

Humans can rebuild severely eroded resilience: Demo with millennia-long records in China's Loess Plateau

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Abstract

There exists growing interest in integrating social and ecological sciences to elucidate human–nature interactions from the perspective of social–ecological systems (SES). The compelling logic in the past is that people inevitably harm nature as they use it; however, people have learned to use it while protecting or even improving it. Nowadays though there is a growing emphasis on transformability into a more desirable SES with deliberate human actions rather than adapting to the existing conditions, this theory has not been tested, due to the lack of large-scale and long-term records. The millennia-long records of humans to alter SES in China's Loess Plateau provide a unique means to test ecological theories and heuristic models. Here, we demonstrated human activities can erode ecological resilience or improve it to provide better ecoservices than the pristine. Relative resilience, calculated as a ratio of annual sediment discharge anomaly to the pristine rate, decreased from 0 at the pristine state to -1 in the 1950s due to deforestation and agricultural expansion, whereas increased to about 0.8 at the present by human intervention of environmental slow variables. Building resilience by attending slow variables rather than controlling disturbance should be the goal of adaptive ecosystem management in a SES.

Keywords social–ecological systems, ecological resilience, ecoservices, soil erosion, environmental slow variables

Significance Statement

Using millennia-long records of humans' alteration of social–ecological systems in China's Loess Plateau, we demonstrated human activities can erode ecological resilience or improve it to provide better ecoservices than the pristine. Combined with ecological theories and heuristic models including adaptive cycles, Panachy, resilience surrogate concept, and hypothesized interplay between resilience and slow variables, we found managing slow variables to build ecosystem resilience is an effective strategy for creating a win–win solution that can benefit both nature and people. We have provided empirical evidence that human interventions can improve both ecosystem services and human well-being. This indicates that building resilience rather than focusing all on disturbance prevention should be the goal of adaptive ecosystem management and restoration.

Introduction

One-third to one-half of the Earth's land surfaces have been transformed or dominated by human actions to provide goods and services for human well-being (1). Humans as “hyperkeystone” species often dominate social–ecological systems (SES) affecting other keystone actors and by modifying environmental factors (2). Humans can destroy or build resilience that can largely determine the trajectory and stability domain of a SES. Study of integrated human–nature systems has expanded rapidly this century (3). A holistic approach introduced by the Millennium

Ecosystem Assessment (2005) integrates ecological and social sciences for analyzing SES, which considers the dynamics of both ecological and human components interactively (4). It views ecosystems through the lens of the services to society, elucidating how these services benefit humanity and how human actions alter ecosystems. People are increasingly asking for evidence that human interventions can improve both ecosystem services and human well-being (3, 5).

As the emergence of SES, resilience has increasingly been used as an approach for understanding the dynamics of SES (6). In ecology, ecosystem resilience was first defined as the magnitude

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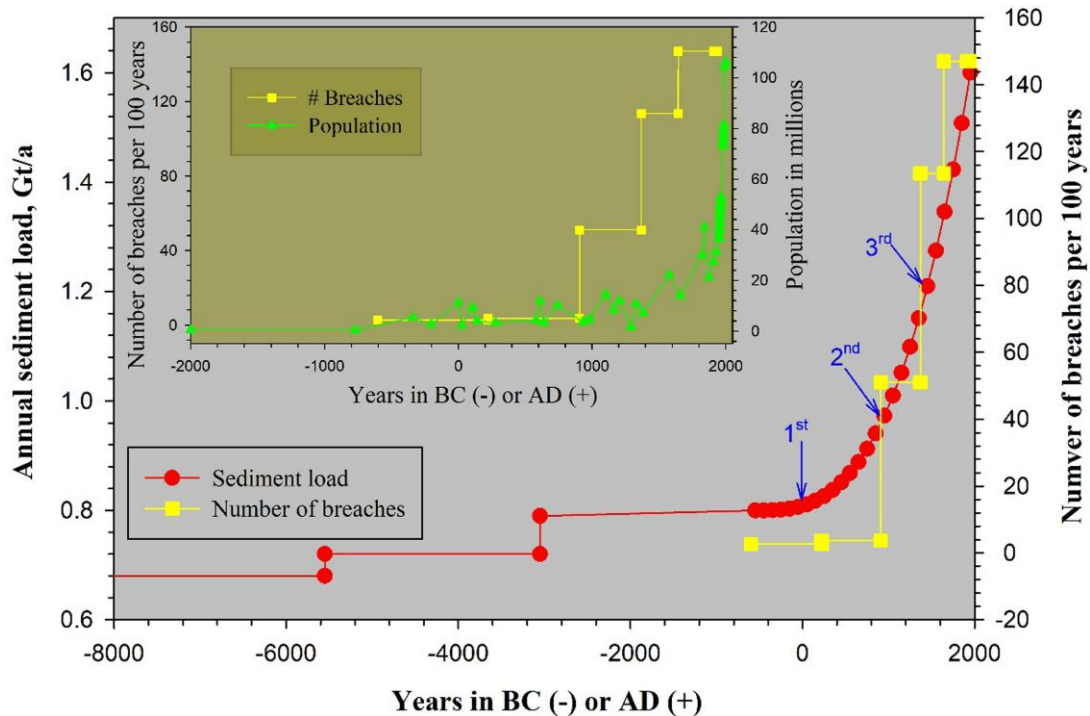


Figure 1 Estimated annual sediment load at the Huayuankou station and number of breaches in the North China Plains before 1950. The Huayuankou station is the outlet of the LP. The annual sediment discharge was estimated using fitted equation: $(512E-13) \times t^3 + 0.8$ from 2500 BP to 1950, showing in the left Y axis. Arrows indicate the three waves of deforestation and agricultural expansion (first wave: Qin and Han Dynasties around 0 AD; second wave: Tang and Song Dynasties between 907 and 1368 AD; and third wave: Ming and Qing Dynasties between 1369 and 1949 AD). Breaching frequency in number of breaches per 100 years is shown in the right Y axis. Temporal evolution of sediment discharge is influenced by slow variables such as climate and land use changes including deforestation and agricultural expansion in the LP. The relationship between population growth and YR breaches over time is also shown in the inset.

of disturbance that a system can experience before it shifts into a different state with different controls on structure and function (7). It was then extended to emphasize its dynamics for renewal and evolution (8). Resilience is not only about being persistent through disturbance but also about the opportunities opened by disturbance for renewal and emergence of new trajectories leading to alternative states (6). In a SES perspective, resilience is defined as the capacity of a SES to sustain a desired set of ecosystem services to humans in the face of disturbance and ongoing evolution and changes (9), stressing the dynamics of the complex adaptive system with interactions across spatiotemporal scales. In this work, the SES-centered definition of resilience is emphasized. The key difference between SES and ecological systems is that human actors can choose whether to foster resilience in the SES through intervention.

To facilitate the identification of a resilience surrogate or ecosystem service index (ESI) for a SES, it is necessary to specifically define resilience in terms of what to what (10). Operational ESI for a particular SES at specific spatiotemporal scales could be selected by identifying the specific disturbance regime and a social choice of the most desired ecosystem services (10, 11). ESI emphasizes ecological resilience as the underlying capacity of an ecosystem to maintain desirable ecosystem services in the face of human use and a fluctuating environment (10, 11). The key assumption of the surrogate theory is that ecosystem dynamics can be understood by analyzing only a few fast and slow variables (12, 13). Slow variables define the underlying structure or configuration of a SES, while fast variables reveal the dynamics of the underlying structure. Resilience, viewed as a dynamic property of a

SES, can be studied through changes in slow and fast variables as well as their interactions. The slow variables that underpin dynamics of the ecosystem are viewed to control the whole system in determining the topology of a stability landscape and the system's position in it (10, 14), and thus, they are regarded as the most important determinants for maintaining or building desirable ecosystem resilience and services (15).

Resilience, adaptability, and transformability are three related key attributes of a SES, which determine its developmental trajectories (14). Resilience provides adaptability for continuous development. Adaptability in a SES stresses the capacity of humans to influence and build resilience by changing the stability landscape or controlling the trajectory of the SES (14). Transformability is the capacity of humans in a SES to create a profoundly new system when ecological, social, or economic conditions render the current system untenable (14). There is an increasing emphasis on transformability into a more desirable SES rather than adaptation to the current conditions in the human-dominated SES (6, 14). This aspirational transformation goal is one of the great challenges for humanity in the decades to come (6), implying an increasing role of humans in managing resilience.

Although the metaphorical concept of resilience has inspired productive hypotheses in ecosystem analyses, an operational measurable surrogate of resilience is necessary to gain insights into system's dynamics from empirical analyses based on limited observations (10, 16). As the cradle of Chinese civilization, Loess Plateau (LP, Fig. S1) has been heavily influenced by humans. Human influence on sediment discharge and ecosystem services in LP began around 2500 BP (17, 18) and followed a similar global

pattern. The millennia-long records of nature–human interactions in China’s LP provide a unique means to test ecological theories of social–ecological resilience responses to human activities and transformability of SES using a resilience surrogate approach. Here, we demonstrate how deforestation and agricultural expansion eroded ecological resilience and how human intervention rebuilt the resilience in the human-dominated SES using the millennia-long records. Such research is imperative in providing scientific basis for developing adaptive management policies and conservation practices that can simultaneously improve both ecosystem resilience and services and for transforming degraded ecosystems into new and more desirable configurations by human intervention (8).

Results

Eroding of resilience before 1950

We estimated that annual sediment discharge increased exponentially from 0.8 Gt/a at 2500 BP to 1.6 Gt/a in the 1950s, which matched well to the number of breaches per 100 years in the lower Yellow River (YR) (Fig. 1). The increasing trends are well explained by the three waves of deforestation and agricultural expansion (17–19), which began near 0 AD for the first wave and further accelerated during 907–1950 AD as a result of the two subsequent waves due to increased population pressure and human needs. The first wave of deforestation largely occurred in the fluvial plains within LP (19), resulting in limited increases in sediment discharge. As the population increased, land clearing and reclamation gradually moved to steep slopes (19) and low mountains during the second wave (907–1368 AD), in which grazing-dominated agriculture gradually changed into cultivation-dominated systems. The natural vegetation destruction and species homogenization under cultivation greatly accelerated in the third wave (1369–1950 AD). The reconstruction of the Great Wall and military reclamation campaign in the Ming Dynasty in the northern LP as well as mass population migration to the region in the Qing Dynasty destroyed forests and grassland at large scales (19, 20). As population and food demand increased (inset in Fig. 1), steeper land was cleared for food production over time, leading to more soil erosion. Higher soil and nutrient losses led to lower crop yields and thus greater poverty, which forced farmers to reclaim more land. This vicious cycle of “more cultivation and greater poverty” created a poverty trap that caused a spiral of poverty and ecosystem degradation. Humans modified the ecosystem by clearing land and received feedback of more severe soil erosion from the ecosystem.

For LP, soil and water conservation function is selected as the key ecoservice, and human activity as the source of disturbance. Based on the theory of resilience surrogate in SES, we define an ESI as a ratio of annual sediment discharge anomaly to the pristine rate of 0.8 Gt/a, since soil and water conservation is the indispensable ecoservice demanded for LP in the face of tremendous hazards of breaching in the Lower YR (see Methods). We used the annual sediment discharge at the outlet of the Middle YR draining LP at Huayuankou (Fig. S1) to compute ESI, ranging from 0 to -1 (Fig. 2). ESI can be seen as a fast variable in the context of the SES, sensitively reflecting the levels and dynamics of the vital ecoservice as well as the health of the SES in LP. The

slowly changing variables in Fig. S2 underpin the dynamics of ESI and control the responses to and feedback from the fast variables. ESI is strongly influenced by the three major waves of natural vegetation destruction.

Each wave can be represented by an adaptive cycle beginning with the destruction phase Ω in Fig. 2 (see Methods and Fig. S5 for adaptive cycles of ecosystem resilience). The three cycles comprised the Ω phase of the higher up cycle (Fig. 3b), while each cycle may comprise of many faster cycles within each wave. Soil erosion degraded soil physical, chemical, and biological properties of soils, leading to decreased plant growth and lesser protection against soil erosion. This positive feedback of “lower productivity and greater soil erosion” continued deteriorating the soil and water conservation function in LP in the past 2,000 years, making the ecosystems increasingly less resilient and less able to provide crucial soil and water conservation services as indicated by the negative ESI reflective of the vicious cycles (Fig. 2). Clearly, the provisioning services people received were at the expense of the ecosystem’s regulating services without proper management of slow variables. Consequently, the ecosystem followed a downward trajectory of evolving from desirable to increasingly undesirable states (Fig. S3A, see Methods for the concept of ecosystem resilience). The accelerated decrease in resilience near 1000 BP was consistent with a rapid increase in sediment fluxes around the world (21), indicating that humans have altered or destroyed ecosystems with the spread of civilization and introduction of agriculture. ESI reached its minimum of -1 during 1919–1950 due to intensified agricultural exploitation and lack of any conservation measures. This was consistent with the worldwide trend that sediment discharges in rivers reached the peak during 1900–1950 (21).

We illustrate that human action can transform ecosystem into less productive or otherwise less desirable states. Humans have degraded the capacity of ecosystem to sustain societal development as indicated by the negative ESI. Regime shifts are increasingly common because of human actions that erode resilience through land use change and resource exploitation, which reduces biodiversity and resilience (8). Regime shifts from desired to less desired states often follow gradual loss of ecosystem resilience as demonstrated here. Human actions can erode resilience by directly altering slow variables such as land use, biodiversity, and soil properties. Those shifts to rigidity traps or poverty traps are difficult to reverse because of the positive feedback that stabilizes the new less desirable states. Reversing the decreasing trend of resilience can be extremely difficult and requires drastic and costly intervention. Transforming such an undesirable basin of attraction to a desirable one has been the major challenge to people in LP since 1950.

Building resilience after 1950

The crisis of the poverty traps and the spiral of ecosystem degradation that reached its peak during 1950–1985 created an opportunity to initiate transformational changes when governments and stakeholders finally realized that the current systems driven by the food security policy in LP were untenable. The four major periods in which different national policies/programs and major conservation strategies predominated could be simulated by four adaptive cycles for LP (Fig. 4). Each cycle started at the renewal phase α , so the subsequent growth phase r could be guided to a

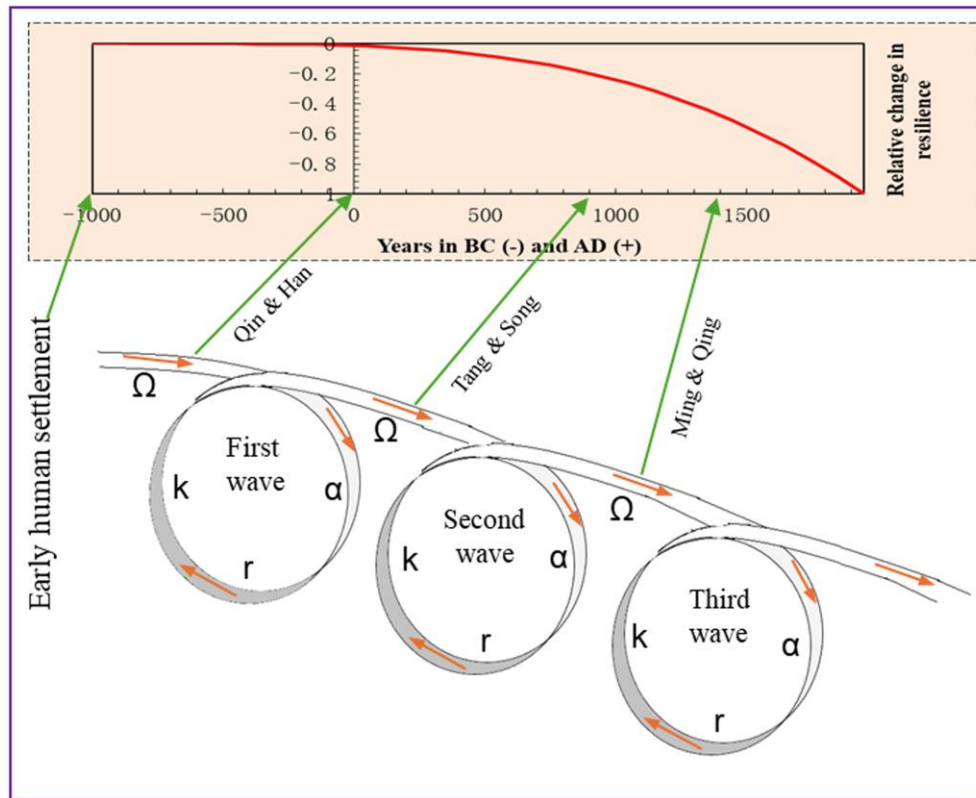


Figure 2 Relative change in resilience (ESI) before 1950. ESI is calculated as a ratio of annual sediment discharge anomaly to the pristine rate of 0.8 Gt/a [(0.8 – annual sediment discharge)/0.8] and is equal to zero at the pristine state. It is negative when sediment discharge is >0.8 Gt/a, suggesting vicious cycles in the LP ecosystem. The three deforestation waves (ie Qin & Han, Tang & Song, and Ming & Qing Dynasties) are represented by three adaptive cycles which constitute the Ω phase of Fig. 3, indicating continuous destruction of the LP ecosystem over 2,000 years. The three deforestation waves began near 0, 907, and 1369 AD as indicated by the arrows. The temporal X axis can be viewed as changes in slow variables such as deforestation and agricultural expansion.

more desirable trajectory determined by the dominant intervention measures and national conservation policies. Terrace building was the main conservation intervention during 1950–1970 of the first cycle, while check dam construction was the dominant measure during 1971–1985 of the second cycle. However, some deforestation and reclamation of marginal steep slopes continued during the first two cycles as driven by the national food self-reliance policy and population pressure (22). The gradual transition from food production to ecological conservation occurred during 1986–1999 of the third cycle, with a strong emphasis on biological intervention supported with continued efforts in building terrace and check dam. The biological emphasis further grew into a full-scale vegetation restoration campaign during 2000–2024 of the fourth cycle, with terracing and check dam building continued as support measures. After the national program of “Grain-for-Green” was launched in 1999, conversion of cropland to forestland and grassland as well as natural restoration of vegetation in the fourth cycle became the principal policy, which increased vegetation cover in the major parts of LP from 29% in 1998 to 46% in 2010 (23) (Fig. S4C–E). This program was one of the most extensive campaigns in China and was recognized as the world’s largest payment for ecosystem service initiative and ecological reconstruction (24). Overall, significant achievements on ecological restoration and poverty alleviation have been made since the 1980s when many natural resource protection laws and national conservation programs have been passed or initiated to transform the degraded ecosystems (Table S1).

Since 1950, sediment discharge to the Lower YR showed a clear stepwise decline (Fig. 3a). Using the average sediment yield of 1.6 Gt/a without any conservation as a reference, total sediment yields were reduced by 6.3, 31.3, 57.5, and 91.9% for the periods of 1949–1959, 1960–1985, 1986–1999, and 2000–2023. Based on sediment data measured at Tongguan (Fig. S1) during a more recent period of 2000–2012, estimated sediment reduction was 34% by terraces and check dams, 23% by vegetation restoration, 21% by reservoir retention and extraction, and 22% due to decrease in precipitation (25). Specifically, terrace farming areas steadily increased since 1960, with faster expansion after 1980 due to increased mechanization in terrace building. Bench terraces control erosion by reducing slope gradient, shortening slope/flow length, and increasing water infiltration and surface storage (Fig. S4F). Check dams are effective in not only reducing gully erosion by raising local base levels but also trapping eroded sediment from upland slopes (Fig. S4G). Approximately 110,000 check dams have been built since the 1950s in LP, which have retained 28 Gt of sediment (26). In addition, more than 3,000 reservoirs have been built in the YR basin and have trapped 8.6 Gt during 1960 to 2011 (27). Overall results showed human intervention over the past 70 years has lowered sediment loads during 2000–2023 to about 16% of the natural baseline level before 2500 BP, indicating that humanity based upon the scientific understanding of the ecosystems can improve the resilience of SES and enhance both provisioning and regulating services with new and more desirable configuration to meet human

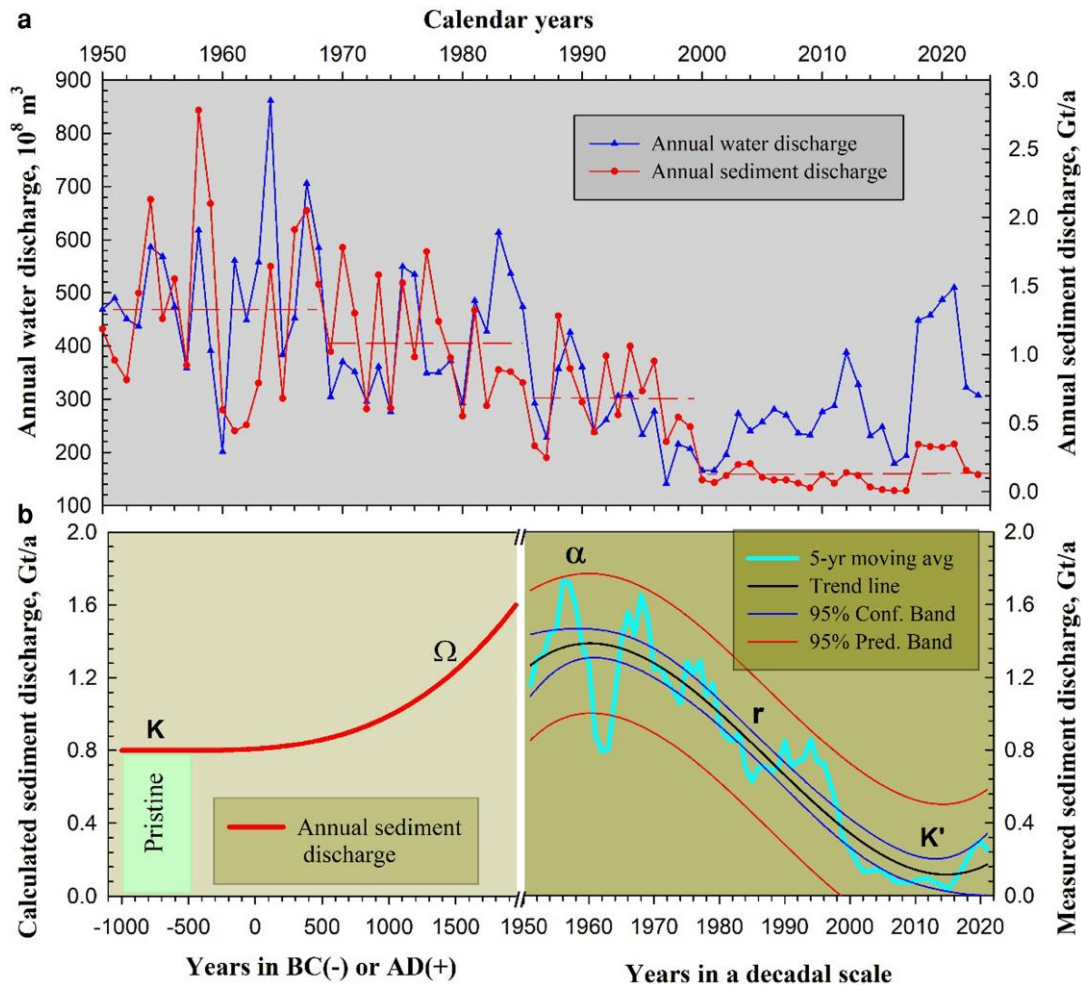


Figure 3 Measured and estimated annual water and sediment discharges. a) Annual sediment and water discharges measured at the Huayuankou station during 1950–2023. Dashed lines indicate the mean sediment discharge for each selected period. b) Estimated annual sediment discharge from 1000 BC to 1950 AD and 5-year moving average of measured annual sediment discharge during 1950–2023 at Huayuankou along with the regression trend line and the 95% confidence and prediction bands. Phases of a large adaptive cycle are indicated at a millennium scale.

and societal needs by deliberately managing slow variables such as land use and topography.

Generally, human action in seeking provisioning services often degrades regulating services, but deliberate positive action can improve both. For example, large-scale construction of bench terraces and check dams can not only enhance soil and water conservation service by reducing surface water runoff and soil erosion but also improve crop yield by increasing plant available soil water, illustrating a win–win solution between provisioning and regulating services in a human-dominated SES through alteration of slow variables. Research showed that crop yields on dam-land (terrace) were 6–10 (3) times higher than those on sloped land (26). Higher yields on the core cropland alleviated the pressure on cultivating steep land. In contrast, farming non-terraced steep land can cause spiral down cycles driven by reciprocal feedback of severe erosion.

The ecosystem states followed an upward trajectory evolving from undesirable to progressively desirable states with deliberate modification of slow variables (Fig. S3B, see Methods for the concept of ecosystem resilience). Efforts to induce more desirable shifts or prevent undesired shifts between ecosystem states should address the slow variables that affect resilience

rather than leave all focus on controlling disturbance (8). Reforestation, conversion of cropland to grassland, and construction of bench terraces and check dams are measures that manipulate slow variables (Fig. S2). Landform evolution of denuding surface relief following the maturity stage takes over millions of years under natural conditions based on the Davis's geomorphic evolution theory, but it only takes decades or much less for human intervention. The modification of these slow variables in the four periods caused three step rises in ESI, and each resilience level corresponded to the conservation phase K of each adaptive cycle (Fig. 4). It may be noted that the K phase is for the entire LP region, and each cycle is composed of many faster and smaller cycles of each ecoregion. Such changes in resilience may indicate the regime shifts as reflected by sudden drops in the time series of the fast state variable of the sediment discharge since 1950 (Fig. 3a). These shifts are in line with the three regime shifts identified from the perspectives of interactions between SES components since 1950 (22). The key ecosystem service of soil and water conservation function was greatly improved, as substantiated by the sediment discharge reduction from ~ 1.6 Gt/a during 1919–1959 to about 0.24 Gt/a during 2020–2023. Compared with the 0.8 Gt/a

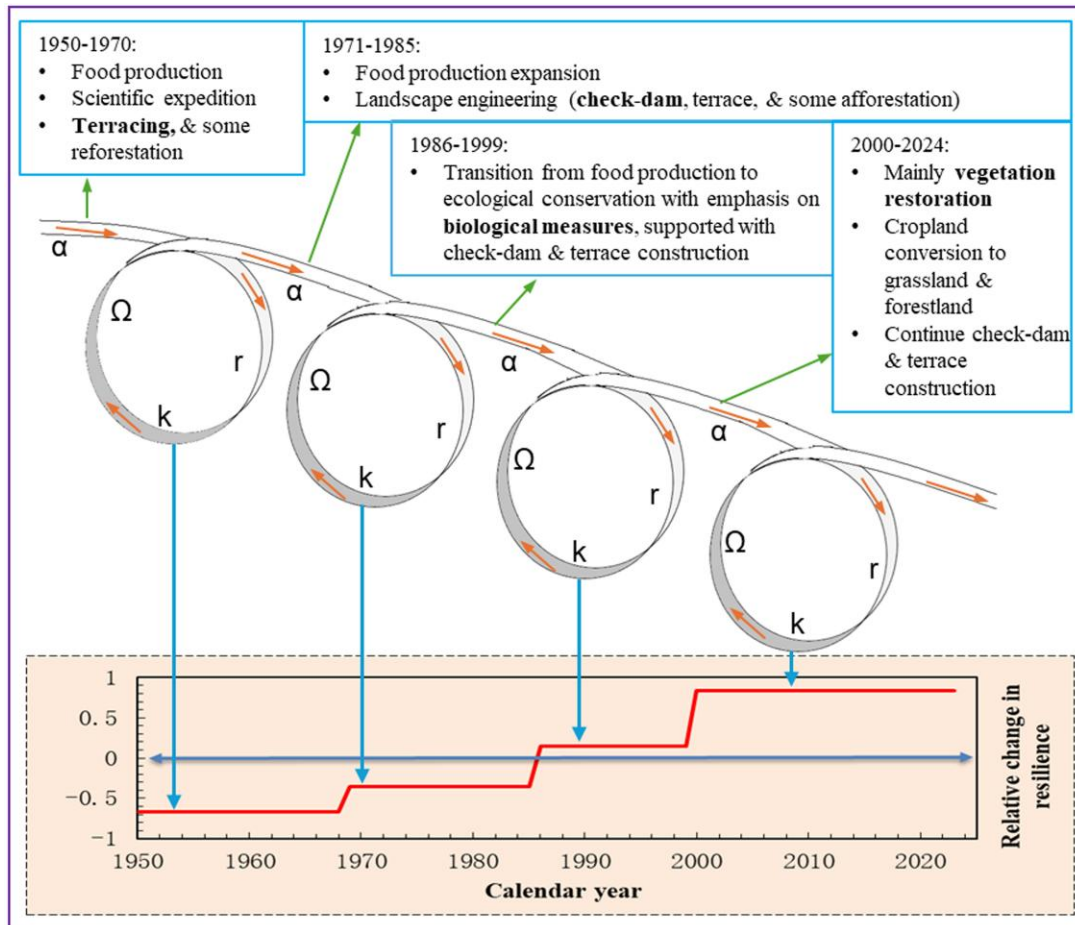


Figure 4 Relative change in resilience (ESI) after 1950. ESI is calculated as a ratio of mean sediment discharge anomaly of each period to the pristine rate of 0.8 Gt/a [(0.8 – mean annual sediment discharge)/0.8] and is equal to zero for the pristine state. It is positive when the mean sediment discharge is <0.8 Gt/a and negative otherwise. A positive value signifies virtuous cycles while a negative value indicates vicious cycles. The four adaptive cycles represented the four periods with distinct intervention policies and measures (the principal measure during each period is in bold font), showing a stepwise increase in resilience (corresponding to the step decrease in mean sediment discharge in Fig. 3a). Each step in relative resilience change can be seen as a manifestation of the K phase in each cycle that can be further broken down into many adaptive cycles at annual or interannual scales. Together, the four cycles constitute the growth phase of the larger adaptive cycle in Fig. 3b, indicating continuous improvement of the LP's ecosystem since 1950.

sediment discharge under the natural baseline (2.5 ka BP), the ecosystem has been transformed from undesirable to much more desirable states with ESI increased from -1 to 0.84 with a pivotal point at 1986 when $ESI=0$, indicating the LP's SES has transformed from a vicious cycle (negative ESI) to a virtuous cycle (positive ESI). The current existing states provide much better soil and water conservation services than the pristine state where ESI equals zero. It should be mentioned that if the soil erosion rate at the pristine state is assumed to be 0.4 Gt/a as suggested by some researchers (17, 28), the calculated ESI would be magnified due to a smaller denominator but still have similar trends and patterns to those when 0.8 Gt/a is used. Although the transition year (when $ESI=0$) would have shifted from 1986 to 2000, the main conclusions such that positive human intervention despite the cost can build resilience that can be more resilient than the pristine state remains intact.

It should be pointed out that ESI reflects not only the ecological transformation in the LP's SES but also the development of the socioeconomic landscape. A more negative value in the 1950s indicates an extremely poor, agricultural society with most of its population living in rural areas. In contrast, a more positive value after 2000 signifies a highly industrialized and urbanized society

with significantly increased wealth and improved living standards. ESI encompasses broader interactions between human activities, social-economic development, and ecological processes.

There are two paradigms in restoration ecology: nature-in-balance and nature-in-flux (29). The former assumes one equilibrium at the end point, while the latter can have multiple states and multiple pathways to reach them, as regulated by external forces such as human intervention, which can bring about the states that are more desirable than that of nature-in-balance as demonstrated in this work by modifying slow variables like landform and land use. Following decades of positive human intervention, the LP's SES, as opposed to that under pristine conditions, has been transformed into more desirable systems in which social and natural components mutually reinforce each other as indicated by positive ESI, progressively achieving ecological and economic sustainability.

Discussion

As the emergence of an SES perspective, ecological resilience has been increasingly used as an approach to understanding the

dynamics of SES (6) and interpreting observed historical records or empirical experimental data. It provides a framework to elucidate how ecosystem services benefit humanity and how human activities alter ecosystems. However, there is no single, universally agreed-upon definition. The concept of resilience is still evolving and has been interpreted in different ways across disciplines and even within ecology itself. The resilience theory has not been definitively “proven” in a simple sense, as it is difficult to apply consistently in practice. While the theory has become a credible framework for managing ecosystems and is supported by empirical evidence in various cases, more empirical experimental evidence is still needed to validate the theory on the ground of inductive reasoning. If more empirical evidence can be found to support the theory, it is more likely the theory is correct. One objective of this study is to test the resilience theory using the long-term empirical records at a large regional scale. The affirmative results contribute to better understanding of the theory.

In practice, quantifying resilience in a consistent way is a major challenge. Researchers continue to develop and refine methods for measuring resilience, but a consensus on the best metrics is still developing. As an alternative, other easily observable ecological or social variables that can act as proxies to reflect the dynamics of resilience are proposed and increasingly used in literature (10, 16). In this work, the soil and water conservation service which is inversely related to soil erosion severity is chosen as a resilience surrogate (ESI), because this service is paramount to people living in the LP region as well as in the North China Plains in the Lower YR. ESI is strongly correlated with ecological resilience in LP. Specifically, ESI was progressively more negative during ecological destruction before 1950 during which poverty traps with little resilience were developed and became predominant, while it exhibited four step increases and became more positive during ecological restoration after 1950 (Fig. 4), indicating the four major regime shifts toward the more resilient and favorable ecological configuration. We theorize that the surrogate index after empirical calibration has the potential to help land managers identify key attributes that indicate (i) the LP ecosystem’s capacity to withstand changes and (ii) the thresholds for transition to new states. In practice, this index focuses on identifying slowly changing variables and their thresholds that can act as early indications of an impending state shift in the system. For example, the four major state shifts during the ecological restoration (Fig. 4) can be calibrated to the corresponding changes of the key slow variables (eg land use change and topographic evolution) such as regional vegetation cover and extent of terrace and check dam construction, and the calibrated relationship can be used to project possible future state shifts.

Soil erosion, which serves as the basis for calculating the ESI, is an integrative variable that encompasses broader interactions between human activities and ecological processes, and thus organically reflects social, economic, and ecological processes in the LP’s SES. Although soil erosion as a critical resilience surrogate cannot fully capture the resilience of the LP’s SES, it can largely reflect the dynamics of the systems, because it is strongly influenced by almost all components of the SES including human activities, economic development, ecological processes, and climate variability. Specifically, deforestation and agricultural expansion before 1950 caused sediment discharge to double the pristine rate. However, ecological restoration through afforestation, biodiversity protection, and terrace/dam/reservoir

building after 1950 reduced sediment discharge to 16% of the pristine rate. Sediment discharge is strongly related to population growth (Fig. 1) and economic development. For agricultural economy before 1950, farmers’ main income was from agricultural production which caused severe erosion and developed poverty traps. In contrast, economic development like industrialization and urbanization provide much higher pay jobs and better living conditions in cities, which directly alleviate pressure on agriculture land and reduce erosion. Moreover, better economies can provide ample investment for ecological restoration. Generally, levels of economic development are inversely related to severity of soil erosion. Lastly, soil erosion is sensitive to climate change. More frequent and heavier storms due to climate change normally cause catastrophic flooding and erosion events. Overall, soil erosion is an integrative variable that can act as a proxy for the resilience of the LP’s SES. The use of this surrogate provides a practical method for assessing relative resilience, identifying critical thresholds for regime shifts, and informing management policies for ecological restoration.

Adaptive cycle concept provides an effective approach for interpreting and understanding the evolution of resilience in LP, as altered by human action over 2,000 years. Since the concept reflects a general pattern of changes in ecosystem resilience, it provides a useful means to organize our thoughts on dynamic changes of ecological resilience over time. Human activities damage ecosystem resilience by deforestation and agricultural expansion, which reduce biodiversity and disrupt ecosystem functions. Based on the historical records, there were three large waves of agricultural expansion due to population growth and wars. These three episodic waves of destruction on resilience would be better characterized and understood by the three adaptive cycles beginning at the release phase at centurial scales before 1950 (Fig. 2). During the restoration after 1950, human intervention primarily took place in four periods governed by different national programs/policies, priorities, and investment. The interventions substantially improved resilience through ecological restoration, enhancement of biodiversity, protection of habitats, and other activities including terrace/dam construction and migration/urbanization. These four periods were well represented by four adaptive cycles at decadal scales, which corresponded well with the four step increases in ESI (Fig. 4), indicating four regime shifts in the LP’s SES.

Panarchy is the theory of how hierarchical systems of linked adaptive cycles operate interactively across multiple scales to build resilience (Fig. S5). The ecosystem in focus is built upon cross-scale interactions with other systems both above and below it. The interconnected structure allows for both stability and innovation within ecological and social systems. In this study, a large adaptive cycle is shown on millennial scales (Fig. 3b), beginning at the pristine K phase around 3 ka BP, experiencing a sustained release phase from 0 to 1950 AD and a reorganizing phase from 1950 to 1970, and reaching a new and more resilient K’ phase at present following four major ecological restoration campaigns after 1950. Within this large adaptive cycle at millennial scales, three adaptive cycles on centurial scales before 1950 (Fig. 2) and four cycles on decadal scales after 1950 can be distinguished (Fig. 4). Furthermore, each cycle can be further broken down into many smaller cycles on shorter temporal scales, meaning that all four phases may exist concurrently at different local levels. For example, a local release phase may

exist in a small watershed or area due to local destruction of floods or fire. These hierarchical interconnected adaptive cycles not only build and foster resilience in the region but also afford opportunities for the emergence of novelty or renewal. This highlights the dangers of over-managing systems to prevent any local release phase, which can lead to rigidity traps where a system becomes vulnerable to a total disastrous collapse.

A key takeaway from this work is that humans, based on ecological principles and scientific understanding, can build a more resilient SES that benefits both nature and people. This conclusion is pertinent to a particular ecosystem of interest operating at a specific spatiotemporal scale which is cross-linked to other systems both above and below it, allowing the movement of resilience across all scales. In this study, resilience on the national scale may have been transferred to LP in the form of economic investment. The compelling logic in the past is that people inevitably harm nature when using it for economic development; however, people have learned to use it while protecting or even improving it. In fact, an increase in resilience on one scale by human intervention does not necessarily mean a decrease in resilience on another scale. For instance, the ecological restoration in LP greatly enhanced soil and water conservation services, which reduced water supply to the Lower YR and threatened agricultural production and urban water consumption in the North China Plains. However, the national projects that transfer water from south China where water is in excess to north China mitigate not only the water shortage in the north but also the flood risk in the south, benefiting both regions. This shows that resilience movement across scales can be a win-win solution for both regions, suggesting that resilience transfer does not have to be zero-sum. Nevertheless, new challenges have arisen during the ecological restoration in LP. For example, large-scale afforestation has increased plant water consumption from deep soil layers, which has led to soil desiccation and requires prudent planning to avoid over-planting.

In summary, human activities and agricultural expansion severely eroded resilience in LP for over 2,000 years, which pushed the LP's SES over to poverty traps with little resilience. However, with the drastic human intervention particularly since the 1980s, the LP's SES has been transformed into a resilient state that is more desirable than the pristine state. According to the principles of building resilience in a SES (9), many social-ecological factors have played important roles in this successful transformation. The major factors are summarized below.

Diversity

Diversity is crucial for building and maintaining resilience. Diversity in a SES includes biodiversity, abiotic diversities including spatial heterogeneity of soils, topography, and climates, and variety of social groups (3). The vast biotic and abiotic diversities with large-scale spatial resilience in the form of ecological memory in LP (Fig. S5, see Methods) makes its ecological restoration possible after large-scale, long-lasting destruction.

Connectivity

Connectivity directly affects resilience because it facilitates recovery after perturbation. Stream and gully areas account for

30 to 60% of the total land area in LP (18). Although check dams are built in the gully bottoms to create core cropland, gully slopes are little disturbed (Fig. S4). The former can be viewed as dynamic reserves and the latter as static natural reserves. The well-connected stream systems, serving as ecological corridors and steppingstones linking various ecological habitats naturally throughout LP, have accelerated the ecological restoration.

Thick loess deposit

The average loess thickness in LP is 50–80 m. The eolian deposits, comprising primarily of silt, are porous, friable, thick, and fertile, which are suitable for cultivation and rapid soil formation. The thick loess deposits make the ecological restoration achievable after severe soil erosion over the 2,000 years. Had the soil layers been shallow like those in the Karst region of China's southwest, the bedrock would have been exposed to the surfaces (called rocky desertification) and hence the degradation would be irreversible. Moreover, the thick loess deposits make the construction of bench terraces and check dams feasible at a large scale.

Land use change and topographic modification

Slow variables (Fig. S2) such as changes in land use, soil properties, and landform are correctly identified for causing regime shifts in LP. Deforestation and agricultural expansion over the 2,000 years degraded resilience, shifting regimes to progressively undesirable states. However, since 1950, natural restoration of vegetation and extensive landform modification by constructing terraces, check dams, and reservoirs have reversed the downward spiral trajectory, providing more resilient regimes which are even more desirable than the pristine state.

Research and experimentation

China has invested heavily in research and technology to support the ecological restoration efforts. New erosion control structures and soil conservation techniques, novel methods of water management and ecosystem monitoring, and comprehensive intervention demonstration models have been developed for each ecoregion in LP based on extensive experimentation. Models for each ecoregion were designed to achieve ecological and economic sustainability. Besides, advances in cultivar breeding and fertilization/water/crop management techniques have substantially increased crop yields, alleviating the pressure on farming steep slopes.

History, culture, and governmental authority

Whether enforcement mechanisms are formal or informal, the enforcers must be seen effective and legitimate by resource users (30). China has a history of centralized authority and strong governance for over thousands of years. This historical context influences

contemporary attitudes toward government authority. China has been infused with Confucianism for >2,000 years, which emphasizes respect for authority. The top-down governmental structure in China is also efficient and effective in addressing pressing ecological crises and environmental problems (30). Additionally, significant economic growth, lifting 0.77 billion people out of poverty (31), furthers respect and support for the government.

State and collective landownership

The state keeps the ownership and delegates the long-term use right to landholders through the land tenure reform. State ownership influences how restoration is planned, implemented, and managed. It legitimizes the governments to establish and enforce regulations and policies related to land use, restoration, and mandate/incentives for adhering to sustainable practices. It provides stability and continuity for long-term restoration efforts.

Broad participation

Broad participation of landholders was central to implementing restoration programs, as most of on-ground conservation works was carried out by landholders. By providing financial incentives and alternative livelihoods, the restoration programs successfully encouraged landholders' participation. Approximately, 100% of households have participated in at least one restoration program in LP since 1980. Broad participation helped improve the programs' legitimacy, aided monitoring and enforcement, and facilitated the collective action required to restore the degraded SES at a large scale.

Economic development

China's rapid economic growth has provided the financial resources needed for expensive ecological restoration programs. The sustained substantial investments from the central government have enabled their successful implementation. Payment to farmers for land use conversion directly alleviated poverty. Restoration activities created additional jobs. Improved agroecosystems enhanced land productivity and therefore household incomes. Additionally, industrialization, urbanization, and infrastructure construction have provided off-farm employment opportunities, which lessened household reliance on farm profitability and reduced the pressure on farming marginal land.

Conclusion

The success of ecological restoration in LP verified the feasibility toward building more harmonious relationships between man and nature in a human-dominated system than under a preanthropogenic condition. It demonstrated that human could alter nature based on sciences in a way that benefits both man and nature. Managing slow variables to build ecosystem resilience should be an effective strategy for creating a win-win solution. Building resilience rather than focusing all on disturbance prevention should be the goal of adaptive ecosystem management and restoration.

We demonstrate that ecosystem resilience comes from slow variables including climate, land use, soil, and landform, and deliberate human intervention can avoid undesirable states and transform a SES into more desirable states. The LP experience supports the hypothesis that win-win solutions are achievable for benefiting both nature and people.

This work shows that ecological resilience concept built upon adaptive cycles can explain the dynamic changes in resilience in the LP's SES, providing more empirical evidence to support the concept. The work also demonstrates that the resilience surrogate theory affords a practical method for assessing resilience, identifying critical thresholds for regime shifts, and informing management policies.

Overall, the successful ecological restoration and improvement in LP represented an extraordinary achievement of human endeavors and contributed greatly to the United Nations' Sustainable Development Goals. It is a result of a well-coordinated effort that combines strong government commitment and support, substantial investments, comprehensive planning and implementation, scientific innovation, community involvement, and adaptive management practices.

Materials and methods

The concept of ecosystem resilience

The broad concept of resilience is often illustrated using a potential diagram, of stable valleys and unstable peaks called a ball-in-cup heuristic in ecology (32–34, 14) (Fig. S3). The ball represents the state of an ecological system, and the cup represents the basin of attraction or stability domain. The basin signifies the resilience that is characterized by the latitude (L), resistance (R), precariousness (P), and tipping point (T) (Fig. S3A). The larger the cup, the greater the resilience. An equilibrium state exists when the ball sits at the very bottom of the cup, and disturbances can shake the ball to a transient position or state within the cup such as the hollow ball in Fig. S3A (33). A regime shift often occurs when a shock to state variables is large enough to move the ball across a tipping point to another cup. More importantly, the shape and size of the cup can expand, contract, or disappear in response to changes in slow variables causing mostly sudden or sometimes gradual regime shifts (34, 35). That is, gradually changing external conditions may have little effect on the state of the ecosystem but nevertheless affect the resilience of multi-stable ecosystems to perturbation (36). Although recent research shows how to estimate potential functions, stability and resilience from long-term records or experiments on whole intact ecosystems (37, 38), easily measurable resilience *surrogate* would open new pathways for testable hypotheses related to system's dynamics via adaptive cycles (10).

Adaptive cycles of ecosystem resilience

The concept of adaptive cycles is a general pattern of change in ecosystem resilience. It plays a key role in organizing our ideas about resilience, as well as in understanding the dynamic aspects of a system's resilience (39). To describe the dynamics of an ecosystem, Holling proposed a heuristic model of an adaptive cycle

composed of four characteristic phases: growth (r), conservation (K), release (Ω), and reorganization (α) (Fig. S5) (40). The r and K phases, comprising a predictable fore loop such as a typical plant succession process, have been the main foci of conventional resource management. The Ω and α phases comprise an unpredictable back loop for possible innovations, which have been largely ignored due to the traditional emphasis on equilibrium. The α phase leads into a new r phase that may resemble the previous r phase or deviate significantly toward a new trajectory to an alternative state for renewal, hinging on slow variables. Furthermore, the cycles occur interactively at different spatio-temporal scales in a nested hierarchy. This interacting set of hierarchically structured scales has been coined as “Panarchy” (39). Panarchy connects adaptive cycles in a hierarchy of both temporal and spatial scales (Fig. S5). The dynamics of a SES at the focal scale cannot be fully understood without considering the cross-scale influences from the scales above and below it (41). Panarchy provides an alternative framework for understanding the changes resilience in a complex adaptive SES and for managing the issues that emerge from interplays between people and nature.

The YR and LP

We test the concept of adaptive cycles for ecosystem resilience using millennia-long records of nature–human interactions in China’s LP. We first introduce YR which flows through LP. YR originates from the Qinghai-Tibet Plateau (mostly >4,000 m asl), flows through LP (1,000–2,000 m asl) and North China Plains (NCP) (<100 m asl), and enters the Bohai Sea, with a total drop of 4,000 m (Fig. S1). YR is about 5,464 km long and drains an area of 7.5×10^5 km². It is divided into Upper, Middle, and Lower reaches at the Toudaoguan and Huayuankou stations, accounting for 51.5, 45.8, and 2.7% of the total drainage area, respectively. The Middle YR draining LP generally contributed about 90% of sediment and 45% of water flow. The Lower YR has a small drainage area because the water course, which is 9 to 15 m above the surrounding NCP due to severe aggradation (42).

YR once carried the second highest sediment loads in the world (43), discharging about 1.6 Gt/a at the Tongguan station (300 km above the Huayuankou station) during 1919–1959 (25, 44). LP lying in the Middle YR was once the most severely eroded region in the world partially due to erodible loess deposits, heavy storms in summer, and sparse vegetation. Frequent avulsions and floods have been the major threats to the lives and prosperity in the Lower YR of the highly populated NCP in the past 2,500 years. The only solution to eradicating YR hazards is to control soil erosion in LP. LP occupies an area of 3.9×10^5 km² and is covered by an average of 50–80 m eolian deposits (44). It has continental monsoon climates with average annual rainfall decreasing from 700 mm southeast to <200 mm northwest, with the corresponding zonal vegetation types from southeast to northwest being deciduous forest, forest–rangeland, rangeland, and desert–rangeland. LP is highly dissected with main geomorphic units being tablelands, flat-topped ridges, round hills, valleys, and gullies (Fig. S4A). The gully length density for most areas is between 3 and 5 km/km², with relative relief being about 100–300 m. River systems and gully networks are well developed with gullies occupying between 30 and 60% of the total area (18).

The high sediment-laden YR roamed over an area of 2.5×10^5 km² in the Lower YR (45) and created NCP, which served as flood-holding plains for the mighty river. The fertile land of NCP nurtured the Chinese civilization throughout the history; however, high sediment loads of the river brought about frequent disasters to people on NCP. There were no levees before 2.5 ka BP during which YR bifurcated into many distributaries roaming freely over the plains (17). The flood-hazards increased after YR became elevated in the last 2–2.5 ka as embankments were built to stabilize river courses (44). In the past 2.5 ka, there were 1,593 avulsions in NCP, resulting in major course switching of 26 times, 7 of which were at grand regional scales (44, 46). Disastrous floods caused tremendous losses of lives and properties. The frequency of avulsions increased considerably over time due to increased deforestation and agricultural expansion in LP as population increased (Fig. 1), with the return periods of 32, 2, 1, and <1 years for 602 BC–907 AD, 907–1368 AD, 1368–1644 AD, and 1644–1949 AD, respectively (18, 19). There were three large-scale deforestations in history, which occurred in the Qin and Han Dynasties (around 0 AD), Tang and Song Dynasties (907–1368 AD), and Ming and Qing Dynasties (1369–1949 AD) (17–19). The severity and extent of vegetation destruction increased over time as the human population grew exponentially and farming tools advanced (17–19). Due to continuous aggradation, the riverbeds of the Lower YR rose 5 to 9 cm per year during 1950–1997 (42). To prevent future avulsion, severe soil erosion in LP, the root cause for aggradation and flooding in the lower reaches, has to be controlled. Thus, soil and water conservation in LP has become the most vital ecosystem service required within the YR basin.

Sediment and flow discharges to Lower YR

Based on the total volumes of the Holocene deposits in NCP as well as in the Bohai and Yellow Seas, the total sediment yield discharged to the Lower YR during the Holocene (ca. 10 ka) was estimated to be $\sim 8 \times 10^{12}$ metric tons, which translates to an average rate of 0.8 Gt/a (45). Further using ¹⁴C chronology of the deposits in NCP, the total sediment was apportioned into four 2500-year periods, with average sediment discharge being 0.68, 0.72, 0.79, and 1.01 Gt/a for each period from the early Holocene to the present (Fig. 1). Based on the reconstruction of the alluvial fans in NCP, a slightly higher rate of 1.08 Gt/a during 6 to 3 ka BP was estimated to be delivered to the Lower YR (20, 46), because a fan depth that was thicker than later confirmed was used in the calculation (42, 45). About 0.27 to 0.4 Gt/a was estimated for the same period (28), for which a smaller area of fans was used. Approximately 0.5 Gt/a was guesstimated for the period of 10 to 2.5 ka BP by assuming that about 67% sediment was deposited in NCP based on the sediment delivery ratio of 33% estimated in the Haihe River basin during the 1950s (17). The consensus of sediment discharge to the sea during the middle Holocene was 0.1–0.2 Gt/a (47). If we use the sediment delivery ratio of 20% (48), the sediment discharge at Huayuankou would be 0.5–1 Gt/a, which well encompasses the 0.8 Gt/a derived based on a comprehensive in-depth study (45). Thus, 0.8 Gt/a during the middle Holocene was taken as a baseline in this work to represent the “pristine or preanthropogenic conditions” prior to agricultural expansion and development.

Given that sediment discharge at the outlet of the Middle YR draining LP at Huayuankou was 0.8 Gt/a before 2.5 ka BP and 1.6 Gt/a during 1919–1950 (44) as well as the average sediment discharge in the last 2,500 years was about 1.0 Gt/a (45), a power function of $Y = a \times t^b + c$ (where Y is annual sediment discharge in Gt/a, and t is number of years since 2500 BP) can be analytically derived using these three constraints with $a = 512E-13$, $b = 3$, and $c = 0.8$. Parameter b is obtained by integrating the power function from 0 to 2,500 years and setting the integral to 2,500 Gt. The model follows the trends of the frequency of the Lower YR breaching reasonably well (Fig. 1). The model predicted a sediment discharge of 0.81 Gt/a around 0 AD. Sediment discharge increased from 0.97 to 1.15 Gt/a from 907 to 1368 AD and further to 1.6 Gt/a in 1950 AD, which corresponded well to the second and third waves of deforestation in LP (17–19). Jing and Chen (20), based on the total sediment deposited both in NCP as well as under the seas during 1494–1855 AD, estimated an average sediment yield of 1.3 Gt/a, which matched well with the rate of 1.35 Gt/a predicted by the model for the same period. Since 1949 AD, the average sediment discharge measured at Huayuankou were 1.50, 1.10, 0.68, and 0.13 Gt/a for the periods of 1949–1959, 1960–1985, 1986–1999, and 2000–2023, and the corresponding stream flows were 50.25, 44.98, 27.51, and 29.07 km³/a (Fig. 3a).

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Supplementary material

Supplementary material is available at [PNAS Nexus](https://www.pnasnexus.org) online.

Competing interest

The authors declare no competing interests.

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Author contributions

Xunchang John Zhang (Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Supervision, Validation, Visualization, Writing—original draft, Writing—review & editing), Jie Chen (Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Writing—original draft, Writing—review & editing), and Guobin

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Data availability

The measured annual water and sediment discharges are available at the repository in Mendeley Data (<https://data.mendeley.com/datasets/kbhr9gmxbs/1>). The data in this study are analyzed with EXCEL.

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