SES in LP identified by our approach.

In ancient China (phases I and II), increasing food demand was mainly achieved by increasing cropland area (34). The government encouraged cultivation for the increasing population, and large areas of forest were cleared (35). Owners of newly developed or reclaimed croplands were allowed to postpone the paying of land taxes, and officials responsible for regional reclamation were rewarded (34). In the early 18th century, the emperor Kangxi of the Qing dynasty decided to permanently freeze the corvée tax quotas for each local government, and no extra corvée taxes were collected because of population increase. This reform of tax policies greatly stimulated both the population and cultivation during the whole period of the Qing dynasty (34). Crops from the Americas with high productivity such as maize, potato, and sweet potato were introduced and popularized by the government of the Qing dynasty in the 18th century (19, 34). The improvement in agricultural productivity (Fig. 5D) caused by these high-yield crops and improvements in irrigation systems (34) made it possible to feed the increased population with a relatively stable cropland area. This improvement resulted in the slow expansion of cultivation and a nonsignificant relationship between population and cropland area in phase II. These new exotic crops are also resistant to drought and cold and can be grown on land of poor quality—land that was not suitable for traditional crops (36). Thus, although the climate was cold in phase II (Fig. 5A), the farming-grazing boundary on the LP shifted northward rather than southward, and more grazing lands were converted into croplands (19, 36). Meanwhile, large numbers of immigrants swarmed into mountain regions and cut down forests for cultivation on steep slopes (19, 37), which explains the increased negative slope between cropland area and forest coverage in phase II. As a traditional agrarian society, population in the LP in the first two phases was sustained by agricultural production that was contingent upon climate and weather conditions (38). Reduction of thermal energy input in cold climate periods or extreme drought and flood events could impede agricultural production (32, 39), which brought price inflation and social conflicts. These, in turn, led to war and population decline (40). Thus, war outbreaks and population decline mostly followed a decline in temperature or more extreme drought and flood events (Fig. 5). Population decline caused the abandonment of some croplands (34), which explains the decrease of cropland area in the cold late 19th century (Figs. 4 and 5A).

Food security was still the priority in the third phase from the 1950s to the 1970s (41). In the 1950s, the Chinese government implemented a policy known as Take Grain as the Key Link (16). The sharp rise in population led to a large increase of farming on sloping land and a continuous reduction of forest and grassland during the 1950 to 1960s (20). To efficiently reduce slope and gully soil erosion and to improve cultivation, numerous soil erosion control measures including terracing, afforestation, and conservation tillage practices were implemented beginning in the 1960s (20). The Chinese government encouraged check dam construction in the LP from the 1950s to the mid-1970s, because it is the most effective way to control soil erosion on the LP (17) and offered the additional advantage of developing large, flat areas behind the dams, the productivity of which is



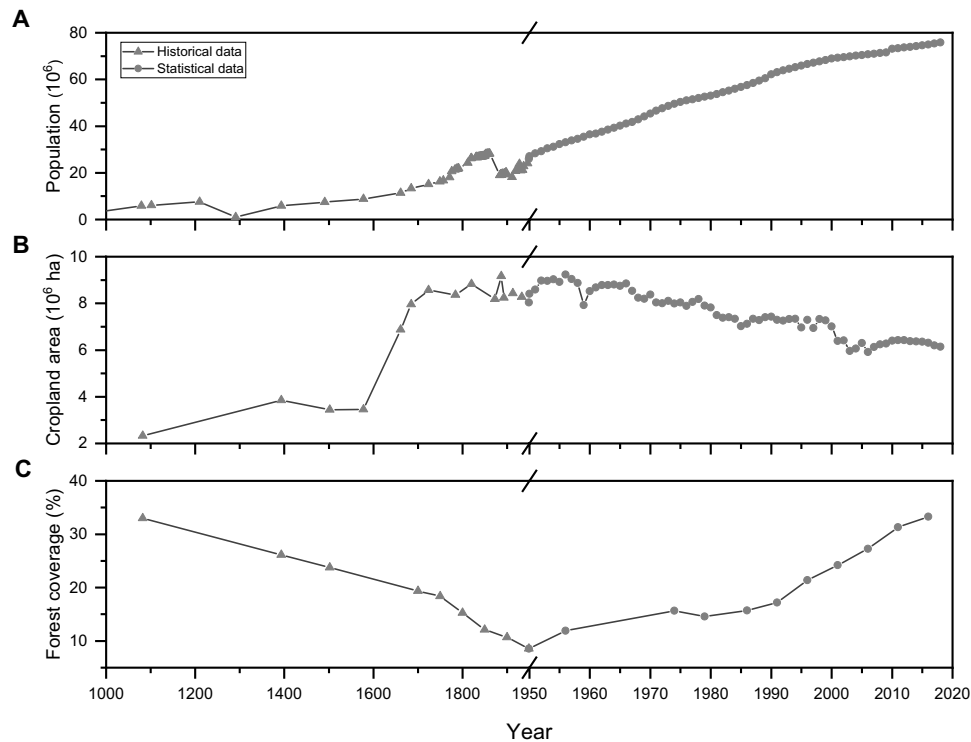
**Fig. 3. Changes of interactions between system components and the evolutionary phases of the SES in the LP.** (A) Relationship between population and cropland area. (B) Relationship between population and forest coverage. (C) Relationship between cropland area and forest coverage. (D) Evolutionary phases of the SES in the LP.

8 to 10 times higher than that of sloping land (42). The increased agricultural productivity (Fig. 5D) caused by landscape engineering and technological advancements such as the use of chemical fertilizer led to the negative relationship identified between population and cropland area in phase III. The economy of China developed rapidly following the Reform and Opening-up policy at the end of the 1970s (43). The agriculture production mode had been shifted from expanding the croplands to improving the productivity and revenue (41). The policy “comprehensive management of small watersheds” was launched to integrate the management of hills, water, forests, and cropland, with the aim of reducing sediment and flooding, and improving agricultural production (20, 43). By the end of 1998, a total of  $4.6 \times 10^4$  km<sup>2</sup> of sloping farmland on the LP had been converted into terraces (17). The Three-North Shelterbelt Forest Program, which was implemented in 1978 and involved more than half of the LP, increased the vegetation cover in the low-coverage areas in the northwest of the LP (17, 44). Furthermore, higher agricultural productivity (Fig. 5D) was achieved through rational land-use practices such as diversified land use for more revenue and increases in chemical fertilizer use, agricultural machinery, and irrigated area (20, 41). These processes led to the negative relationship between population and cropland area and the positive relationship between population and forest coverage in phase IV. Major floods and droughts in the late 1990s triggered Chinese government actions on maintaining and restoring ecosystem services for national ecological security and sustainable development (45, 46). With the increasing awareness of the need for environmental protection, the

central government implemented the GTGP (41), which aimed to reduce natural disaster risk by restoring forest and grassland, while improving livelihood options and alleviating poverty (47). The LP was prioritized as a pilot region for the GTGP (48). By the end of 2014, 37.38 billion yuan (in 2015, 6.28 yuan = US\$1) had been invested in the Shanxi and Shaanxi provinces, and the total forested area in the two provinces was  $39.37 \times 10^3$  km<sup>2</sup>, of which about 30% was converted from cropland (48). Consequently, forest coverage in the LP increased (48), explaining the enhanced positive relationship between population and forest coverage in phase V. Because the conversion of cropland to forest and afforestation of barren land occurred simultaneously, the relationship between cropland and forest coverage became nonsignificant in phase V. The GTGP also released rural labor from crop production and promoted the shift to non-farm activities (49), while economic development, industrialization, and urbanization have also played important parts in improving farm-household income and reducing the pressure on land to provide livelihoods (45, 50).

### Effects of social-ecological interactions in different phases

The effects generated by social-ecological interactions varied over time (Fig. 6 and section S3). By identifying different evolutionary phases, better understanding of how SES problems emerged and how they were dealt with can be achieved. In phase I, phase II, and the early part of phase III, the government only pursued the solution of local food demand while sidelining the importance of environment. Expansion of cultivation and forest clearance resulted in environmental



**Fig. 4. Changes of the system component indicators over the past 1000 years. (A)** Population. **(B)** Cropland area. **(C)** Forest coverage.

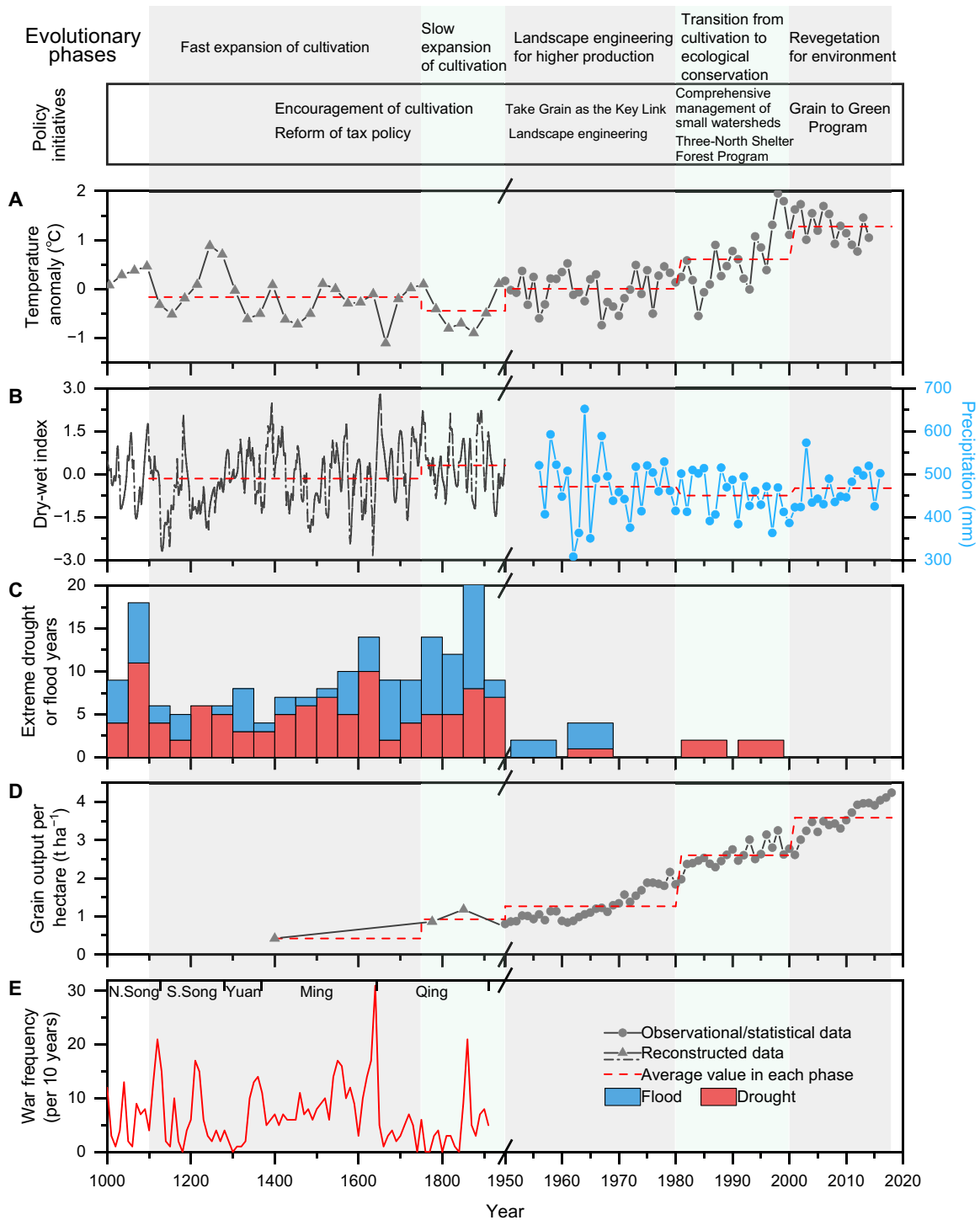
degradation and severe soil erosion (18). The latter led to increased sediment load in the YR (33, 35) and, subsequently, more frequent levee breaches in the lower YR (19) and faster extension of the YR delta (33) (Fig. 6). In these phases, the LP had been trapped in a vicious circle: Overcultivation and excess deforestation caused impaired soil fertility, and the subsequent decline in grain yield further intensified the need for more cultivation and deforestation (17). In phases III and IV, landscape engineering, including terracing, check dams, and reservoir construction, significantly contributed to the decreasing sediment load of the YR and the following slower extension of the YR delta (Fig. 6, B and D) (23). The Three-North Shelterbelt Forest Program in phase IV also helped control soil erosion in the LP. Unfortunately, the program did not properly consider the importance of species diversity and landscape pattern, and the trees used too much soil water (25). In phase V, the priority has moved from food security to environmental protection. Large-scale vegetation restoration reduced soil erosion in the LP and the sediment load of the YR (Fig. 6B) (23). However, the accompanying change of water-sediment dynamics generated cross-scale effects, which resulted in a shift of the YR delta to an erosional phase (Fig. 6D) (51), potentially affecting more than 2 million people and biodiversity in distant but coupled environments (52). The increased evapotranspiration caused by large-scale revegetation caused soil desiccation (25) and affected water availability (53). In some areas, mismanagement of the planted vegetation, including the introduction of exotic plant species and high-density planting, has led to the formation of dry soil layer (21), which may be a serious obstacle to sustainable land use (25). The average natural runoff in the lower YR in phase V decreased compared with that in phase IV, although the average precipitation in this phase is higher than that in phase IV (Figs. 5B and 6C). Without considering the conflicting demands for water be-

tween the ecosystem and humans, local revegetation is approaching sustainable water resource limits (53). Although the grain production in the whole LP still increased in phase V (Fig. 6A), grain productions in some counties decreased because of the conversion of cropland to forest and grassland (48). Further expansion of the GTGP may threaten local food supply (21). In addition, as cropland area declined (Fig. 4B), local people commonly increased agrochemical inputs to maintain and enhance land productivity for food security (54). Consequently, diffuse pollution from agriculture has increased, which has affected the quality of local land, groundwater, surface water, and agricultural product quality (54).

## DISCUSSION

The success or failure of many environmental policies and management practices depends on their ability to address the complex temporal and spatial relationships of SES (55). Our study provides a temporal lens for understanding the dynamics of SES.

Unlike current approaches for identifying the regime shifts of a SES based on the change points in a time series of social and/or ecological variables (10), we examined the regime shifts from the perspectives of interactive processes between SES components, and we identified five evolutionary phases (regimes) as fast expansion of cultivation, slow expansion of cultivation, landscape engineering for higher production, transition from cultivation to ecological conservation, and revegetation for environment in the LP in the past 1000 years. These identified evolutionary phases were highly aligned with historical reality—there existed significant changes in some drivers and local and spillover effects during shifts of the evolutionary phases. Our findings, although from an empirical study, is important to call for more theoretical investigation in the future.

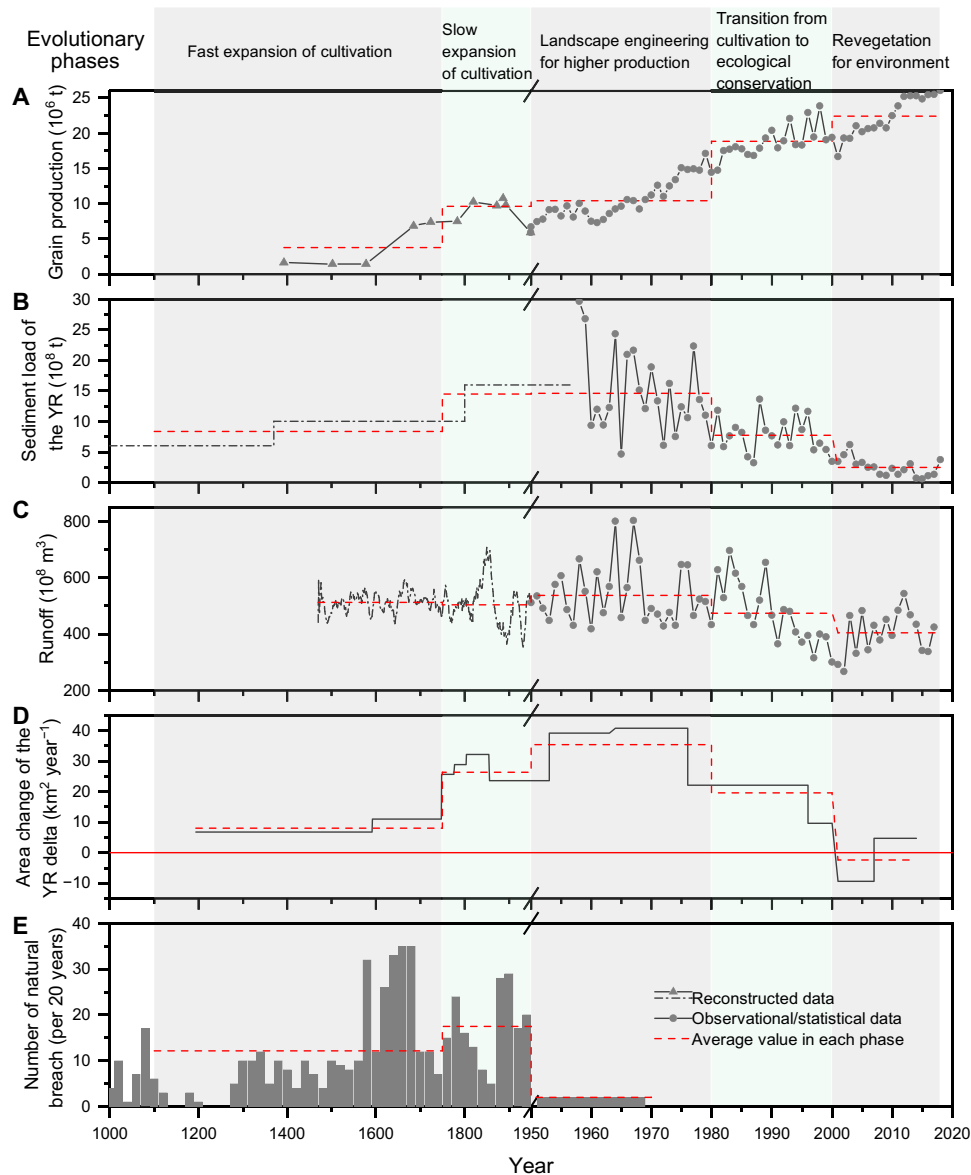


**Fig. 5. Drivers of changes in social-ecological interactions in the LP.** (A) Temperature anomaly. (B) Proxy precipitation index and precipitation. (C) Extreme drought or flood years in north China. (D) Grain production per hectare. (E) War frequency in north China.

In addition, as our framework links the states (phases) of the SES to their drivers and effects, it could provide an explicit roadmap for future SES management by identifying which state (phase) we would like our SES to be in and which drivers (policies and technology/engineering) should be used for reaching that state. Our approach may shed light on other large SES management regions with long

development histories and cross-scale effects, e.g., the Amazon, the Congo, and the Mekong River basins (56).

The implications of our findings on the evolution and effects of the SES in the LP are significant. One of them is the lessons from single-goal driven and locally focused SES management in the LP. The SES practices focused on food security in the first three phases,



**Fig. 6. Effects of social-ecological interactions in different evolutionary phases of the SES in the LP. (A)** Grain production in the LP. **(B)** Sediment load of the YR. **(C)** Natural runoff in the YR. **(D)** Change in area of the YR delta. **(E)** Number of natural breaches in the lower YR.

resulting in local environment degradation and generating negative spillover effects in distant coupled systems. The soil erosion control measures and revegetation in the LP reduced soil erosion and sediment load in the YR but contributed to the shift of the YR delta into an erosion state (51). Furthermore, mismanagement of the planted vegetation in some areas caused formation of a dry soil layer (25), which had negative influences on both water availability and food production. Therefore, SES management needs an integrated and systemic perspective, which progresses from pursuing a single goal to considering social-ecological interaction (55) and from focusing on local effects to considering cross-scale effects. With such a perspective, some undesired regimes can be avoided, e.g., the vicious circle of overcultivation and degradation in phases I, II, and III in the LP. But the question on how we should manage these social-ecological interactions remains; it needs further study, acknowledg-

ing the drivers of climate change and increasing human activities in the Anthropocene (8, 23).

It should be noted that the use of multiple data sources, in particular, use of less data and reconstruction data in the historical periods, could lead to less accurate conclusions. These different data sources with their different degrees of reliability have been highlighted during the analysis (section S4 and table S1). It should also be noted that the system components of the SES could be more complex and the relationships between system components may be nonlinear (1). Looking ahead, the mechanisms of social-ecological interaction change should be explored to predict future changes (10), with the ultimate objective of defining, achieving, and maintaining a desired or sustainable state of SES.

In conclusion, we proposed a framework for identifying the regime shifts of a SES based on the change of interactions between

system components and use it to analyze the evolution of the SES in the LP over the past 1000 years. By empirically linking the state (phase) of the SES in the LP to its drivers and effects, we can better understand how SES issues emerged and how they should be addressed. Lessons of single-goal driven and locally focused SES management in the LP highlight the necessity of an integrated and systemic perspective in future SES management.

## METHODS

### Data sources

The data required for describing the components of the SES in the LP and their relationships and the drivers for, and effects of, the changes in relationships based on the proposed framework (Fig. 2) are summarized in tables S1 and S2. The datasets we used are combinations of historical records and reconstructed data for historical periods, together with observational and statistical data for the period after 1949. Historical population data were obtained from the chronicles of the two study area provinces, which are official government publications and are widely used in historical studies (19, 57). Data regarding historical cropland areas were extracted from published literature that integrated data from official government publications and local chronicles authorized by the government (31, 34). The data for historical grain production were estimated on the basis of the cropland area and grain yield per unit area in the different periods. Hence, provincial grain yields per unit of cultivated area were collated for 1400, 1776, and 1851 CE (31). No data regarding grain yields were available for dates earlier than 1400 CE.

The historical forest cover in the LP has been a controversial topic. Some historical literature indicate slightly more than 50% of the plateau was forested between the Western Zhou dynasty (1066 to 771 BCE) and the Spring-Autumn period (770 to 221 BCE) (58). In contrast, some paleoenvironmental records, such as pollen, indicate that dense forests were only distributed in mountain areas of the LP during the Holocene (59). However, the pollen studies are mainly at the fossil pollen sites, and the interval of vegetation distribution change on the LP derived from pollen data is 1000 years (59), which is too coarse to be analyzed in any detail in our study. In addition, both historical literature and paleoenvironmental records agree that the forested area of the LP steadily declined as population increased during the historical period (57). Thus, we chose to use the historical records to reflect the forest coverage of the entire region. The historical forest coverage in the LP during the Song dynasty (960 to 1280 CE) and Ming dynasty (1368 to 1644 CE) was derived from the published literature (57, 58). These documents are the only sources that estimate the forest cover of the LP over the past 1000 years. In addition, forest coverage for each individual province, for the period 1700–1949, was obtained from a previously published paper (37), which estimated the forest cover based on historical documents of the Qing Dynasty, modern surveys, and statistics.

The reconstructed winter half-year temperature for eastern China, the proxy precipitation index (dry-wet index) dataset for north China, the extreme drought and flood events and war frequency in north China, and the shift of the farming-grazing boundary in the LP during the past 1000 years were garnered from previous works (28–30, 32, 33). The sediment load of the YR within different periods in the past 1000 years was obtained from published literature (35), which is the only source of the historical sediment load of the

YR and has been widely used in other studies (21). The natural runoff of the YR at Sanmenxia station was derived from a previously published paper (60). It was estimated from YR flood alarm data during the Qing dynasty and from the drought and flood distribution of China in the last 500 years and is the only source of historical runoff data for the YR. The change in area of the YR delta was collected from published papers (61, 62), which use historical information. The natural breach of the lower YR, which is derived from official and local historical records spanning more than 2000 years, was obtained from a published paper (19).

The population, cropland area, and grain production data of Shaanxi and Shanxi provinces from 1949 to 2018 were obtained from the National Bureau of Statistics of China ([www.stats.gov.cn](http://www.stats.gov.cn)). The forest coverage of the two provinces after 1949 was collated from national forest resource surveys for the following periods: 1950–1962, 1973–1976, 1977–1981, 1984–1988, 1989–1993, 1994–1998, 1999–2003, 2004–2008, 2009–2013, and 2014–2018 ([www.forestry.gov.cn](http://www.forestry.gov.cn)). We chose the sediment load at Tongguan station (Fig. 1A), where the YR flows out of the LP, to represent the sediment load of the YR. The sediment load at Tongguan station from 1950 to 2018 and the natural runoff at Sanmenxia station were obtained from the Bureau of Hydrology, the Yellow River Conservancy Commission and collated from the Yellow River Water Resources Bulletin ([www.mwr.gov.cn/sj/](http://www.mwr.gov.cn/sj/)). Annual precipitation and temperature after 1949 were obtained from the National Meteorological Administration of China (<http://data.cma.cn>). The data are used in official government publications and have been widely used in previous research (23, 37). The change in area of the YR delta and extreme drought and flood events in north China were collated from published papers (52, 62, 63).

### Identification of the evolutionary phases of a SES

First, we detected times of abrupt changes in the relationships between the system components. These turning points in the relationships during the study period were analyzed using a PLR method. PLR is a statistical method that allows switching regressions to give separate results for several segments of an independent variable (64). We used PLR to perform linear regression in two segments according to time. The boundary time between the segments is considered to be the turning point. PLR can be expressed as

$$Y = \begin{cases} a_1X + b_1, T \leq T_1 \\ a_2X + b_2, T > T_1 \end{cases}$$

where  $Y$  is the dependent variable,  $X$  is the independent variable,  $a_1$  and  $a_2$  are the slopes of the linear segments,  $b_1$  and  $b_2$  are the intercepts of the linear segments, and  $T_1$  is the turning point.  $T_1$  was selected using two criteria: (i) the time point with the least residual sum of squares of the regression lines and (ii) either  $P$  value of the two regression lines before and after the breakpoint being less than 0.05. After the identification of a turning point, the other turning points of the segment (if they exist) were determined by the same method, until no further time points met the criteria of turning point identification.

By detecting the turning point in the relationships, each relationship between system components can be divided into several periods. Then, the evolutionary phases of the SES can be determined by identifying the periods in which all the relationships remain unchanged.



## SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at <http://advances.sciencemag.org/cgi/content/full/6/41/eabc0276/DC1>

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