# Coupling human and natural systems for sustainability: experiences from China's Loess Plateau

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**Abstract.** Addressing the sustainability challenges that humanity is facing in the Anthropocene requires the coupling of human and natural systems, rather than their separate treatment. To help understand the dynamics of a coupled human and natural system (CHANS) and support the design of policies and measures that promote sustainability, we propose a conceptual cascade framework of "Pattern-Process-Service-Sustainability", which is characterized by coupling landscape patterns and ecological processes, linking ecological processes to ecosystem services, and promoting social-ecological sustainability. The use of this framework is illustrated by a review of CHANS research experiences in China's Loess Plateau (LP), a well-known region for its historically severe soil erosion and successful ecological restoration achieved in recent decades. Ecological restoration in the LP has greatly increased its vegetation coverage and controlled its soil erosion. However, some accompanied issues like soil drying in some areas due to the introduction of exotic plant species and the mismanagement of planted vegetation, and water use conflicts between vegetation and human caused by the trade-off between carbon sequestration and water supply, have started to threaten the long-term sustainability of the LP. Based on the comprehensive understanding of CHANS dynamics, the social-ecological sustainability of the LP can be improved through enhancing water and food security, implementing basin-wide governance, maintaining ecological restoration achievements, and promoting rural livelihood transition. The research experience accumulated on the LP offers examples of the application of the "Pattern-Process-Service-Sustainability" framework. Future research using this framework should especially focus on the integrated research of multiple processes, the cascades of ecosystem structure, function, services, and human well-being, the feedback mechanisms of human and natural systems, and the data and models for sustainability.

## 1 Introduction

In the Anthropocene, accelerated landscape modification and climate change are altering the earth's surface processes, leading to a series of social and environmental issues (Steffen et al., 2007; Lewis and Maslin, 2015). Climate change, forest loss, ecosystem degradation, and the depletion of resources are global concerns, threatening the sustainability of human society (IPBES, 2019; MA, 2005). Addressing human society toward a path of sustainable development has become an urgent item

on the research agenda of the scientific community and policy makers (UN, 2015). To promote international cooperation on sustainable development, in 2000 the UN millennium declaration agreed on the eight Millennium Development Goals, and in 2015 the launch of the 2030 Agenda by the UN announced the 17 Sustainable Development Goals (SDGs). However, recent reports suggested that it may not be possible to achieve the SDGs by 2030 (UN, 2019), mainly due to the complex and intertwined nature of these pressing sustainability challenges that human beings face (Biggs et al., 2021). In recent decades, a growing consensus in academia has been reached, asserting that sustainability challenges cannot be properly addressed until humans and nature are treated as an entirety (Biggs et al., 2021; Cumming, 2014).

The coupled human and natural systems (CHANSs), which are also referred to as coupled human and earth systems, human and environment systems, and social-ecological systems, describe a complex phenomenon in which human processes and natural processes interact and co-evolve (Wang et al., 2018b; Quintas-Soriano et al., 2021; Ostrom, 2009; Liu et al., 2009; Fu and Wei, 2018; Cumming, 2014). In CHANSs, humans alter the ecosystem patterns and processes to obtain desired ecosystem services, such as food, fresh water, and timber; natural processes can affect human systems through environmental degradation and disasters, such as soil erosion, floods, and droughts (Wang et al., 2018b; Quintas-Soriano et al., 2021; Ostrom, 2009; Liu et al., 2009; Fu and Wei, 2018; Cumming, 2014). CHANSs provide a holistic and integrated perspective to combine the human and natural dimensions and elucidate their complex feedback mechanisms (Liu et al., 2013a; Tian, 2017; Partelow, 2018), which is needed to develop innovative insights and solutions to the sustainability challenges that characterize the Anthropocene (Liu et al., 2021). As CHANSs involve multiple natural and human processes interacting at different scales, this complexity poses a challenge for researchers to understand their dynamics (Liu et al., 2007; Nelson et al., 2007; Rocha et al., 2015; Gunderson et al., 2017). However, research paradigms that explicitly guide sustainability practices based on deepened understandings of the interactions between humans and nature are still limited. To fill this knowledge gap, we propose a conceptual cascade framework of "Pattern-Process-Service-Sustainability" (Fu and Wei, 2018) to better observe, analyse, and understand the dynamics of CHANSs and promote their sustainability.

This framework provides instructive steps to study CHANSs and support sustainability practices, that is, coupling landscape patterns and ecological processes, linking ecological processes to ecosystem services, and promoting social-ecological sustainability. Pattern-process coupling provides a critical approach for integrated research and a comprehensive understanding of the mechanisms of natural processes, such as the carbon-water cycle, ecohydrological processes, and soil-vegetation-atmosphere interactions (Fu et al., 2019). Ecosystem services (ESs) are the benefits that people directly or indirectly obtain from ecosystems, and their changes will affect human well-being and sustainable development (Costanza et al., 2017). Ecological processes and functions transform into services when they can, directly and indirectly, benefit humans (Costanza et al., 2017). Unlike the research on pattern-process coupling, ES research places a greater emphasis on the social dimension or human need of ecosystems. Managing ecosystem processes to sustain the provision of ESs is the basic way to improve sustainability (Fu et al., 2013), constituting an important bridge between science and policy. For example, through land-use planning and management, the land use structure can be optimized to obtain the desired and sustainable provision of ESs. To

elucidate the complex feedback mechanism of CHANSs, it is necessary to couple patterns and processes, and link processes and services (Wang et al., 2018b), and the findings obtained could support policy-related decisions that enhance sustainability. This paper starts with a detailed introduction of the proposed framework and its components, then systematically illustrates the use of this framework to study the dynamics of CHANSs and support decision making for the promotion of sustainability through a review of research experiences in China's Loess Plateau (LP). Over the last 20 years, researchers have conducted extensive studies on the landscape patterns, ecological processes, and ESs of the LP, making it an ideal region for summarizing research experiences and providing guidance for the CHANS studies. Finally, several future directions of the "Pattern-Process-Service-Sustainability" are proposed by revealing the limitations of current studies.

## 2 The Pattern-Process-Service-Sustainability framework

The proposed "Pattern-Process-Service-Sustainability" framework (Fig. 1) provides a paradigm for researchers to study CHANSs and identify practical solutions for the adaptation to environmental change (Fu and Wei, 2018). The earth's surface landscape has been extensively shaped and modified by natural forces and human activities, which are reflected in the pattern of landscape components (Steffen et al., 2015; Steffen et al., 2007). The term "pattern" generally refers to a spatial pattern of landscape components, including their properties of size, type, number, and spatial distribution; and the term "process" indicates the dynamic features of the occurrence and evolution of incidents or phenomena (Fu et al., 2011a). Patterns and processes interact with each other, which can be expressed as "patterns influence processes, and processes change patterns" (Fu et al., 2011a; Fu et al., 2019). For example, land-use configurations can influence soil erosion processes; and hydrological processes, such as floods, can quickly alter the land-cover pattern of alluvial plains. These reciprocal effects between patterns and processes are critical to understanding the coupling mechanisms of CHANSs (Fu and Wei, 2018).

ESs are defined as the ecosystem characteristics, processes, or functions that directly or indirectly contribute to human well-being (Costanza et al., 2017). A better understanding of ESs, and especially of the links between them and ecological processes, is crucial to accurately assess and predict ES dynamics. The relationships between ecological processes and ESs are complex: multiple ESs may share the same ecological process, or multiple ecological processes may support the same ES (Bennett et al., 2009; Fu et al., 2013). In addition, ecological processes interact with each other, rather than exist independently (Fu et al., 2015). For instance, both soil conservation and water yield services are affected by rainfall events, runoff, and vegetation dynamics. Therefore, changes in ecological patterns and processes caused by both natural forces and human activities can affect multiple ESs through cascade effects, resulting in trade-offs and synergy effects between services (Fu et al., 2013). Specifically, a trade-off occurs when one service increases and another one decreases; while synergy indicates the presence of the same variation trend for both services (Bennett et al., 2009). Only when ecological processes and ESs are considered together, it is possible to comprehensively understand the driving mechanisms of ESs and to identify the critical processes that could be regulated to optimize them (Fu et al., 2013).
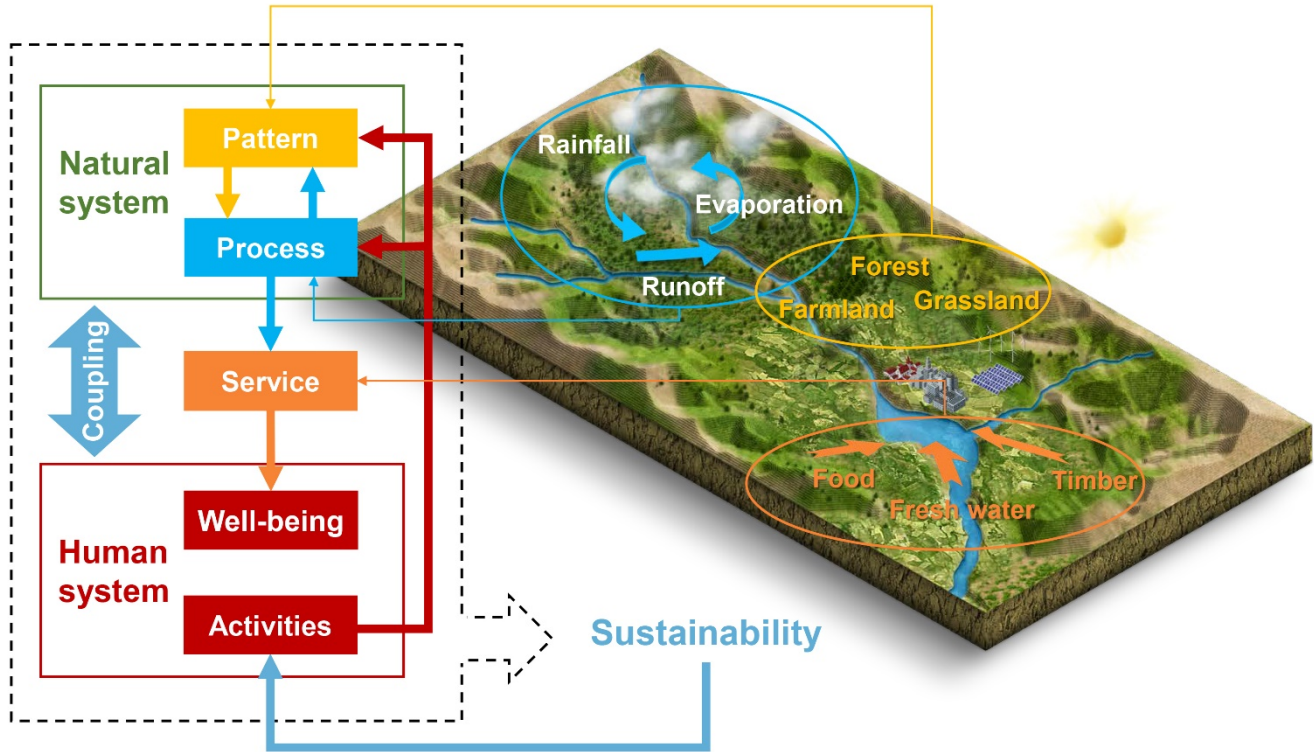
**Figure 1:Illustration of the "Pattern-Process-Service-Sustainability" framework.** Pattern, process, service, and sustainability in the coupled human and natural system (left) and diagram of typical patterns, processes (e.g., hydrological processes) and ESs (e.g., provision services) (right).

The practical implications of CHANSs studies are to promote the "Sustainability" of the coupled systems (Ostrom, 2009; Liu et al., 2013a). A deep understanding of "Pattern-Process-Service" interactions can help us figure out the causes of the unsustainable status of a CHANS and provide the scientific basis for designing policies or measures that promote its sustainability. Both environmental changes and human activities can affect the interactions between landscape patterns and ecological processes, and directly or indirectly affect the ESs upon which humans depend (Fu et al., 2019). Targeted sustainability activities such as land use optimization provide feasible and effective ways to manage landscape patterns and ecosystem processes and to mitigate trade-offs and enhance synergies among ESs, which finally bring win-win gains between human and nature and improve the sustainability of CHANSs. Thus, the above-mentioned analytical paradigm for practical management can be integrated into a cascade framework of "Pattern-Process-Service-Sustainability" (Fu and Wei, 2018). To use this paradigm for the promotion of CHANS sustainability, it is necessary to couple landscape patterns and ecological processes, link ecological processes to services, and bridge science and policy (Fu et al., 2015). In the following sections, research conducted in China's LP was used as an example to illustrate how this framework is applied to empirical studies.

## 3 China's Loess Plateau

The LP (Fig. 2), located in central China, is the largest and thickest loess deposit in the world, covering an area of 640,000 km$^2$ (Fu et al., 2017). It is characterized by a continental monsoon climate with an average annual precipitation of 400 mm (Table 1), and most of the plateau is located in a semiarid zone, based on the aridity index (Chen et al., 2007). Because the

115 loess is highly fertile and easy to cultivate (Wang et al., 2010), early Chinese agriculture and civilization developed around the LP since the Neolithic era (Barton et al., 2009; Sun et al., 2018). However, due to the anthropic impacts affecting the area for thousands of years, the LP has suffered from soil erosion, land degradation, natural disasters, and extreme poverty (Fu et al., 2017). These undesired social and ecological outcomes resulted from the mutually reinforcing feedback between natural and human processes (Wu et al., 2020).

120 **Table 1 Regional characteristics of the LP** (Fu et al., 2017; He et al., 2021)

| Natural characteristics | | Socioeconomic characteristics | |
|---|---|---|---|
| Annual mean temperature | 8-14 ℃ | Population | Increased from 42 million in 1950 to 109 million in 2019 |
| Annual mean precipitation | ~ 400 mm | Per capita GDP | 7380 USD (2019) |
| Annual mean potential evapotranspiration | > 1000 mm | Urbanization rate | ~ 56% (2019) |
| Soil type | Los orthic entisols, dark and soild-cumulic ustic isohumisols, ustic lubisols, etc. | Main crop | Wheat and maize |
| Vegetation type | From nowthwest to southeast: desert, desert-steppe, steppe, forest-steppe, and forest | Grain self-sufficiency rate | Incrased from 62% in 1950 to 108% in 2019 |
| Geomorphology | Loess Yuan, Liang, Mao, and various valleys of different erosion magnitude | Ecological restoration project | Three-North Shelterbelt Development program (1978), Soil and Water Conservation Program (1983), and Grain for Green program (1999) |

The erosion susceptibility of loess, periodic extreme rainfall events, sparse vegetation, long-term and intensive farming activities shaped the fragile ecological environment on the LP, exacerbating the sensitivity of the region to extreme climatic events and human disturbances (Fu et al., 2017). As the human population increased, more deforestation and land reclamation

125 occurred to meet the growing demand for food and firewood. Long-term human-induced vegetation degradation also exacerbated soil erosion, turning more than 70% of the once-flat plateau into a region dominated by hills and gullies (Zhao et al., 2013). In addition, the Yellow River, the second largest river in China, flows through the LP and receives nearly 90% of the sediment load from this region (Wang et al., 2016). Due to a large amount of sediment deposited in the lower reaches of the river, frequent flood and breach events have historically occurred, causing huge losses to the residents living in the alluvial

130 plain (Chen et al., 2012; Chen, 2019). Furthermore, severe soil erosion caused a decline in land productivity and grain yield, and therefore more land needed to be reclaimed to feed the growing population (Chen et al., 2007). This vicious cycle seems to have determined the "fall" of the LP into a social-ecological trap.

To break out of this negative cycle, the Chinese government has taken numerous efforts to restore vegetation and control soil erosion in the region, in order to establish a sustainable development path. Since the 1970s, numerous soil and water conservation measures have been implemented, including the construction of terracing and check-dams, integrated watershed management for soil and water conservation, and vegetation restoration (Fu et al., 2017; Yu et al., 2020). Among them, the Grain-to-Green Program (GTGP), implemented in 1999 in the LP, is the largest and most successful (Feng et al., 2016; Wu et al., 2020). Since the beginning of the 21st century, the vegetation coverage in the LP has significantly increased and soil erosion has been effectively controlled (Fu et al., 2011b). According to the MODIS NDVI data, more than 70% of the LP showed a significant "greening" trend from 2000 to 2015, mainly distributed in the central and southern parts (Fig. 2).

Despite the success of the GTGP, many uncertainties remain in relation to the effects of ecological restoration on social-ecological sustainability (Fu et al., 2017), whose achievement in the LP has become the focus for researchers and policy makers. In the last two decades, extensive studies have been conducted on the CHANS of the LP to better understand its multiple natural and human processes, and to support policy measures for ecological restoration (Feng et al., 2010; Fu et al., 2011a; Fu et al., 2017). The representative social-ecological context of the LP and the extensive studies make it an ideal region for summarizing the research experiences of CHANS. In the following section, a review of CHANS studies conducted on the LP using the "Pattern-Process-Service-Sustainability" framework is reported.
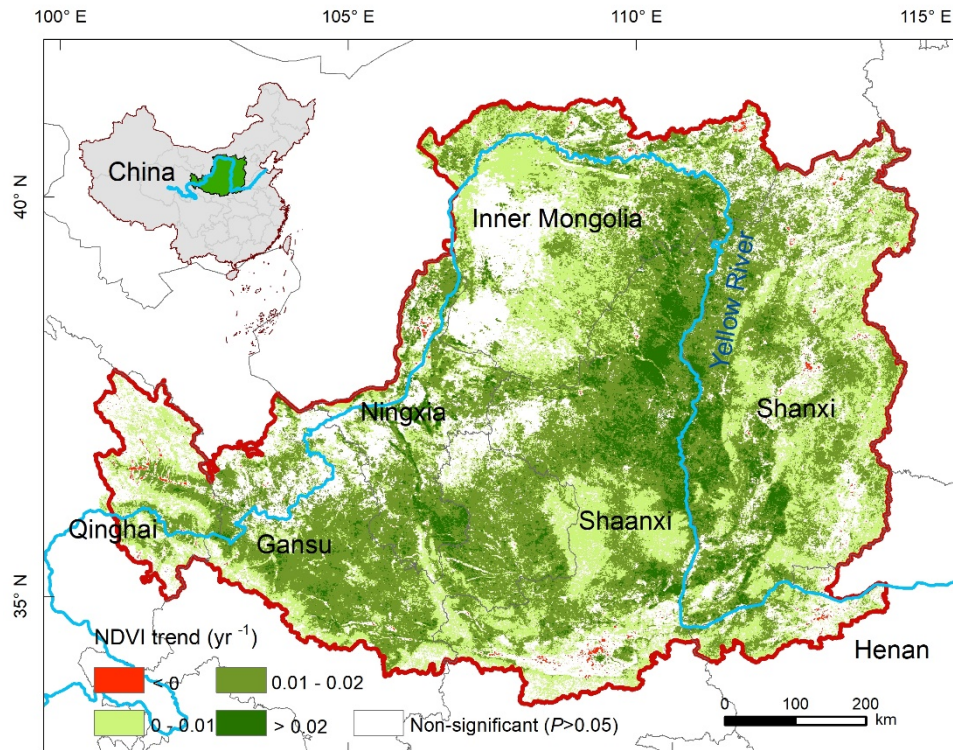
**Figure 2: Location of the Loess Plateau and its normalized-difference vegetation index (NDVI) trend from 2000 to 2015.**

## 4 Application of the framework in the LP

### 4.1 Coupling patterns and processes

Through a process of natural evolution, the atmosphere-soil-vegetation interaction reaches a dynamic equilibrium, forming a relatively stable vegetation pattern (Zhang et al., 2018). However, deforestation and afforestation can alter this equilibrium and cause a series of ecohydrological effects that influence water, carbon, soil processes, and the overall ecosystem sustainability (Feng et al., 2016; Zhang et al., 2018). The GTGP, launched in 1999, converted slope croplands into forest or grasslands, thus altering the landscape pattern in the LP (Fu et al., 2011b). Therefore, understanding the ecohydrological effects caused by vegetation restoration through the coupling of patterns and processes is of great significance to direct subsequent ecological restoration measures (Fu et al., 2011a). In order to achieve such understanding, researchers have conducted numerous studies on soil erosion processes, carbon-water processes (Feng et al., 2016), and flow-sediment relationships in the LP (Wang et al., 2016).

In the context of ecological restoration, the pressing task is to understand the soil erosion dynamics in the LP, and what land use pattern will result in the best soil and water conservation effect. Based on long-term field monitoring and control experiments (such as the building of runoff plots), studies have found that rainfall events characterized by high intensity, short duration, and high frequency had the most erosive effect (Wei et al., 2007); and the most severe annual erosion rates appeared in drought years, rather than in wet years (Wei et al., 2010); therefore more attention should be paid to rainfall variability and distribution to understand soil erosion processes in the LP. For vegetation patterns, shrubs are a superior choice to control soil erosion compared to other vegetation types (Wei et al., 2007; Zhou et al., 2016), because of their differences in canopy structure and surface litter layer (Zhou et al., 2016). Comparative experiments confirmed that soil compaction processes occurred during revegetation, which resulted in the increase of runoff and a non-significant decrease of soil erosion in runoff plots, even though vegetation increased (Liu et al., 2012). Furthermore, the combination of plant traits, such as a small mean root diameter and great root tensile strength, can exert the greatest soil erosion control effect (Zhu et al., 2015). Overall, the main drivers of soil erosion in the LP include the characteristics of precipitation (e.g., intensity and duration), vegetation patterns, soil properties, and vegetation traits, which could inspire effective practices to prevent soil erosion (Zhou et al., 2016).

Ecological restoration in the LP altered the carbon and water cycles, even creating a severe carbon-water conflict (Fig. 3). After the implementation of the GTGP, the NPP (Net Primary Productivity) and NEP (Net Ecosystem Productivity) have steadily increased, and a total of 96.1 Tg of additional carbon was sequestered from 2000 to 2008, transforming the LP from a net carbon source to a net carbon sink (Feng et al., 2013). However, the introduced vegetation will inevitably consume a large amount of water resources, causing a conflict between plant growth and water consumption. Numerous field monitoring and experiments have reported that soil moisture decline and soil desiccation occurred in the LP due to vegetation restoration (Chen et al., 2010; Liang et al., 2018; Wang et al., 2013; Yao et al., 2012). In addition, the remote sensing and model-based approach reached similar conclusions, namely that overplanting is responsible for soil drying in the LP (Zhang et al., 2018). Based on currently revegetated areas and water demand for human consumption, Feng et al. (2016) estimated a threshold of

NPP of 400 ± 5 g C m⁻² yr⁻¹ in the LP, above which the population will suffer water shortages, and the results indicated that the NPP in these revegetated areas was close to this limit. Future climate change will affect this permissible NPP threshold. Considering the maximum, median, and minimum scenarios of precipitation change and future changes in plant water-use efficiency, permissible NPP by 2050 is 578 ± 48 g C m⁻² yr⁻¹, 473 ± 41 g C m⁻² yr⁻¹, and 309 ± 29 g C m⁻² yr⁻¹, respectively (Feng et al., 2016). Moreover, Zhang et al. (2018) estimated the equilibrium vegetation cover over the LP based on an ecohydrological model and ecosystem optimality theory (i.e., minimum water stress assumption), and compared it with the actual vegetation cover obtained from remote sensing data. The results showed that the current vegetation cover (0.48 on average) has already exceeded the climate-defined equilibrium vegetation cover (0.43 on average) in many parts of the LP, especially in the middle-to-east regions (Zhang et al., 2018). In addition to excessive vegetation density, the types of introduced vegetation can also have a great impact on soil drying. Field experiments showed that soil moisture conditions were better where native species, rather than exotic species, grew. For example, pine and *Robinia pseudoacacia* plantations may not be appropriate for ecological restoration in a semi-arid loess hilly area such as the LP, due to the high-water consumption and poor water retention of these plants (Chen et al., 2010; Liang et al., 2018). Even land abandonment is a more effective method to maintain soil water than revegetation with introduced plants (Yao et al., 2012; An et al., 2017).

Runoff and sediment transport have a great impact on biogeochemical processes that determine ecosystem health in river basins (Gao et al., 2016; Gao et al., 2017). Understanding the dominant mechanism behind the variation of flow-sediment relationships is crucial to ensure sustainable water management (Gao et al., 2017). The LP used to contribute nearly 90% of the Yellow River sediment (Wang et al., 2017). However, a sharp reduction (58%) in the river sediment was detected after 1979 (Wang et al., 2017) (Fig. 3). Based on the relationship between cumulative sediment load and cumulative precipitation, this sediment reduction trend can be classified into three periods: 1951–1979 (1.35 ± 0.65 Gt y⁻¹), 1980–1999 (0.73 ± 0.28 Gt y⁻¹), and 2000–2010 (0.32 ± 0.24 Gt y⁻¹) (Wang et al., 2016). To elucidate the complex driving mechanism of sediment load change, an attribution method was developed to analyse 60 years of runoff and sediment load observations from the traverse of the Yellow River over the LP (Wang et al., 2016). The results showed that human activities are the main cause of sediment reduction in the Yellow River. Specifically, before 2000, landscape engineering, terracing, and the construction of check dams and reservoirs were the primary factors driving the sediment load reduction, accounting for 54%; while after 2000, the main contributor was vegetation restoration, accounting for 57% (Wang et al., 2016). Reduced runoff and sediment in the Yellow River can produce a series of ecological and socio-economic effects. For instance, sediment reduction can improve the water quality, but it can also lead to the shrinking of the Yellow River delta, and inadequate environmental flows may affect aquatic habitats (Wu et al., 2020).

In summary, the studies on soil erosion and water-carbon processes, and on flow-sediment changes after vegetation restoration in the LP (Feng et al., 2016; Gao et al., 2016; Wang et al., 2016; Zhou et al., 2016) are of great significance for the establishment of future vegetation restoration measures. However, there are still some limitations in current studies. First, the coupling level of multiple ecological processes is still insufficient. For example, soil erosion is simultaneously affected by multiple natural and anthropogenic factors, including precipitation, terrain, soil properties, land use and land cover types, and even vegetation

root traits (Zhou et al., 2016; Zhu et al., 2015). The current studies in the LP mainly coupled only two or three processes, such as precipitation and land use and land cover types (Zhou et al., 2016), which may increase the uncertainty of the results. Second, as the upper, middle, and lower reaches of the Yellow River are interrelated, ecological restoration carried out in the LP area located in its middle reaches will inevitably influence the areas in the lower reaches, however, a basin-wide perspective to study the ecohydrological effects caused by ecological restoration in the LP is still lacking (Wang et al., 2017).
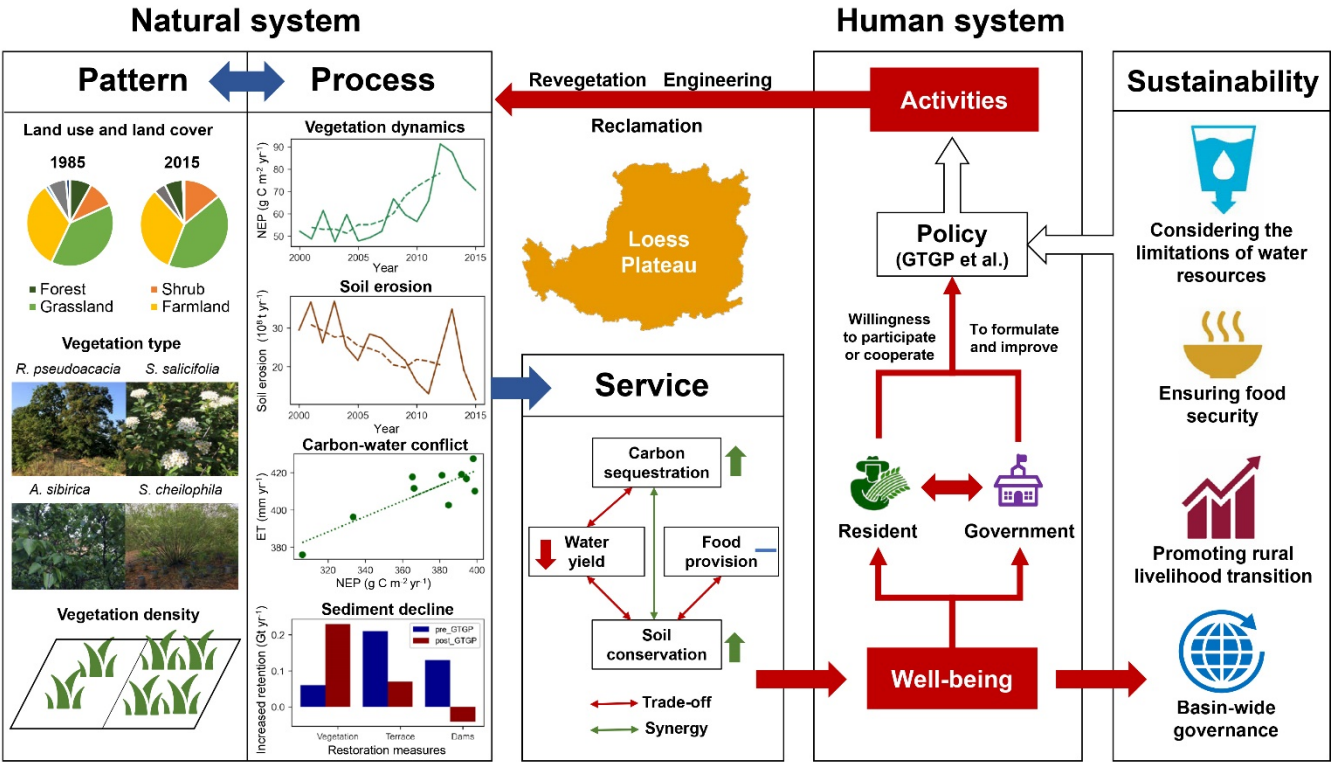
**Figure 3: Illustration of the coupled human and natural system studies of China's Loess Plateau using the "Pattern-Process-Service-Sustainability" framework.** Data used in this figure were obtained from (Wang et al., 2016; Feng et al., 2016; Liu et al., 2019; Wu et al., 2019).

### 4.2 Linking ecological processes to ESs

By coupling patterns and processes, researchers found that the ecological restoration program has altered the soil erosion and water-carbon processes and flow-sediment relationships in the LP (Feng et al., 2016; Wang et al., 2016). As ecological processes underpin the delivery of ESs, changes in these natural processes in the LP will affect ESs that local residents depend on (Fu et al., 2013). Linking ecological processes to ESs can help understand the complex relationships among ESs and support optimized ecosystem management measures (e.g., minimize trade-offs and maximize synergies) and sustainability of CHANSs (Fu et al., 2013). Regarding this aspect, a large number of studies about land use and land cover change, ES assessments, and their trade-off and synergy analysis have been conducted in the LP over the past two decades.

Ecological restoration has changed the LP's land use and land cover (Fig. 3). From 2000 to 2015, cultivated land in the LP decreased by 12.06%, while shrubland, grassland, artificial surfaces, and water bodies increased by 19.64%, 3.76%, 96.02%, and 20.21%, respectively (Liu et al., 2019). The long-term AVHRR NDVI average changed after 1999, the slope increased from 0.0018 $y^{-1}$ in the 1982–1998 period to 0.0053 $y^{-1}$ in 1999–2015 (Wu et al., 2019). The piecewise linear regression demonstrated that most breakpoints in the NDVI time series were detected between 1999 and 2002 (Wu et al., 2019). This means that, since the GTGP implementation in 1999, the LP has been greening.

By combining multi-source data, such as land use and land cover, remote sensing, and statistics, and by utilizing site-based monitoring data to set localized parameters, many ES assessments have been conducted in the LP at multiple scales (Lu et al., 2014; Zheng et al., 2016; Su et al., 2020). Using the universal soil loss equation (USLE, $A=R×K×L×S×C×P$), the soil conservation service was quantified, and the results showed that total soil erosion in the LP significantly decreased by $0.96×10^8$ t $y^{-1}$ between 2000 and 2015 (Wu et al., 2019). The sediment load between the Toudaotai and Tongguan stations decreased significantly by $0.25×10^8$ t $y^{-1}$ during the same period (Wu et al., 2019). Accordingly, the nutrient (N and P) retention service increased in the areas subjected to revegetation (Li et al., 2019). The carbon sequestration service, which was quantified by the terrestrial Carnegie-Ames-Stanford Approach (CASA) ecosystem model, showed a significant increasing trend. Estimates showed that the total regional NPP increased by $9.3 ± 1.3$ g C $m^{-2}$ $y^{-1}$ between 2000 and 2010 (Feng et al., 2016). The spatial extent of the increased NPP and ET observed from MODIS (Moderate Resolution Imaging Spectroradiometer) coincides with that of GTGP implementation (Feng et al., 2016), indicating that vegetation restoration, rather than climate change, is the main cause of the estimated increase of annual NPP or ET in the LP. However, water-related ESs, such as water supply and baseflow regulation, decreased dramatically at watershed (Luo et al., 2019) and regional scales (Lü et al., 2012; Wang et al., 2017). In contrast, the food provision service did not seem to be negatively affected by the reduction in cultivated land (Lü et al., 2012; Li et al., 2019), and the total grain output in the LP increased by 56.7% from 2000 to 2015, due to improved agricultural production techniques (Wu et al., 2019).

The assessments of ESs further provide the basis for the analysis of their trade-off and synergy relationships (Fig. 3). Overall, the same ES types (e.g., provisioning and regulating services) tended to show synergistic relationships, possibly due to the fact that they shared similar ecosystem processes and drivers (Bennett et al., 2009). For example, four provisioning services, namely grain production, oil crop production, livestock supply, and water supply, in the LP showed synergistic relationships, the exception being that between water supply and oil crop production (Li et al., 2019); and three regulating services, namely, carbon sequestration, soil conservation, and N and P retention, were positively correlated with each other (Li et al., 2019). Although the negative impact of vegetation restoration on agricultural production is small, the trade-off between food supply and regulating services still exists in some local areas. The trade-off between water yield and soil conservation and the trade-off between water yield and carbon sequestration services have received more attention, because of the importance of water resources for the sustainability of the LP ecosystem (Jia et al., 2014; Su et al., 2020). In addition, there are scale effects on the trade-offs and synergies among ESs. For example, studies have reported that NPP and water yield, and sediment retention and water yield showed trade-offs at the watershed scale, while they were not correlated at the LP scale (Su et al., 2020). Therefore,

it is necessary to elucidate the relationships among ESs at multiple scales to promote their sustainable use and facilitate policy-making. Hu et al. developed a spatial assessment and optimization tool for regional ESs (SAORES) to evaluate and optimize regional water yield, soil erosion control, carbon sequestration, and food supply services in the LP (Hu et al., 2015). Based on multi-objective trade-offs among ESs, SAORES was able to provide suggestions for maximizing key ESs and optimizing land-use patterns in the context of the GTGP (Hu et al., 2015).

In summary, the assessments of critical ESs and the analyses of their trade-off and synergy relationships in the LP provide theoretical support for the spatial optimization of ESs. However, there are still research gaps that should be considered in future investigations. First, current studies mainly focused on the provision of ES, but the ES demands and well-being of local residents, have been largely neglected. The residents of the LP are stakeholders with an interest in ESs and ecosystem management, and neglecting their demand and well-being may threaten the sustainability of ecological restoration outcomes (Dong et al., 2021). Second, as distant regions are connected by telecoupling processes, the use of ESs in one region may be affected by the management of ESs in other locations (Koellner et al., 2019), however, current studies mainly focus on place-based assessments of ESs, largely neglecting the flow of ESs between regions.

## 4.3 Social-ecological sustainability

Studies that coupled patterns and processes, and linked processes to services can reveal the interactions among social-ecological components, and help us figure out the causes of the unsustainable status of a CHANS and the corresponding solutions. Although the vegetation coverage has improved greatly and soil erosion has been well controlled in the LP after two decades of ecological restoration, some accompanied issues have started to threaten the long-term sustainability of the LP. The carbon-water conflict accompanied with revegetation is a typical example (Feng et al., 2016). Due to high-density planting, introduction of exotic plant species, and mismanagement of planted vegetation, large areas subjected to revegetation suffered soil drying (Chen et al., 2015; Wang et al., 2011). Studies have shown that the current vegetation cover has already exceeded the climate-defined equilibrium vegetation cover in many parts of the LP (Zhang et al., 2018). Considering the minimum water needed for socioeconomic activities, local revegetation in the plateau is approaching sustainable water resource limits (Feng et al., 2016), threatening the sustainability of the CHANS. In addition, although the total grain production in the LP increased because of the development of agricultural facilities and application of modern technologies (Wu et al., 2019), some counties still faced a decrease in grain production due to the conversion of cropland to forest or grassland, and further revegetation may threaten the local food supply (Chen et al., 2015). To obtain a higher yield from the declining cropland areas, local people tended to increase the use of agrochemicals to maintain or enhance land productivity (Wang et al., 2014). As a result, diffused pollution from agriculture has increased, and the quality of local land, groundwater, and surface water have been affected (Wang et al., 2014). Another important issue is the spillover effects of the LP on the telecoupled regions. In the past, the expansion of cultivation and deforestation to meet local food demand caused environmental degradation and severe soil erosion in the LP (Fu et al., 2017). The sediments produced flowed into the Yellow River, leading to the rising of riverbed levels (Chen et al., 2015) and extension of the Yellow River delta (Kong et al., 2015). After ecological restoration, the improved

environment and decreased soil erosion in the LP led to the subsequent reduction of sediment load and runoff in the lower Yellow River (Wu et al., 2020). The Yellow River delta has shifted to an erosional phase (Bi et al., 2014), which might affect more than two million people and the biodiversity in distant, but coupled, ecosystems (Zhou et al., 2015). Based on a deep understanding of the ecohydrological effects caused by vegetation restoration, changes in critical ESs and their trade-off and synergy relationships, the social-ecological sustainability in the LP can be enhanced through the following targeted policies and management (Fig. 3).

**Enhancing water and food security:** The LP is mainly located in arid and semi-arid regions, and water security is the priority issue that should be considered by scientists and policy makers (Lu et al., 2014). In response to this issue, some overplanted areas may need to be reasonably thinned to reduce vegetation density, and a better fit of plant species and planting density to the LP's natural environment (e.g., precipitation gradient), as well as adaptive management of revegetation areas, are needed for the ensuing ecological restoration process (Lü et al., 2012; Feng et al., 2016). Considering that new large-scale vegetation restoration has deviated from the current social-ecological contexts of the LP, future restoration should be more refined and targeted, pay more attention to the key ecologically vulnerable areas, and avoid the one-size-fits-all governance approaches (Wang et al., 2017). Besides, it is necessary to consider the impact of climate change on NPP and water yield to meet future challenges of water shortage. To achieve food security, relevant stakeholders should better manage the existing croplands, adopt advanced agricultural production and water-saving techniques to improve food yield per unit area, and simultaneously avoid agricultural pollution. In addition, more new croplands can be created by filling gullies, where conditions allow it (Liu et al., 2013b; Wang et al., 2018a).

**Implementing basin-wide management:** Scientists and policy makers need to consider not only the local ecohydrological effects caused by vegetation restoration in the LP but also its spillover effects on distant regions through telecoupling processes (Wu et al., 2020). The establishment of a basin-wide ecosystem and land use management regime is needed to support sustainable water use and sediment regulation (Zhou et al., 2015; Wang et al., 2016; Wang et al., 2017). The interconnected sub-hydrological units of the Yellow River Basin span various human-defined boundaries and are managed by different agents, resulting in institutional fragmentation. Considering the holistic nature of the basin, policy makers and managers of the LP should cooperate and coordinate with middle-stream and downstream stakeholders to integrate management of river water and sediment (Wang et al., 2019). Specifically, cross-border and cross-scale coordination exerted by a higher-level authority is an effective means to overcome institutional fragmentation. This is because a third party or a higher administrative agency with whole-basin responsibility can promote effective coordination on a basin level by establishing social ties indirectly linking actors across administrative levels (Wang et al., 2019).

**Maintaining the GTGP achievements:** The sustainability of the conservation achievements obtained from the GTGP is affected by the post-program land use plans of participants (Page and Bellotti, 2015; Deng et al., 2016). A study of the effects of regional ESs changes and individual characteristics on participants' post-program land reconversion willingness in a watershed of the LP has shown that participants with a higher household income, more household employment change, higher household involvement in crop production, and higher ecological awareness tended to not reconvert their GTGP land to

agriculture use (Wu et al., 2021a). At the regional level, the changes in water yield and grain production services would affect the reconversion willingness of participants with different individual characteristics (Wu et al., 2021a). With a more comprehensive understanding of the effects of multiple-level factors on the reconversion willingness, the sustainability of the GTGP achievements can be enhanced by diversifying and improving the household income of participants (Bryan et al., 2018), enhancing the participants' ecological awareness and recognition of ecological benefits obtained from the program (Song et al., 2014), and providing place-based solutions and protection priorities of ESs (Wu et al., 2021a).

**Promoting rural livelihood transition:** The overdependence of the local people on agriculture for livelihood is the main cause of the previous social-ecological trap in the LP (Wu et al., 2021a). Promoting rural livelihood transition toward a development path with low ecological impact is critical for the long-term social-ecological sustainability of the LP. The GTGP converted numerous croplands to forest or grassland, which released local rural labour from crop production, promoted the transformation to non-farm activities (Liu et al., 2008; Uchida et al., 2009), improved rural household income, and simultaneously decreased income inequality (Li et al., 2011). In parallel to the GTGP, multiple factors like economic development, industrialization, and urbanization, also influence the livelihoods and income of rural households (Ouyang et al., 2016; Bryan et al., 2018). A comprehensive analysis proved that local economy and investment played dominant roles in the improvement of rural household income in the LP, while tourism, investment, and rural migration could boost non-farm work participation and effectively use the surplus labourers released from the GTGP, indirectly increasing income (Wu et al., 2021b). To promote socioeconomic development in the LP and enhance the benefits that participants gain from non-farm work, it is necessary to promote initiatives that can create more local non-farm employment and help non-farm participation, such as promoting tourism industry, attracting more visitors and investment from outside, and providing training for new earning skills (Wu et al., 2021b; Cao, 2011; Yin et al., 2014). Meanwhile, barriers for rural labour migration should be overcome by offering equal opportunities and information services to migrant workers (Yang et al., 2018), especially to rural labourers that have fewer local employment opportunities and wages.

## 5 Future directions of the Pattern-Process-Service-Sustainability paradigm

In this review, the LP was used as an example to illustrate the adoption of the "Pattern-Process-Service-Sustainability" paradigm to analyse the dynamics of CHANS and identify management priorities to enhance sustainability. After the implementation of the GTGP in 1999, the LP has achieved the general "win-win" gains of restoring the environment and promoting socioeconomic development (Wu et al., 2019). However, water limits and land shortages are becoming the boundary of regional development (Wang et al., 2018a). It is necessary to readjust the revegetation strategy and promote socioeconomic development and livelihood transition, and consequently, the social-ecological sustainability of the LP (Wang et al., 2018a; Li et al., 2017). By revealing the limitations of current studies, future research using the "Pattern-Process-Service-Sustainability" paradigm to observe, analyse, and understand the dynamics and changes of CHANSs should especially focus on the following aspects:

(1) Integrated research on multiple processes. CHANSs are complex systems in which multiple natural and social processes interact and co-evolve (Quintas-Soriano et al., 2021), and therefore only focusing on one, or a few, of them may not reveal the essential laws behind complex phenomena (Fu et al., 2019). Multiscale systematic research quantifying the interactions among the hydrological, pedologic, atmospheric, biological, and socioeconomic processes is necessary to provide integrative and convincing guidance to achieve sustainability (Fu, 2020). The driving mechanisms behind these interactions should also be further studied. This proposed research can specifically investigate the interactions among water, soil, atmosphere, and ecosystem, and their ecological effects; the biogeochemical processes and mechanisms on the earth's surface; and the interactions of different earth spheres and their response mechanisms to global change (Fu, 2020).

(2) Cascades of ecosystem structure, function, services, and human well-being. As a link between nature and human society, the ES concept has become an important component of the scientific discourse, and a research object in science and policy (Carpenter et al., 2009). Understanding the ES delivery process from ecosystems to human society is essential to effectively manage ecosystems (Mandle et al., 2021). The research frontiers of ES cascades involve the identification of the spatial mismatch between ES supply and demand, the differentiation of ES supply and human use, and the analysis of interregional ES flows to support cross-regional management cooperation (Koellner et al., 2019; Vallecillo et al., 2019; Zwierzchowska et al., 2018). In addition, the relationship between ESs and human well-being has also become an important research topic (Mandle et al., 2021). Further research needs to explore the coupling mechanisms of ES cascade components, clarify the dominant mechanisms of ES trade-offs to enhance and optimize ESs for the achievement of regional ecological security.

(3) Feedback mechanisms of human and natural systems. Human and natural systems interact and co-evolve over time and have substantial impacts upon each other, with causality operating in both directions (Fu and Li, 2016; Quintas-Soriano et al., 2021). Understanding the complex interactions and feedbacks of CHANSs is one of the core research objectives in the field of sustainability. Future research needs to examine the bidirectional feedbacks between human and natural systems, the dynamics and resilience of CHANSs, the interactions between humans and nature at multiple scales (e.g., telecoupling), the structural and dynamic fit of human and natural systems, and the capacity boundaries of CHANSs (Wang et al., 2018b).

(4) Data and models for sustainability. Field monitoring, control experiments, and remote sensing of natural systems at multiple scales provide abundant datasets to understand ecological processes (Wei et al., 2010; Feng et al., 2010; Yao et al., 2012; Zhou et al., 2016; Liang et al., 2018), while the development of information technology and big data can help detect human activities and strengthen the spatiotemporal links between socioeconomic and natural processes. However, due to the scale mismatch between natural and social-economic processes, data assimilation is needed to integrate data from different scales, disciplines, and sources, and form a CHANS dataset for further sustainability analyses (Fu, 2020). In addition to the system dataset, the development of a model, or model systems, is crucial for integrated CHANS research. This kind of model can be realized through the integration of multiple ecological, human, and socioeconomic models (Fu and Li, 2016).

## 6 Conclusion

A deep understanding of the reciprocal effect between landscape patterns and ecological processes, and complex linkages between ecological processes and ESs that support human well-being is crucial for promoting social-ecological sustainability. The conceptual cascade framework of "Pattern-Process-Service-Sustainability" proposed in this review can help researchers observe, analyse, and understand the dynamics of CHANSs, diagnose the causes of the unsustainable status, and support the design of policies and measures that promote sustainability. To illustrate the use of this framework, this review systematically examines the CHANS research experiences in China's LP, in terms of coupling landscape patterns and ecological processes, linking ecological processes to ESs, and promoting social-ecological sustainability.

Since 2000, the vegetation coverage in the LP has increased and soil erosion has been well controlled due to ecological restoration. However, overplanting, the introduction of exotic plant species, and the mismanagement of planted vegetation have also led to soil drying in some regions subjected to revegetation, and a trade-off between carbon sequestration and water supply has been identified at multiple scales. Some social-ecological issues, such as water resource limit, local food scarcity, and negative spillover effects, have emerged in the LP, posing a threat to its sustainable development in the future. To promote social-ecological sustainability, scientists and policy makers should pay more attention to water and food security, basin-wide governance, maintenance of ecological restoration achievements, and rural livelihood transition.

Considering the typicality of the social-ecological context in the LP, we believe that research experiences from this region are relevant for CHANS studies in the rest of the world. Future research using the "Pattern-Process-Service-Sustainability" paradigm should especially examine the integrated research on multiple processes, the cascades of ecosystem structure, function, services, and human well-being, the feedback mechanisms of human and natural systems, and the data and models for sustainability.

**Data availability**

No data sets were used in this article.

**Author contributions**

B.F. designed the research. Xutong Wu, Z.W., and Xilin Wu performed the literature review. B.F., Xutong Wu, Z.W., S.W., and Xilin Wu contributed to the interpretation and writing.

**Competing interests**

The authors declare no competing interests.

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