Do adaptive policy adjustments deliver ecosystem-agriculture-economy co-benefits in land degradation neutrality efforts? Evidence from southeast coast of China

Chong Jiang · Yixin Wang · Zhiyuan Yang · Ying Zhao

Abstract Ecosystem restoration projects (ERPs) facilitate land degradation neutrality (LDN). However, the response dynamics and interactions of sectors within ecosystem-agriculture-economy nexus (EAEN) have not been sufficiently explored, which constrains the coordinated efficacy of LDN efforts. To bridge the knowledge gaps, the present study selected a land restoration hotspot in southeastern China as a case to investigate the simultaneous responses of the EAEN sectors to ERPs from a novel social-ecological system (SES)–based LDN perspective. Various biophysical models and Manne-Kendall trend test as well as multi-source spatially explicit data and socioeconomic statistics were applied to quantify the co-evolution of natural and socioeconomic indicators. ERPs converting cropland to woodland and grassland promoted vegetation restoration, reduced soil erosion, and enhanced carbon sequestration. However, cropland loss initially resulted in a decline in grain productivity. Policy adjustments and improvements in ecosystem restoration efforts and agricultural production conditions improved food security and increased agricultural production capacity. Effective policymaking and favorable resident engagement

Jiang C. and Wang Y. contributed equally to this manuscript.

C. Jiang
Key Laboratory of Coupling Process and Effect of Natural Resources Elements, Beijing 100055, China

C. Jiang
Southern Marine Science and Engineering Guangdong Laboratory (Guangzhou), Guangzhou 511458, China

C. Jiang
Changsha Comprehensive Survey Center of Natural Resources, China Geological Survey, Changsha 410600, China

C. Jiang · Y. Zhao (✉)
Dongying Base of Integration Between Industry and Education for High-Quality Development of Modern Agriculture, Ludong University, Dongying 257509, China
e-mail: yzhaosoils@gmail.com

C. Jiang (✉)
Guangzhou Institute of Geography, Guangdong Academy of Sciences, Guangzhou 510070, China
e-mail: jiangchong1987@gmail.com

Y. Wang
Research Institute of Management Science, Hohai University, Nanjing 211100, China

Z. Yang
Department of Infrastructure Engineering, The University of Melbourne, Parkville, Victoria 3010, Australia

accelerated the transformation from a grain-production-based agriculture to diversified industries and, by extension, economic output, income, and population. The success of socioeconomic development under the SES framework for LDN demonstrated that this strategy could achieve the desired environmental, agricultural, and economic targets. EAEN under the SES conceptual framework provides an inclusive, comprehensive LDN perspective and improves ERP efficacy. The findings of the present work might be applicable to other land restoration areas challenged by the complex interactions among multidimensional factors. Comparably successful implementation of these ERPs could be realized if individual environmental and socioeconomic conditions are thoroughly considered during the formulation of coordinated development policies.

Keywords Co-evolution · Nexus sectors · Ecosystem restoration · Social-ecological system · Win-win outcomes

Abbreviations

AVHRR	Advanced very-high-resolution radiometer
CASA	Carnegie-Ames-Stanford approach
ERPs	Ecosystem restoration projects
ES	Ecosystem service
EAEN	Ecosystem-agriculture-economy nexus
FRC	Forest restoration and conservation
GDP	Gross domestic product
LDN	Land degradation neutrality
LUC	Land use/cover
MODIS	Moderate-resolution imaging spectroradiometer
NPP	Net primary productivity
NDVI	Normalized difference vegetation index
RCWG	Returning cropland to woodland and grassland
RUSLE	Revised universal soil loss equation
SES	Social-ecological system
SWCPs	Soil and water conservation projects
SLM	Sustainable land management
TEK	Traditional ecological knowledge

Introduction

The land in > 23% of all global terrestrial regions has undergone degradation (FAO, 2019). Consequently, ecosystem sustainability has been challenged and ~ 1.5 billion people worldwide are affected by this deterioration (Pasquale et al., 2020). If the current rate of intensive exploitation is not effectively controlled, > 90% of the surface of the Earth could be degraded by the year 2050 (Pasquale et al., 2020; Wuepper et al., 2020). Land degradation neutrality (LDN) was proposed to mitigate and reverse anthropogenic terrestrial deterioration. It is regarded as a major sustainable development goal of the United Nations (UNCCD, 2016; United Nations, 2015). Massive ecosystem restoration projects (ERPs) and soil and water conservation projects (SWCPs) have been launched in both developed and developing countries across the globe to mitigate and reverse land degradation, sustain ecosystems, and ensure adequate ecosystem service (ES) supply (Adams et al., 2016; Bednarska et al., 2018; Cao et al., 2018, 2020; Danneyrolles et al., 2017; Hruska et al., 2017; Sanchez Meador et al., 2017). However, numerous ecosystem restoration efforts have failed (Arsénio et al., 2020; Buisson et al., 2018; Staentzel et al., 2019). This deficiency implies the existence of complex interactions such as trade-offs, synergy, and nonlinear relationships among multiple natural ES. Positive and negative interactions occur between ecological systems and human society (Hausner et al., 2018). In drylands, there are also trade-offs between soil retention and water yield as well as positive correlations between carbon sequestration and soil retention (Abera et al., 2019). Urban expansion and socioeconomic development have negative impacts on agricultural production and biodiversity maintenance (Pereira et al., 2018, 2020). Trade-offs and synergistic relationships undergo strong spatiotemporal variability across geographical regions and changes in regime and stage (Torday & Miller, 2015).

In a complex social-ecological system (SES) consist of multiple nexus sectors, natural and human interventions such as climate variabilities, landscape transformations, and other internal and external disturbances might trigger system feedbacks and chain reactions, in particular for co-evolution and regime shifts of nexus sectors as well as their determinants and critical thresholds, which have generally been ignored or poorly understood (Lu et al., 2021; Safriel, 2017; Virapongse et al., 2016). Even if the nexus perspective was integrated into ERP and LDN efforts, existing literatures

mostly depended on a few narrow indicators such as biomass (Cao et al., 2020), vegetation cover (Hu et al., 2021), surface runoff (Zhuang et al., 2021), groundwater (Lu et al., 2021), and other biophysical indicators (Okpara et al., 2018). Therefore, a lack of systematic, comprehensive, and dynamic assessments of SES incorporating nexus approaches fails to support formulation of targeted and adaptive environmental governance strategies and schemes (Orr et al., 2017).

To achieve sustainable land management (SLM) and mitigate land degradation, SES and nexus approaches should be integrated into ERP challenges (Orr et al., 2017). This innovative strategy could help elucidate the complex interactions between land systems and human society (Cowie et al., 2018). SES is a complex, adaptive, coupled human-environment system that encompasses the human society and biological ecology subdomains (Fischer et al., 2015; Leslie et al., 2015). In the context of LDN, the SES approach furnishes a novel interdisciplinary framework for integrating multiple spatiotemporal changes in land systems and provides guidance for framing interlinked human and ecological systems (Verburg et al., 2015). Adoption of this approach could clarify the changes in SES shape, influence the ecological functions of terrestrial ecosystems, and eventually mitigate and reverse land degradation (Okpara et al., 2018; Safriel, 2017).

To realize the LDN target, the livelihoods of residents, institutions, enterprises, and other socioeconomic sources must be considered (Barkemeyer et al., 2015; Reed et al., 2015). Traditional land management practices regard human interventions as external drivers that lead to the deterioration of soil quality and the loss of ecological function (Cowie et al., 2018; Reed & Stringer, 2016). Conventional command-and-control methods provide steady-state resource management and facilitate reactive, top-down hierarchal processes (Akhtar-Schuster et al., 2017; Sietz et al., 2017). However, the complex spatiotemporal interactions among nexus sectors and conflicting stakeholder perspectives have required resources managers and stakeholders to develop innovative, integrated environmental management approaches that integrate evolving social and ecological systems from a nexus perspective (Lu et al., 2021; Zhuang et al., 2021). In this manner, social re-orientation is stimulated, the management mode is upgraded, and conflicts

with traditional management approaches are created (Ostrom, 2010; Westley et al., 2011).

An integrated nexus approach under the SES framework facilitates LDN within the context of rapid environmental change and intensive human activity because it is a self-adaptive management mode that emphasizes the interactions among biophysical processes and stakeholder collaboration (Safriel, 2017; Sims et al., 2017). The engagement of local residents and communities is essential for combating land degradation challenges (Stavi & Lal, 2015). For this reason, it is crucial to understand the perceptions, plans, and actions of stakeholders in response to complex biophysical processes (Kust et al., 2017). The nexus-based LDN approach under the SES framework achieves LDN by integrating ecological, agricultural, and economic factors across multiple spatiotemporal scales and ecosystems (Okpara et al., 2018). In this way, it supports policy formulation, guides project implementation, and addresses land degradation (Chasek et al., 2015; Virapongse et al., 2016).

In China, adverse climate conditions and intensive human disturbances such as unsustainable agricultural reclamation and inappropriate urbanization have temporarily increased short-term economic profit and grain provisions (Nkonya et al., 2016). They have nonetheless resulted in the degradation of > 27.5% of the territory and further aggravated ES degradation (Taniguchi & Yamanaka, 2017). Environmental degradation threatens resident livelihoods which leads to poverty (Wuepper et al., 2020). The latter worsens ecosystem degradation and deviates the affected region from sustainable development through ecosystem-agriculture-economy nexus (EAEN) effects and "poverty trap" feedback (Cao et al., 2017, 2020). Here, Longyan City in the hilly red soil region of southern China was selected as the target study area because it presents with severe soil loss and rapid ecosystem restoration. It served as a representative case study to determine the responses of the EAEN sectors to human interventions and policy adjustments and establish their implications for ecosystem restoration efforts. The objectives of this research were to (1) explore the spatiotemporal responses of the EAEN sectors (including soil loss, carbon sequestration, grain production, and economic profit) to ERPs and SWCPs; (2) identify and justify the regime shifts and critical timings of the changes in the nexus sector; and (3) use the SES-based LDN

approach to clarify the roles of engineering practices, stakeholder engagement, and policy adjustments in achieving target ERP efficacy. The EAEN under the SES conceptual framework offers a comprehensive LDN perspective that includes multiple dimensions, which could eventually optimize and improve the efficacy of ecosystem restoration efforts.

Materials and methods

Study site descriptions

Longyan City in Fujian Province is located in the subtropical zone of southeastern China and has an area of 19,027 km² (Fig. 1a). Its landscape is dominated by low mountains and hills (Fig. 1b), with an elevation varying from 98 to 1695 m, and the relatively high mountains lay around central and eastern border

areas. Its long history of agricultural cultivation has resulted in soil loss and severe erosion (Zhong et al., 2013). In response to the pressure of rapid population growth and extensive agricultural production, woodlands, grasslands, and wetlands have been converted into croplands (Cao et al., 2017, 2018). Land reclamation rapidly increased in the hilly areas and the cultivation slope has become steeper (Li et al., 2020; Wang et al., 2020; Zhong et al., 2013). Between 1949 and 1998, the population and the cultivated land area in the region have increased by 1.74 million and 72,189.9 ha, respectively. The area has numerous slopes with gradients of 15–25° and > 25°. Sloping cropland accounts for > 50% of the total cropland area. Deforestation and wasteland reclamation have worsened soil erosion, increased the frequency of drought and flood disasters, and reduced ecosystem sustainability (Li et al., 2020; Wang et al., 2020). The upper and middle reaches of the Ting and Jiulong
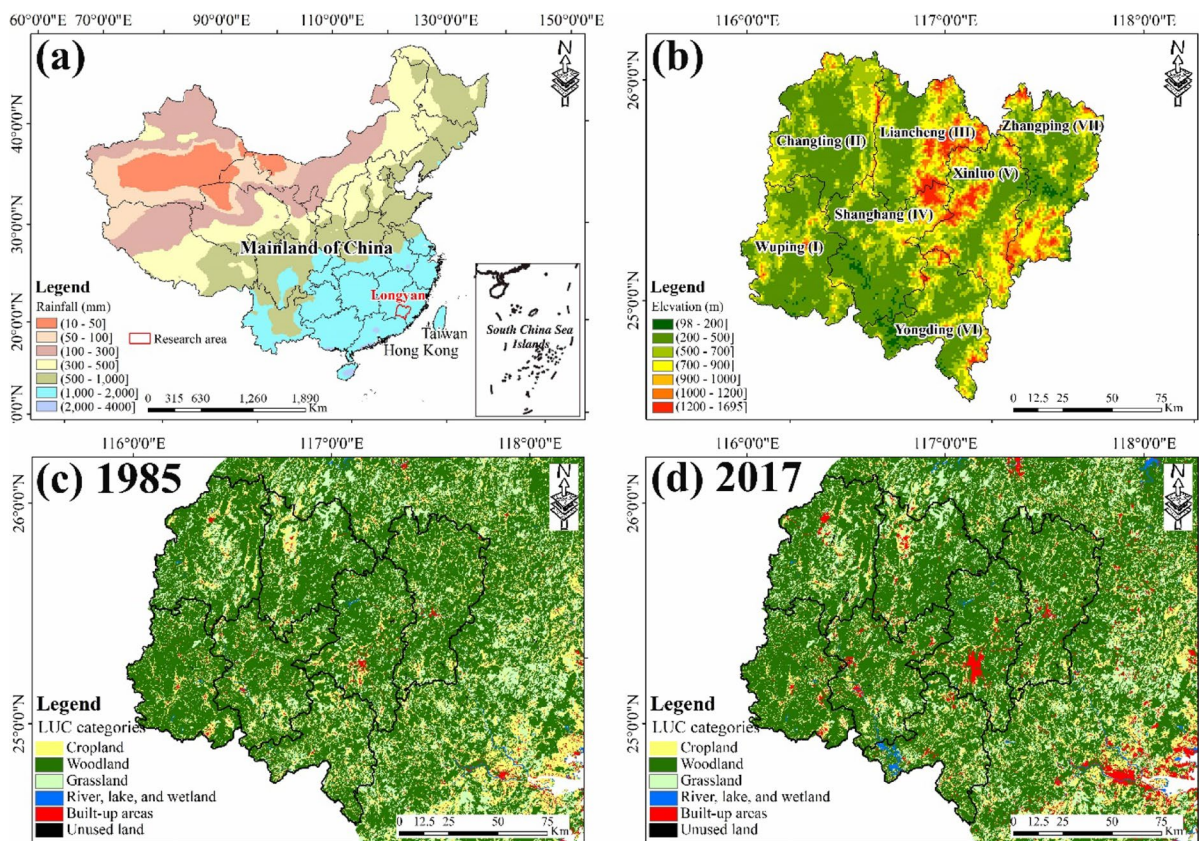

Fig. 1 **a** Geographic location of study site; **b** elevation distribution and administrative division; **c–d** LUC maps for 1985 and 2017, respectively

Rivers around Changting County (Fig. 1b) present with the most severe soil erosion in the hilly red soil region of southern China because of deforestation, grassland reclamation, and slope cultivation (Cao et al., 2017, 2018). Over 2.46 million tons of eroded sediment accumulate annually in the Ting and Jiulong Rivers, and 2/3 of it originate from sloping cropland (Chen et al., 2020).

To combat land degradation, several ecosystem restoration projects (ERPs) and soil and water conservation projects (SWCPs) have been conducted in Longyan City and the surrounding mountain areas over the past few decades (Cao et al., 2017, 2018; Zhong et al., 2013). Forest restoration and conservation (FRC) and returning cropland to woodland and grassland (RCWG) are two of the most aggressive ERPs implemented. They were initiated in the late 1970s and 1999, respectively (Li et al., 2020). FRC and RCWG comprise afforestation and reforestation in barren hills, wasteland areas, terraces, and croplands with steep slopes, 15–25° slope in important water source areas, or severe desertification and pollution. Other measures include forest conservation and hillside closure to facilitate afforestation (Fig. S1). As of 2007, the RCWG was suspended to achieve ≥ 0.12 billion ha target cropland area and safeguard food security. This measure prevented any further cropland occupation. Nevertheless, hillside closure to facilitate afforestation is ongoing.

As of 2005, the government has allocated ¥1.9 billion to consolidate RCWG efforts and ensure the long-term livelihoods of the affected residents. The funds were used mainly to establish grain fields and rural energy facilities, promote ecological migration, and develop other industries. The local communities provided training to help restore employment and income for the affected farmers. The latter were encouraged to interplant beans and other dwarf crops and develop the forest economy to mitigate the loss of vegetation and soil. Between 2007 and 2016, the average annual per capita growth rate of disposable farmer income affected by the RCWG was 14.7%, and it was 1.8% higher than the national mean. The RCWG caused the rural labor force to migrate to other areas, and the annual income of migrant workers has reached ¥50 million. The production structure was transformed from a grain-based to a diversified economy. Grain production changed from extensive planting and thin harvesting to intensive farming.

Animal husbandry moved from bulk farming to pen feeding. The introduction of RCWG helped concentrate agricultural production factors; promoted the development of wood, grain, and oil, fruits, and animal husbandry; and improved agricultural production capacity (Cao et al., 2017, 2018; Zhong et al., 2013).

Conceptual framework and study workflow

In theory, the EAEN-based LDN approach under the SES framework considers land system dynamics as both natural and societal processes (Safriel, 2017). It also integrates nexus evolution into LDN efforts. However, application of this approach to mitigate and adapt to environmental change in SLM has not previously been explored (Okpara et al., 2018). This strategy for the achievement of LDN is a systemic worldview interlinking environmental governance perspectives with land restoration. It also considers humans as part of nature rather than external drivers. From the nexus perspective under the SES framework, land systems are open nonlinear systems involving complex trade-offs, synergy, and interactive socioeconomic and biophysical domains and processes across multiple spatiotemporal scales (Fig. 2a; Chasek et al., 2015; Fischer et al., 2015). Changes in human perception, management practice, resource use mode, and other interventions such as ecosystem conservation investments, agricultural technology developments, and industrial structure transformations constantly modify and feed back to the land (Virapongse et al., 2016). The successful accomplishment of LDN requires a comprehensive understanding of ecological, agricultural, and socioeconomic dimensions. The mechanisms by which socioeconomic variables interact with the land system and the direct and indirect responses of their associated ecological functions must be elucidated. To improve ERP efficacy, the EAEN-based LDN approach under the SES framework must identify the dominant drivers and pressures such as ecological, agricultural, social, economic, and cultural variables that influence land degradation. It must also assess close interactions across multiple spatiotemporal scales (Fig. 2a) and environmental variables such as climatic conditions, soil properties, vegetation species, and topographic structures that influence the ongoing and existing degradation and their regime shifts and critical transition points. SLM and LDN must also consider human

Fig. 2 **a** Social-ecological system (SES)–based land degradation neutrality (LDN) framework and **b** study workflow
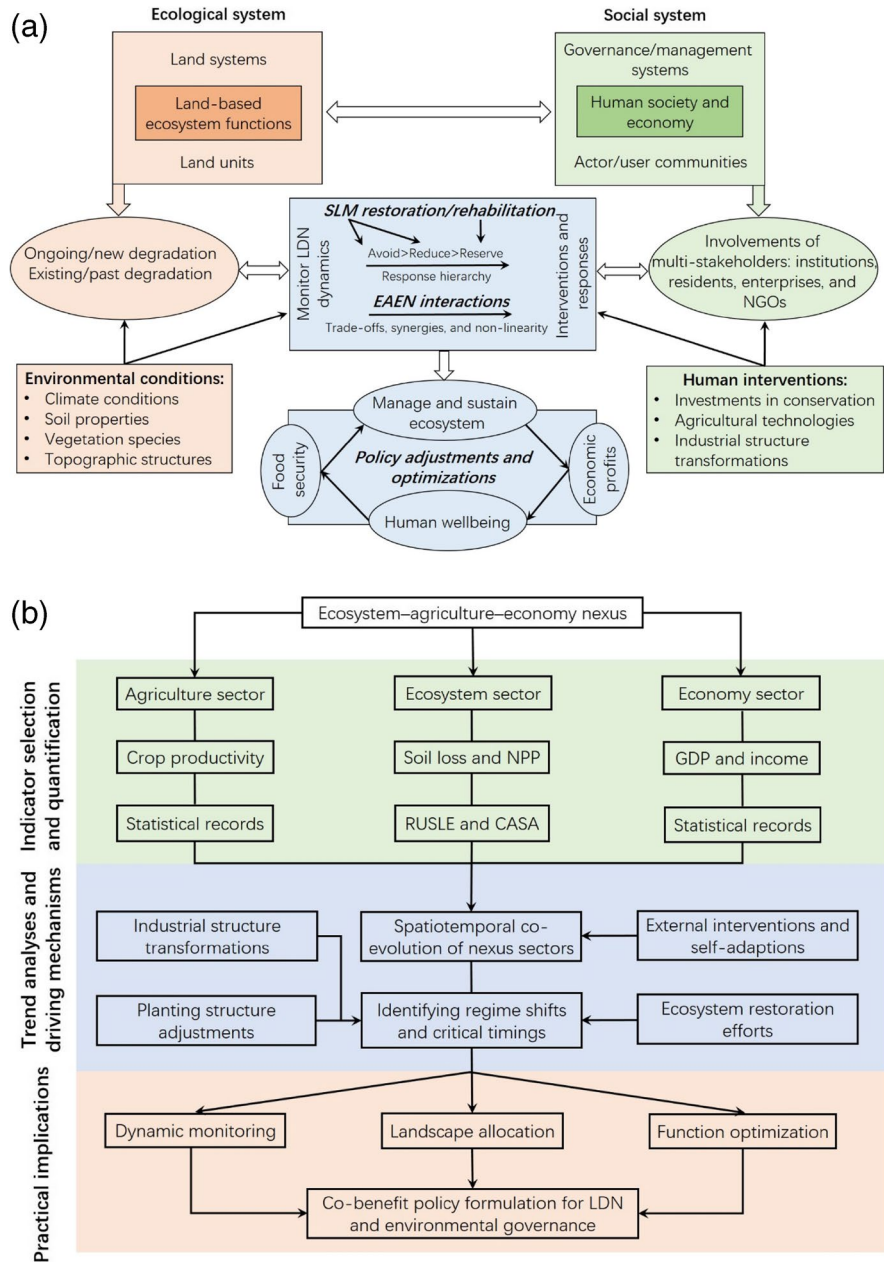
interviews, promote and coordinate the engagement and contributions of land managers and multiple stakeholders in land degradation and restoration efforts, and maximize reciprocal benefits (Okpara et al., 2018; Palomo et al., 2011).

Based on the available data and the prevailing environmental challenges of the research area, vegetation cover, carbon sequestration, and soil erosion modules were selected to reflect the natural changes occurring within the context of ecosystem restoration (Fig. 2b). ERPs affect food supply (crop productivity), economic output value, gross domestic product (GDP), population, and resident income and expenditure. These ecological and social variables are widely applied to reflect the evolution of EAEN in SES and may be evaluated via biophysical model simulations and statistical records (Cowie et al., 2018; Okpara et al., 2018; Orr et al., 2017; Torday

& Miller, 2015). The workflow of the present study is shown in Fig. 2b.

Data collection and preprocessing

The timespan of the present study was set as 1985–2017. Although the time series of individual socioeconomic indicators were longer than 1985–2017, some of them even started from 1970, the model-based natural indicators can only date back to 1985 because the bad data availability of remote sensing images and other datasets before 1985, which were used as input parameters of biophysical models. Therefore, we unified the timeframe of multiple indicators to present consistent analyses for this study.

Multisource datasets including soil, vegetation, climate, topography, land use/cover (LUC) maps, and socioeconomic records were compiled for the LDN and EAEN assessments (Table S1). They were collected according to the input parameters of the revised universal soil loss equation (RUSLE) (Jiang et al. 2019b,b) and the Carnegie-Ames-Stanford approach (CASA; Potter et al., 1993) used to quantify soil loss and carbon sequestration, respectively. LUC maps with 30 m × 30 m spatial resolution for 1985, 1990, 1995, 2000, 2005, 2010, 2015, and 2017 were plotted by machine learning techniques and visual interpretation of Landsat TM/ETM/OLI_TIRS images for the corresponding periods (Liu et al., 2014). The LUC maps were used to quantify LUC transformations and estimate RUSLE input parameters. To reduce possible error in visual interpretation, the accuracies of the LUC map analyses were cross-validated by comparing them against the China land cover and other LUC datasets (Yang & Huang, 2021) using global land cover products with a fine classification system at 30 m (Zhang et al., 2021), and the original satellite images from different time periods (Figs. S2 and S3). The overall interpretation accuracy was > 94% which exceeded the basic accuracy requirements for a regional scale assessment. Maps of climate, soil, vegetation, and topography were used to estimate rainfall erosivity, soil erodibility, land surface cover, management, slope length, and steepness factors in RUSLE. Gauge-based climate and spatially explicit vegetation cover datasets were applied to assess carbon sequestration. The spatial data were preprocessed and resampled to unify projection and coordinate systems (i.e., World Geodetic System-1984) and spatial

resolutions (i.e., 1 km × 1 km) on ArcMap Platform and to avoid uncertainty and error arising from model simulations and data outputs. In consideration of a long timeframe for more than three decades, two normalized difference vegetation index (NDVI) datasets including an advanced very-high-resolution radiometer (AVHRR) [third-generation product (GIMMS-3g)] with 8 km × 8 km spatial resolution and a moderate-resolution imaging spectroradiometer (MODIS) MOD13A3 dataset with 1 km × 1 km spatial resolution were adopted for consistent generation of a long-term product with the same radiation features and spatial resolution. Data were radiometrically and geometrically corrected (Sun et al., 2015).

Methodology

The study uses soil loss and carbon sequestration as indicators to represent ecosystem sector in EAEN because these two variables are easily assessed and commonly used indicators to reflect direct impacts of ERPs (Ouyang et al., 2016). Generally, the ecological impacts of ERPs include but not limited to soil loss and carbon sequestration, such as habitat maintenance, water yield, climatic regulation, and aquatic purification (Ouyang et al., 2016). While the 33-year scale assessment for these indicators rely on relatively complex biophysical models and input parameters, they are the indirect aspects of LDN efforts, which are not as close associate with vegetation restoration as that of soil loss and carbon sequestration. The core and direct target of ERPs is to achieve LDN target and further support carbon neutrality strategy; thus, this study does not include other ecological indicators.

Soil loss assessment by RUSLE

Soil loss is widely used as an indicator of regional-scale (catchment, county, district, country, or continent) land degradation and soil quality (Panagos et al., 2015; Zare et al., 2017). It was empirically demonstrated that RUSLE is a highly reliable model for soil loss quantification especially in the northern drylands of China (Chen et al., 2020; Ferreira et al., 2018; Jiang et al. 2019b,b; Li et al., 2020; Pereira et al., 2020; Sousa & Srbek-Araujo, 2017). The RUSLE method was gradually developed from site experiments conducted on specific soil degradation and landscape-scale processes. It was upscaled to

spatial units based on generalized empirical parameters and the regression relationships between in situ plot experiment measurements and remote sensing images (Duan et al., 2020; Gardner et al., 2019; Mace et al., 2018). The primary RUSLE formula is

$$SL_{ij} = R_{ij} \times K_{ij} \times L_{ij} \times S_{ij} \times C_{ij} \times P_{ij} \qquad (1)$$

where SL_{ij} is the soil loss (erosion modulus) at unit i and time j, R_{ij}, K_{ij}, L_{ij}, S_{ij}, C_{ij}, and P_{ij} are rainfall erosivity, soil erodibility, slope length, slope steepness, surface cover, management, and support practice at unit i and time j, respectively. Calculations and specific formulae are shown in Table S2.

To validate and calibrate the RUSLE estimates for Longyan City, the present study cross-compared the spatiotemporal series and patterns of the assessment against those of prior studies conducted in the same or adjacent regions (Chen et al., 2020; Li et al., 2020; Wang et al., 2020). Comparisons of the soil loss between Longyan City and the surrounding regions were spatiotemporally consistent. Nevertheless, the absolute values were not identical because the input parameters and data sources differed among studies.

Carbon sequestration assessment by CASA

The present study used the net primary productivity (NPP) index to reflect carbon sequestration. This parameter has been widely applied to monitor vegetation growth and biomass assessment (Chen et al., 2015; Chen et al., 2017; Li et al., 2021). The CASA developed by Potter et al. (1993) was used to quantify NPP. It was based upon the theory of light use efficiency (Li et al., 2021). The principal equation is:

$$NPP_{i,j} = APAR_{ij} \times \rho_{ij} \qquad (2)$$

where $NPP_{i,j}$ is the NPP of unit i at time j, $APAR_{ij}$ is the photosynthetically active radiation at unit i and time j, and ρ_{ij} is the light use efficiency parameter at unit i and time j estimated by Zhu et al. (2006) and according to in situ observations and model simulations.

Agricultural production and economic profit assessments

The productivity levels of grain, oil, and cash crops, forest and livestock products, and commodities between 1985 and 2017 were used to indicate agricultural sector changes in EAEN. City-level statistical records of population size and composition, resident income and expenditure, GDP, and the composition of economic output value were used to reflect changes in socioeconomic conditions.

Statistical analyses

The Manne-Kendall test (Kendall, 1975; Mann, 1945) is a non-parametric statistical testing approach, which has the advantage of not following a certain distribution or being disturbed by a few outliers. This method can not only test the trend of changes in time series, but also check whether there has been a mutation in the time series. It is more suitable for type and sequence variables, with strong applicability and convenient calculation (Kendall, 1975; Mann, 1945). The Manne-Kendall test is not only a diagnostic and predictive technique for climate variables, but also has been widely used for trend and mutation detections of ecological and hydrological variables. Therefore, the Manne-Kendall test was used for this study to detect change trends and abrupt changes in the EAEN-related variables. Significance levels of $p = 0.05$, $p = 0.01$, $p = 0.001$, and $p = 0.0001$ were used to assess the confidence level of the test.

Results

EAEN evolution and regime shifts

The NDVI, NPP, and soil erosion modulus were selected to identify the responses of natural ecosystems to ERP and reflect changes in the ecosystem (Fig. 3). Between 1985 and 1998, vegetation cover, carbon sequestration, and erosion modulus slightly but nonsignificantly declined ($p > 0.1$). However, they significantly ($p \leq 0.05$) increased after RCWG was implemented in 1999 (Fig. 3). The trends in NDVI and NPP reached significance levels of $p = 0.0002$ and $p = 0.0001$, respectively. Hence, vegetation was rapidly restored within the context of the ERPs. The erosion modulus increased because of fluctuations in rainfall. Nevertheless, the mean erosion modulus between 1999 and 2017 (4.5 t ha^{-1}) was 36.7% lower than that between 1985 and 1998 (7.1 t ha^{-1}). Thus, the ERPs reduced the erosion intensity. Grain productivity rapidly increased between 1985
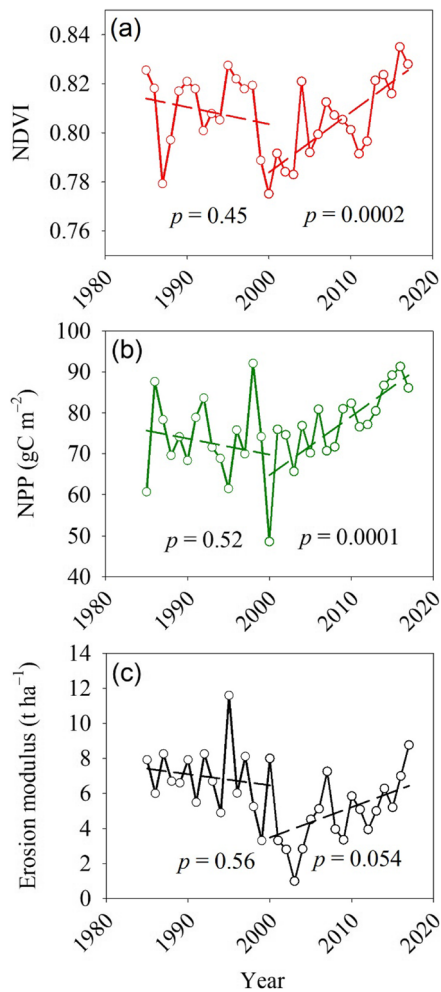
Fig. 3 Temporal changes and trend slopes for **a** NDVI, **b** NPP, and **c** soil erosion moduli between 1985 and 2017

and 1998 but declined after 1999 (Fig. 4a). RCWG replaced the cropland with woodland and grassland (Fig. 1c–d) and caused a decline in grain production. However, the latter has steadily increased since 2008 (Fig. 4a). The EAEN regime shifts were divided into three phases, namely, 1985–1998 (phase I), 1999–2007 (phase II), and 2008–2017 (phase III) and were based on the transitions in grain productivity. Interactions among the nexus sectors differed among the three phases (Fig. 5). In phase I, aggressive agricultural reclamation increased grain productivity and economic profit but had a negative impact on vegetation cover and NPP and resulted in soil loss. In phase II, massive ecosystem restoration efforts substantially restored vegetation, enhanced carbon sequestration,

and reduced soil loss. However, there were negative trade-offs between the agricultural production/economic and ecological sectors. In phase III, there was synergy or positive feedback among all three sectors, the ERPs and the other interventions concurrently sustained the ecosystem, farmer livelihood was improved, and grain productivity increased.

Causes of EAEN evolution and regime shifts

Policy adjustment was a major cause of the regime shift from phase II to phase III in EAEN. The ecosystem restoration efforts suspended the conversion of cropland to woodland and grassland, ensured sufficient cropland area for grain production, and safeguarded the food supply. Afforestation projects and the suspension of hillside cultivation promoted ecosystem restoration. Field terracing and other agricultural production techniques have significantly progressed since 2005 (Fig. 6). These developments were reflected by increases in power, fertilizer, plastic film, diesel, and pesticide consumption and eventually in grain production as well (Fig. 6).

Local governments and communities encouraged residents affected by RCWG to plant oil crops, peanuts, sugarcane, flue-cured tobacco, and other cash crops to develop the livestock industry. They also guided residents in the cultivation of forest products such as tea, fruit, timber, bamboo, pine resin, palm flake, and chestnuts to increase economic profit and compensate for the economic loss incurred as a result of investment in RCWG. Figure 4b–d shows that crop productivity and yield and the proportions of cash crops gradually but significantly increased between 1985 and 2017. However, grains accounted for the largest proportion of all crops. Livestock (meat, milk, and eggs) and forest (tea, fruit, timber, bamboo, pine resin, chestnuts, and palm flake) products rapidly increased (Fig. 4e−h). Ecological, economic, and timber forest accounted for > 80% of the total afforestation area before 2010 (Fig. S1(b)), increased the economic benefits of afforestation, and enhanced farmer engagement in afforestation projects. The RCWG projects did not alter increasing trends in GDP or resident income or expenditure (Fig. 7a and d). The proportion of agriculture has significantly declined since 1985 (Fig. 7b, c). Formerly predominant agriculture was gradually replaced by animal husbandry, but both accounted for ~ 40% in 2017. The RCWG projects caused an abrupt decreases and increases in the agricultural and non-agricultural populations, respectively, by 2002 (Fig. 7e). Therefore,

Fig. 4 Temporal variations in **a** grain productivity, **b**–**d** cash crop productivity and their proportions in total productivity, and **e**–**h** livestock and forest product productivity
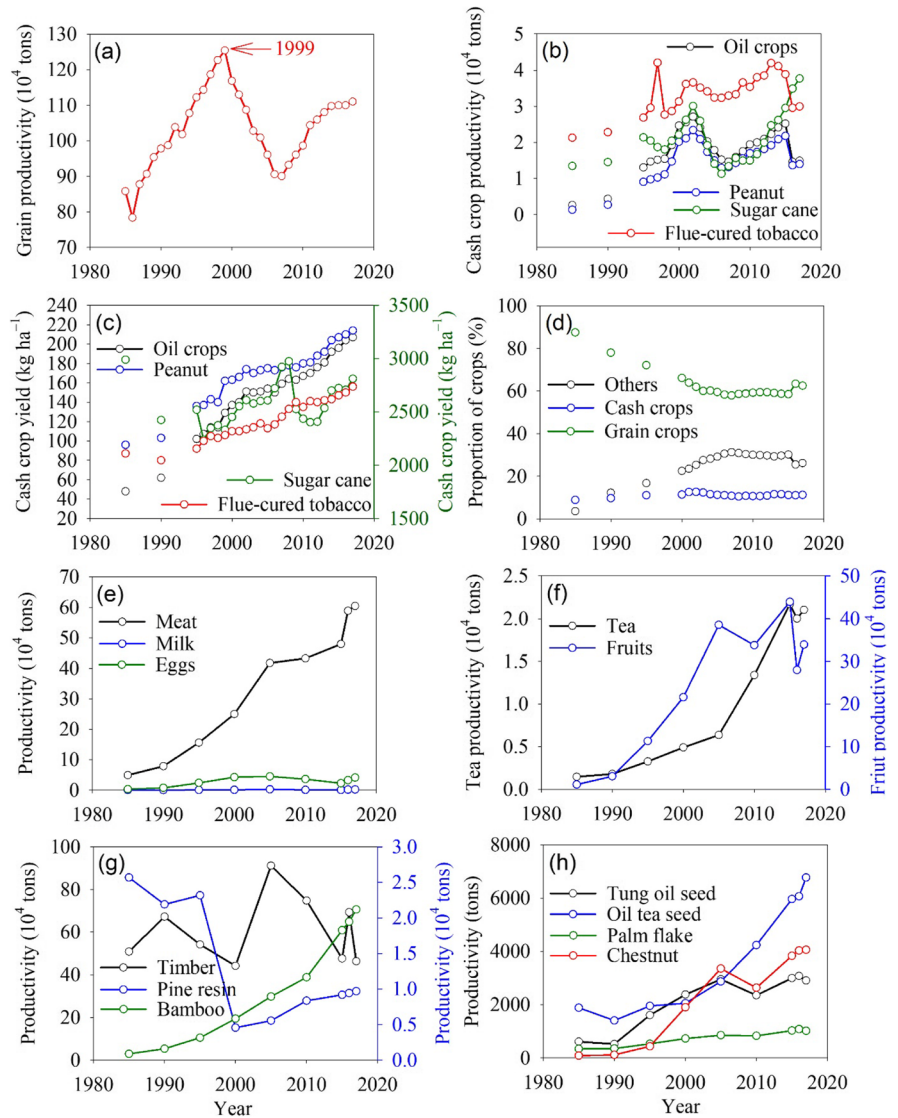
the industrial structure of Longyan City was transformed from agriculture to diversified industries and the compositions of the economic output, income, and population changed accordingly.

Discussion

Strengths of EAEN-based LDN under theoretical SES framework

Existing ecosystem restoration efforts include afforestation, reforestation, and other revegetation practices that outweigh direct ecological effects such as soil loss control, carbon sequestration, and biodiversity maintenance. Nevertheless, they do not address resident livelihood, agricultural production, or the interactions among EAEN sectors driven by external interventions and policy adjustments (Cao et al., 2017, 2018, 2020). The Natural Forest Conservation Project does not propose or implement adaptive strategies that ensure socioeconomic development after LUC conversion from cropland to woodland and grassland (Cao et al., 2017). Woodland and grassland reduce the area of cropland available for agricultural production and its associated goods and economic
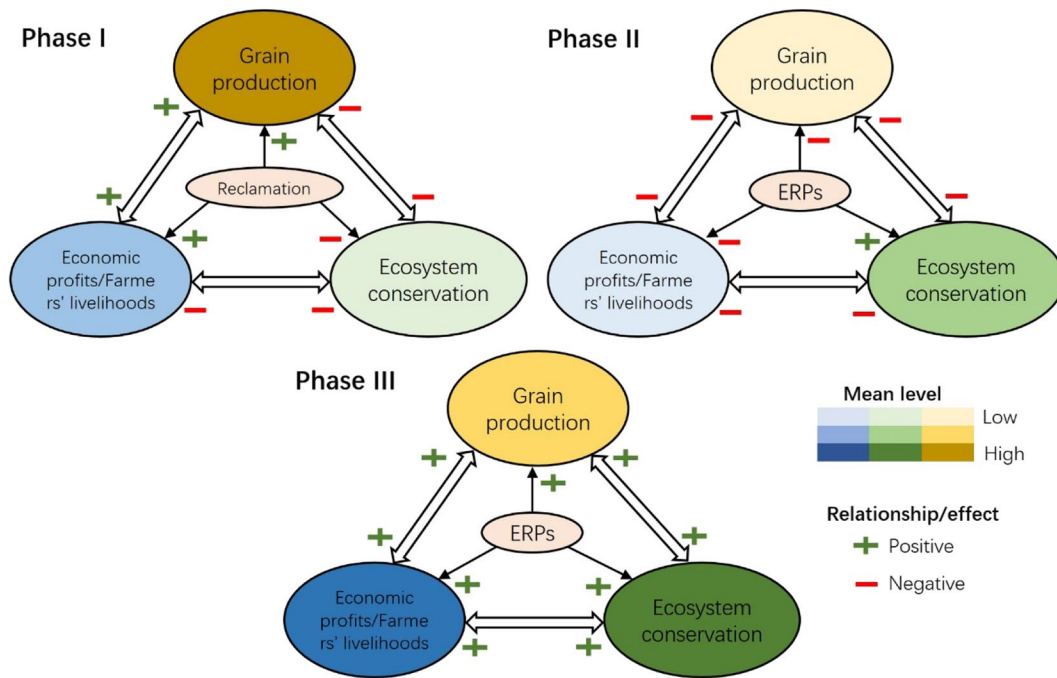
Fig. 5 Evolution of EAEN and its interactions in various ecosystem restoration phases: **a** phase I, 1985–1998; **b** phase II, 1999–2007; and **c** phase III, 2008–2017

benefits, threaten short-term profit for local farmers and communities, and impede the long-term success of ecosystem conservation and restoration efforts. The lack of timely policy interventions to sustain agricultural production and farmer livelihood attenuated the expected benefits of the Three Norths Shelterbelt Project initiated in 1978 (Cao et al., 2017, 2018, 2020). This project reduced cropland and provided subsidies to mitigate the economic losses incurred by farmers. However, the latter did not have new types of employment. Moreover, the subsidies disbursed during the implementation of the ecological resettlement project did not suffice to improve the livelihoods of the farmers participating in it (Zhong et al., 2013). Some resettled farmers supplemented their income by engaging in unsustainable agricultural reclamation and other activity when the basic subsidies provided by the governments were no longer available (Cao et al., 2017). Poverty alleviation and ecosystem restoration are closely associated because the ecosystem itself is the source of resident income and ESs. LUC conversions directly determine the interactions between ecological (ERP efficacy) and economic (farmer livelihood) benefits. Hence,

poverty alleviation and ecosystem restoration must be simultaneously addressed in a coordinated manner (Cao et al., 2017, 2018, 2020).

The present case study in Longyan City demonstrated that the ERPs in the RCWG context delivered ecosystem restoration-agricultural production-livelihood co-benefits by integrating EAEN evolution with LDN efforts under the SES framework. This win-win strategy balanced the requirements of ecosystem conservation, grain production, and resident livelihood. ERPs rely upon the engagement of institutions, private enterprises, communities, non-governmental organizations (NGOs), and local residents as they invest in ecological industries and create employment for residents (Cao et al., 2018, 2020; Feng et al., 2019). This new approach increases the likelihood of achieving LDN targets through positive engagement of the residents and advancements in economic benefits and farmer livelihood.

The adaptive, co-benefiting SES-based LDN approach is more transparent and comprehensive than the traditional "command-and-control" governance procedure. The former incorporates a wide variety of theoretical and practical ecological knowledge, fosters

Fig. 6 Temporal changes in agricultural production conditions between 2005 and 2017: power, fertilizer, plastic film, diesel, and pesticide consumption
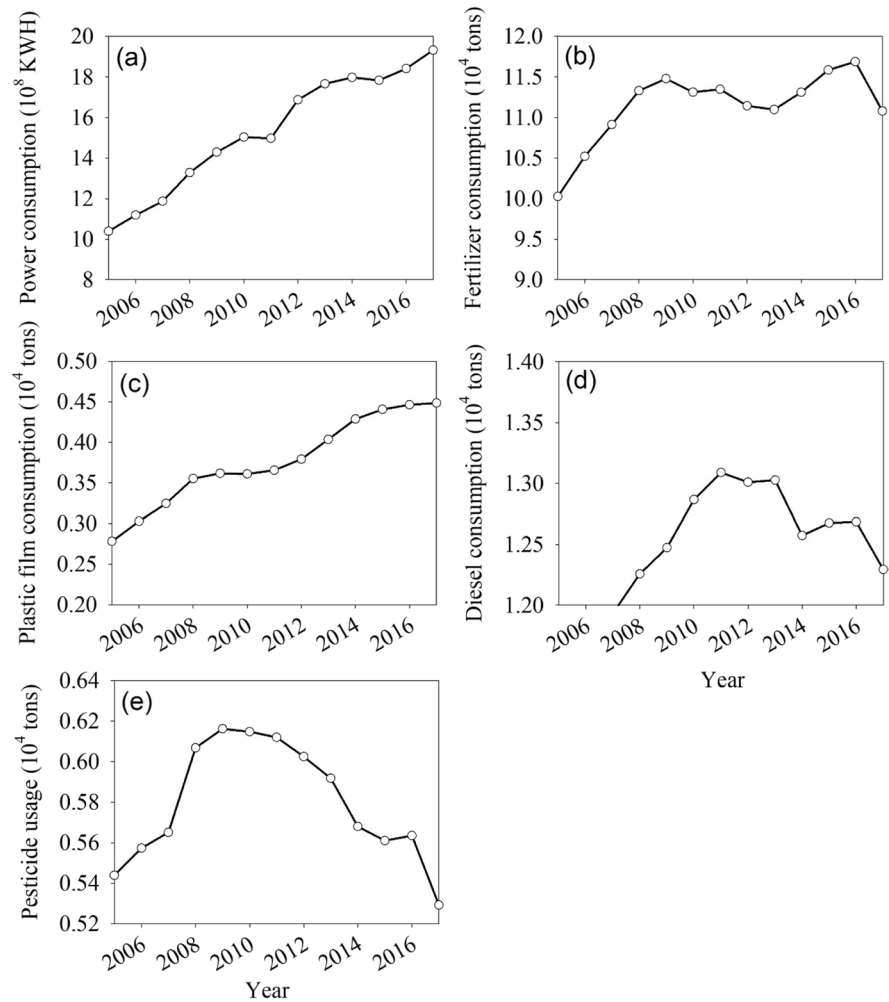
early, positive engagements of multiple stakeholders, and encourages collaboration among land managers and users in decision-making and implementation. A prerequisite for the realization of the LDN target via the SES approach is to consider humans as a part of nature rather than a compartment separate from it. This strategy reflects the functions of humans in nature, influences the perceived roles of human activity in environmental change, and facilitates the achievement and maintenance of a secure, well-functioning environment (Gómez-Baggethun et al., 2013; Verburg et al., 2015). Human activity alters LUC and land use management practices. Socioecological feedback is determined by various human interventions such as ERPs and SWCPs as well as societal beliefs and perceptions and the evaluation and interpretation of land resources (Braito et al., 2017; Okpara et al., 2018; Reed et al., 2010).

The EAEN-based LDN under the SES framework identifies regime shifts in the ERPs from a systematic planning perspective. It incorporates multiple sectors and their interactions and guides the adjustment and optimization of ecosystem restoration practices. During the initial ERP period of 1999–2007 in the study region, massive afforestation/reforestation projects facilitated ecosystem restoration but reduced the total area of cropland available for agricultural production, caused a rapid decline in grain productivity, and diminished food security (Fig. 4a). As of 2008, however, the relationship between ecosystem restoration and grain production has shifted from trade-off to synergy because of adjustments in the RCWG policy, terrace construction, and improvements in agricultural production conditions. The foregoing measures gradually reconciled the cropland shortage. This

Fig. 7 Temporal changes in **a** per capita GDP, **b–c** economic output value composition, **d** resident income and expenditure, and **e** population composition
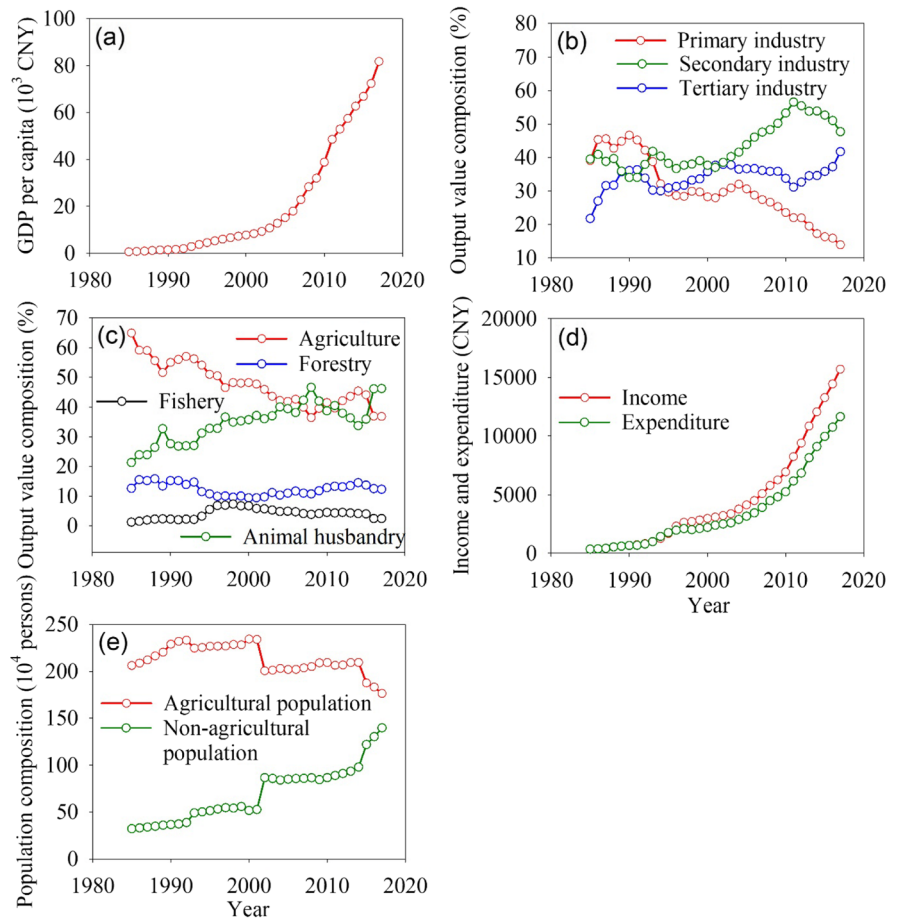
regime shift demonstrated the advantages of EAEN coordinating multiple dimensions. It optimized targeted ecosystem restoration for specific ERP phases from the systematic perspective of the SES framework. It also showed that phase shift timings must be identified to adopt policy regulations and other interventions that will help ensure food and ecological security and stabilize resident livelihood.

Limitations and applications of the EAEN-based LDN approach

In summary, the EAEN approach under the SES framework systemically integrates ecosystems, agriculture, and the economy, guarantees livelihoods, and offers a more inclusive and comprehensive perspective for LDN including social and ecological dimensions. The systematic SES-based LDN approach provides a more comprehensive insight of social and ecological aspects of LDN efforts, examining their

multi-scale dynamics, interactions (i.e., synergies and trade-offs), and processes, which are of vital importance to redirect LDN scheme beyond practices that are perceived as occurring in a static context, and substantially advance systemic processes that combat current degradation challenges (Okpara et al., 2018). However, it has certain limitations. It is unclear which types of SES factors are important or how remote social systems undermine the capacity of local communities to regulate their land systems (Chazée et al., 2017). In addition, it is still absolutely necessary to gain an understanding of what kind of social-ecological factors matter, and how to incorporate social data into LDN planning with an assistance of elaborate spatially explicit datasets, which guarantees that socio-cultural priorities can be distinctly articulated in spatiotemporal terms (Verburg et al., 2015). The current LDN scheme is static, prescriptive, and technical and does not fully consider the multi-scale dynamics, interactions, and processes involved in

LDN efforts (Safriel, 2017). Hence, the dynamics, social preferences and attitudes, and trade-offs among multiple LDN targets must be included (Okpara et al., 2018). There have been very few instances of the successful practical application of SES-based LDN theory (Braito et al., 2017). Little guidance exists on how to move from recognition of the need to address SES aspects of land systems, to incorporating these into LDN planning (Reed et al., 2015). Thus, restoration practices must be able to transition from addressing the SES aspects of land systems to incorporating them in ERP planning.

Traditional ecological knowledge (TEK) of the local population is vital in the EAEN-based LDN approach and should be integrated to improve ERP efficacy. TEK is normally derived from the direct experience of the local people through land-related livelihood practices and culturally transmitted across generations (Chazée et al., 2017; Okpara et al., 2018; Reed et al., 2010). Local TEK may enable policymakers and planners to understand land degradation and the factors driving it and help them enforce and adjust restoration practices. Therefore, the inclusion of TEK in SES-based LDN may facilitate ecosystem restoration efforts and substantially contribute to the success of LDN (Akhtar-Schuster et al., 2017; Alagona et al., 2012; Braito et al., 2017).

The ecosystem-agriculture-economy co-benefits of the LDN efforts achieved through adaptive policy adjustments in the Longyan City scenario is applicable to other regions that are also negatively impacted by land degradation. Comparable success may be achieved if managers and policymakers clearly understand the specific environmental conditions and the socioeconomic requirements of the residents affected by ecosystem restoration efforts (Akhtar-Schuster et al., 2017). Managers and policymakers should first identify the unique, vital local resources that may be cultivated, developed, and industrialized. They must then identify the principal factors interfering with sustainable socioeconomic development and the establishment and maintenance of healthy ecosystems (Braito et al., 2017; Feng et al., 2019).

Existing deficiencies and further improvements of ERP and LDN efforts

The ERPs initiated in Longyan City in 1999 were relatively effective at mitigating soil erosion. The average erosion modulus between 1999 and 2017 was lower than that between 1985 and 1998 (Fig. 3c). However, there were certain deficiencies in this approach. The overall forest cover in the red soil hilly area was high but the soil nutrient levels in the severely eroded woodland areas were low and the soil structures were poor (Chen et al., 2020). Hence, it was difficult for vegetation to establish there (Cao et al., 2017, 2018). The understory vegetation was inadequate and consisted of a single plant species (Zhong et al., 2013). Low biodiversity levels aggravate soil erosion (Fig. 8; Li et al., 2020; Wang et al., 2020). During afforestation, the original topography and vegetation are destroyed, the woodland soil is loose, and the cohesive force of the soil is attenuated (Fig. 8a). If protective understory vegetation is lacking, soil erosion may readily occur (Feng et al., 2020; Li et al., 2020). Excessive fuelwood harvesting and litter layer removal reduce nutrient return and diminish soil quality and erosion resistance (Wang et al., 2020). Forest vegetation plays a vital role in soil erosion control. The lack of understory vegetation results in the inability to restrain slope runoff (Chen et al., 2020). Therefore, tree growth should be promoted, optimal canopy density should be maintained, the vertical structure of forest vegetation should be developed, and understory vegetation should be restored to reduce soil erosion. In this manner, soil nutrient content and water retention may be improved in the eroded area and ecological restoration can be promoted (Li et al., 2020). Soil fertility should also be enhanced through chemical and organic fertilizers. Soil structure and quality should be improved by applying soil conditioners that effectively control erosion.

LDN efforts and ERPs must enable timely monitoring of the interactions among ecological and economic benefits and their regime shifts (Fig. 9). These are determined by financial investments in ecosystem conservation, socioeconomic variables, and other interventions and they play critical roles in maintaining SES and ERP sustainability (Feng et al., 2020; Li et al., 2020; Wang et al., 2020). SES predevelopment is characterized by ecosystem restoration and LDN (phase I in Fig. 9). Ecological and economic benefits may increase concurrently depending upon environmental conditions and ecosystem restoration practices. In this phase, the ecological benefits exceeded the economic profits and the ERPs were
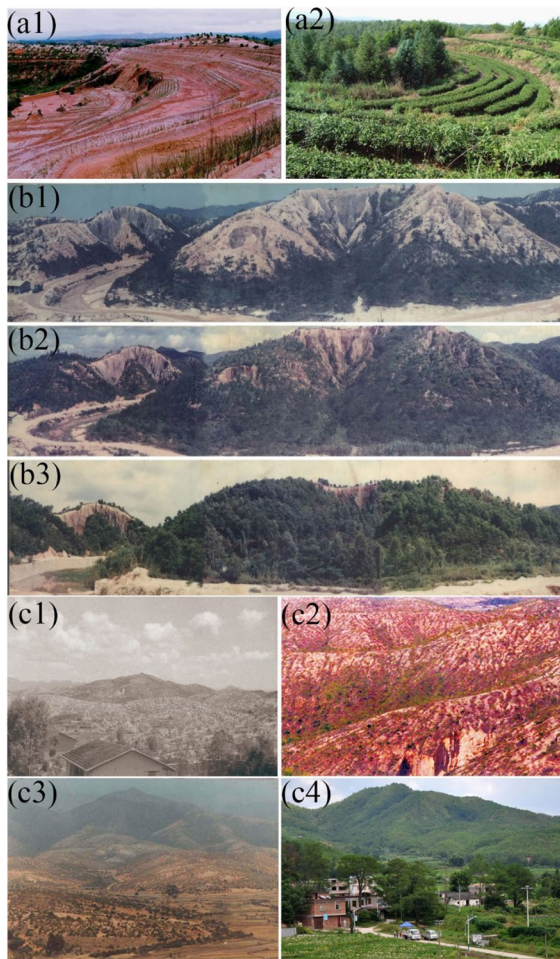
Fig. 8 Representative ERP case area in hilly red soil region of southern China: **a** land degradation and restoration in Changting County, Longyan City (Zhong et al., 2013); **b** ecological restoration in Zhuhai City, Guangdong Province (Zhuang et al., 2021); and **c** ecosystem restoration progress in Changting County, Longyan City

application of soil conditioners, the cultivation of green manure crops, the administration of chemical fertilizers, and topographic reconstruction such as terracing. The foregoing practices enhance nutrient supply and water retention and ensure long-term ERP sustainability (Chen et al., 2020; Yuan et al., 2020). In contrast, unfavorable human interventions such as soil quality degradation caused by agricultural reclamation, deforestation, inappropriate afforestation practices, and urbanization mitigate ecological benefits, upset the ecological-economic balance, and offset ERP efficacy (Chen et al., 2020; Yuan et al., 2020).

Future ERPs should focus on long-term governance integrity, concentrate on improving the ecological function of the forest community, and endeavor to realize regional medium- and long-term ecosystem conservation objectives. Close attention must be paid to the dynamics of ecological and economic elements such as natural supply and societal demand as well as the balance between them driven by climatic fluctuations and socioeconomic disturbances including industrial structure transformation, population growth, and urban expansion. In this manner, land management strategies may be adjusted in a timely manner to promote ecosystem restoration and facilitate achievement of the LDN target.

Conclusions

This study quantified the soil loss dynamics and EAEN evolution from 1985 to 2017 based upon RUSLE and CASA approaches and explored the regime shifts of nexus sectors and their interactions and drivers from EAEN-based LDN perspective under SES framework. The study concluded that ERPs promoted vegetation restoration and carbon sequestration, and substantially reduced soil loss. Although ERPs initially reduced grain productivity, the timely and effective policy regulation and the positive engagement of residents in ERPs reconciled the trade-offs between grain production and environmental conservation, improved agricultural production capacity, and ensured food security. The present study demonstrated that the EAEN-based LDN strategy under the SES framework achieved co-benefits in the form of ecosystem restoration, agricultural production, and livelihood improvement. Moreover, this approach is transferable to

healthy. In phase II, the economic profits rapidly surpassed the ecological benefits but the ERPs nonetheless remained at the sustainable development stage. The subsequent rapid increase in economic profits induced by aggressive, exploitative activity caused the economic profits to outstrip the ecological benefits. Thus, the regime was no longer in equilibrium and it entered the reversibly unsustainable development stage (phase III) followed by the irreversibly unsustainable development stage (phase IV). Favorable human interventions include positive, efficacious ecosystem restoration practices such as the

Fig. 9 Regime shifts in ecological benefits and economic profit in SES under LDN context
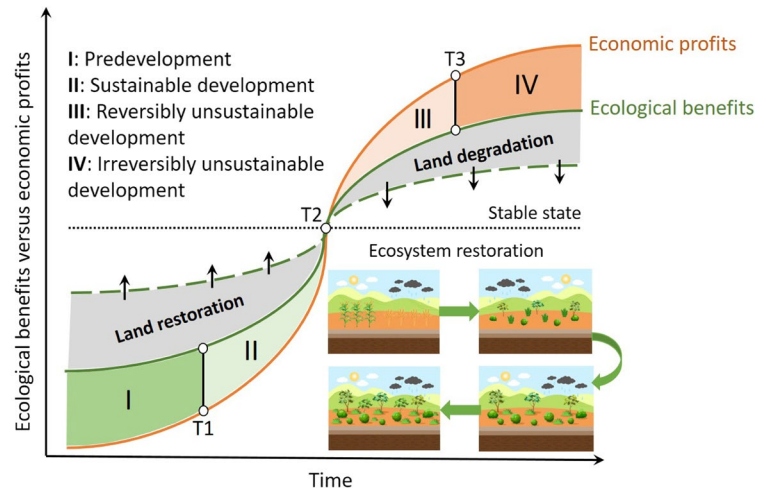
Ecological benefits = f (vegetation cover, ERPs and SWCPs, and other interventions)
Economic profits = f (industrial structure, population size, investment, others)

other regions affected by land degradation. A systematic EAEN-based LDN approach is inclusive, transparent, and comprehensive, integrates social and ecological demands, and may avert potential conflicts and trade-offs between them. It emphasizes the dynamic and evolving interactions and processes and the social and ecological consequences associated with positive and negative policy interventions. The foregoing factors are essential for re-orienting LDN efforts beyond a static, prescriptive, and technical context. However, further investigation into the EAEN-based LDN approach is required to identify and explain the social-ecological factors affecting co-benefits for ecosystem restoration and resident livelihood as well as the contributions of perceptions, preferences, values, and stakeholder engagement to nexus evolution. Future research should also attempt to incorporate SES strategies into systematic LDN planning and actions, achieve and maintain SES resilience, and sustain LDN targets.

Data availability All obtained data during this work are included in this manuscript.

Declarations

Ethics approval All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors and are aware that, with minor exceptions, no changes can be made to authorship once the paper is submitted.

Competing interests The authors declare no competing interests.

References

Abera, W., Tamene, L., Tibebe, D., Adimassu, Z., Kassa, H., Hailu, H., Mekonnen, K., Desta, G., Sommer, R., & Verchot, L. (2019). Characterizing and evaluating the impacts of national land restoration initiatives on ecosystem services in Ethiopia. *Land Degradation and Development, 31*, 37–52.

Adams, C., Rodrigues, S. T., Calmon, M., & Kumar, C. (2016). Impacts of large-scale forest restoration on socioeconomic

status and local livelihoods: What we know and do not know. *Biotropica, 48*(6), 731–744.

Akhtar-Schuster, M., Stringer, L., Erlewein, A., Metternicht, G., Minelli, S., Safriel, U., & Sommer, S. (2017). Unpacking the concept of land degradation neutrality and addressing its operation through the Rio Conventions. *Journal of Environmental Management, 195*(Part 1), 4–15.

Alagona, P., Sandlos, J., & Wiersma, Y. (2012). Past imperfect: Using historical ecology and baseline data for conservation and restoration projects in North America. *Environmental Philosophy, 9*(1), 49–70.

Arsénio, P., Rodriguez-Gonzalez, P. M., Bernez, I., Dias, F. S., Bugalho, M. N., & Dufour, S. (2020). Riparian vegetation restoration: does social perception reflect ecological value? *River Research and Applications*. https://doi.org/10.1002/rra.3514

Barkemeyer, R., Stringer, L. C., Hollins, J. A., & Josephi, F. (2015). Corporate reporting on solutions to wicked problems: Sustainable land management in the mining sector. *Environmental Science & Policy, 48*, 196–209.

Bednarska, A. J., Wyżga, B., Mikuś, P., & Kędzior, R. (2018). Ground beetle communities in a mountain river subjected to restoration: The Raba River, Polish Carpathians. *Science of the Total Environment, 610-611*, 1180–1192.

Braito, M. T., Bock, K., Flint, C., Muhar, A., Muhar, S., & Penker, M. (2017). Human-nature relationships and linkages to environmental behaviour. *Environmental Values, 26*, 365–389.

Buisson, E., Jaunatre, R., Regnery, B., Lucas, M., Alignan, J. F., Heckenroth, A., Muller, I., Bernez, I., Combroux, I., Moussard, S., Glasser, T., Jund, S., Lelievre, S., Malaval, S., Vecrin-Stablo, M. P., & Gallett, S. (2018). Promoting ecological restoration in France: Issues and solutions. *Restoration Ecology, 26*, 36–44.

Cao, S., Shang, D., Yue, H., & Ma, H. (2017). A win–win strategy for ecological restoration and biodiversity conservation in southern China. *Environmental Research Letters, 12*, 044004.

Cao, S., Xia, C., Li, W., & Xian, J. (2020). Win–win path for ecological restoration. *Land Degradation and Development, 1–9.* https://doi.org/10.1002/ldr.3739

Cao, S., Xia, C., Yue, H., Ma, H., & Lin, G. (2018). Targeted control measures for ecological restoration in Western Fujian, China. *Land Use Policy, 76*, 186–192.

Chasek, P., Safriel, U., Shikongo, S., & Fuhrman, V. F. (2015). Operationalizing zero net land degradation: The next stage in international efforts to combat desertification? *Journal of Arid Environments, 112*, 5–13.

Chazée, L., Requier-Desjardins, M., Ghouat, N., & El Debs, R. (2017). La planification locale, outil de durabilité environnementale: le cas des zones humides méditerranéennes. *New Mediterr, 16*(1), 62–72.

Chen, A., Li, R., Wang, H., & He, B. (2015). Quantitative assessment of human appropriation of aboveground net primary production in China. *Ecological Modelling, 312*, 54–60.

Chen, J., Xiao, H., Li, Z., Liu, C., Ning, K., & Tang, C. (2020). How effective are soil and water conservation measures (SWCMs) in reducing soil and water losses in the red soil hilly region of China? A meta-analysis of field plot data. *Science of the Total Environment, 735*, 139517.

Chen, P., Shang, J., Qian, B., Jing, Q., & Liu, J. (2017). A new regionalization scheme for effective ecological restoration on the Loess Plateau in China. *Remote Sensing, 9*, 1323.

Cowie, A. L., Orr, B. J., Castillo Sanchez, V. M., Chasek, P., Crossman, N. D., Erlewein, A., Louwagie, G., Maron, M., Metternicht, G. I., Minelli, S., Tengberg, A. E., Walter, S., & Welton, S. (2018). Land in balance: The scientific conceptual framework for Land Degradation Neutrality. *Environmental Science & Policy, 79*, 25–35.

Danneyrolles, V., Dupuis, S., Arseneault, D., Terrail, R., Leroyer, M., Römer, A., Fortin, G., Boucher, Y., & Ruel, J. C. (2017). Eastern white cedar long-term dynamics in eastern Canada: Implications for restoration in the context of ecosystem-based management. *Forest Ecology and Management, 400*, 502–510.

Duan, X., Bai, Z., Li, R., Li, Y., Ding, J., Tao, Y., Li, J., Li, J., & Wang, W. (2020). Investigation method for regional soil erosion based on the Chinese Soil Loss Equation and high-resolution spatial data: Case study on the mountainous Yunnan Province, China. *Catena, 184*, 104237.

FAO. (2019). *Soil erosion: The greatest challenge to sustainable soil management*. Food and Agriculture Organization of the United Nations.

Feng, Q., Tian, Y., Yu, T., Yin, Z., & Cao, S. (2019). Combating desertification through economic development in northwestern China. *Land Degradation and Development, 30*, 910–917.

Feng, S., Wu, L., Liang, B., Wang, H., Liu, H., Zhu, C., & Li, S. (2020). Forestation does not necessarily reduce soil erosion in a karst watershed in southwestern China. *Progress in Physical Geography, 1–16*.

Ferreira, C., Pereira, P., & Kalantari, Z. (2018). Human impacts on soil. *Science of the Total Environment, 644*, 830–834.

Fischer, J., Gardner, T., Bennett, E., Balvanera, P., Biggs, R., Carpenter, S., Daw, T., Folke, C., et al. (2015). Advancing sustainability through mainstreaming a social-ecological systems perspective. *Current Opinion in Environment Sustainability, 14*, 144–149.

Gardner, C. J., Bicknell, J. E., Baldwin-Cantello, W., Struebig, M. J., & Davies, Z. G. (2019). Quantifying the impacts of defaunation on natural forest regeneration in a global metaanalysis. *Nature Communications, 10*, 4590.

Gómez-Baggethun, E., Corbera, E., & Reyes-García, V. (2013). Traditional ecological knowledge and global environmental change: Research findings and policy implications. *Ecology and Society, 18*(4), 72.

Hausner, M. B., Huntington, J. L., Nash, C., Morton, C., McEvoy, D. J., Pilliod, D. S., Hegewisch, K. C., Daudert, B., Abatzoglou, J. T., & Grant, G. (2018). Assessing the effectiveness of riparian restoration projects using Landsat and precipitation data from the cloud computing application ClimateEngine.org. *Ecological Engineering, 120*, 432–440.

Hruska, T., Toledo, D., Sierra-Corona, R., & Solis-Garcia, V. (2017). Social–ecological dynamics of change and restoration attempts in the Chihuahuan Desert grasslands of Janos Biosphere Reserve, Mexico. *Plant Ecology, 218*, 67–80.

Hu, S., Ma, R., Sun, Z., Ge, M., Zeng, L., Huang, F., Bu, J., & Wang, Z. (2021). Determination of the optimal ecological water conveyance volume for vegetation restoration in an arid inland river basin, northwestern China. *Science of the Total Environment, 788*, 147775.

Jiang, C., Zhang, H., Wang, X., Feng, Y., & Lev, L. (2019a). Challenging the land degradation in China's Loess Plateau: Benefits, limitations, sustainability, and adaptive strategies of soil and water conservation. *Ecological Engineering, 127*, 135–150.

Jiang, C., Zhang, H., Zhang, Z., & Wang, D. (2019b). Model-based assessment soil loss by wind and water erosion in China's Loess Plateau: Dynamic change, conservation effectiveness, and strategies for sustainable restoration. *Global and Planetary Change, 172*, 396–413.

Kendall, M. G. (1975). *Rank-correlation Measures* (p. 202). Charles Griffin.

Kust, G., Andreeva, O., & Cowie, A. (2017). Land degradation neutrality: Concept development, practical applications and assessment. *Journal of Environmental Management, 195*, 16–24.

Leslie, H., Basurto, X., Nenadovic, M., Sievanen, L., Cavanaugh, K., Cota-Nieto, J., Erisman, B., Finkbeiner, E., Hinojosa-Arango, G., Moreno-Báez, M., Nagavarapu, S., Reddy, S., et al. (2015). Operationalizing the social-ecological systems framework to assess sustainability. *PNAS, 112*(19), 5979–5984.

Li, H., Wu, Y., Liu, S., & Xiao, J. (2021). Regional contributions to interannual variability of net primary production and climatic attributions. *Agricultural and Forest Meteorology, 303*, 108384.

Li, Z., Ning, K., Chen, J., Liu, C., Wang, D., Nie, X., Hu, X., Wang, L., & Wang, T. (2020). Soil and water conservation effects driven by the implementation of ecological restoration projects: Evidence from the red soil hilly region of China in the last three decades. *Journal of Cleaner Production, 260*, 121109.

Liu, J., Kuang, W., Zhang, Z., Xu, X., Qin, Y., Ning, J., Zhou, W., Zhang, S., Li, R., Yan, C., Wu, S., Shi, X., Jiang, N., Yu, D., Pan, X., & Chi, W. (2014). Spatio-temporal characteristics, patterns and causes of land-use changes in China since the late 1980s. *Journal of Geographical Sciences, 24*(2), 195–210.

Lu, Z., Feng, Q., Xiao, S., Xie, J., Zou, S., Yang, Q., & Si, J. (2021). The impacts of the ecological water diversion project on the ecology-hydrology-economy nexus in the lower reaches in an inland river basin. *Resources, Conservation and Recycling, 164*, 105154.

Mace, G. M., Barret, M., Burgess, N. D., Cornell, S. E., Freeman, R., Grooten, M., & Purvis, A. (2018). Aiming higher to bend the curve of biodiversity loss. *Nature Sustainability, 1*, 448–451.

Mann, H. B. (1945). Non-parametric tests against trend. *Econometrica, 13*, 245–259.

Nkonya, E., Anderson, W., Kato, E., Koo, J., Mirzabaev, A., von Braun, J., & Meyer, S. (2016). Global cost of land degradation. In E. Nkonya, A. Mirzabaev, & J. von Braun (Eds.), *Economics of land degradation and improvement – a global assessment for sustainable development*. Springer.

Okpara, U. T., Stringer, L. C., Akhtar-Schuster, M., Metternicht, G. I., Dallimer, M., & Requier-Desjardins, M. (2018). A social-ecological systems approach is necessary to achieve land degradation neutrality. *Environmental Science & Policy, 89*, 59–66.

Orr, B. J., Cowie, A. L., Castillo Sanchez, V. M., Chasek, P., Crossman, N. D., Erlewein, A., Louwagie, G., Maron, M., Metternicht, G. I., Minelli, S., Tengberg, A. E., Walter, S., & Welton, S. (2017). *Scientific conceptual framework for land degradation neutrality. A Report of the Science-Policy Interface*. United Nations Convention to Combat Desertification (UNCCD).

Ostrom, E. (2010). Polycentric systems for coping with collective action and global environmental. *Global Environmental Change Part A, 20*, 550–557.

Ouyang, Z., Zheng, H., Xiao, Y., Polasky, S., Liu, J., Xu, W., Wang, Q., Zhang, L., Xiao, Y., Rao, E., Jiang, L., Lu, F., Wang, X., Yang, G., Gong, S., Wu, B., Zeng, Y., Yang, W., & Daily, G. C. (2016). Improvements in ecosystem services from investments in natural capital. *Science, 352*(6292), 1455–1459.

Palomo, I., Martin-Lopez, B., Lopez-Santiago, C., & Montes, C. (2011). Participatory scenario planning for protected areas management under the ecosystem services framework: the Donana social–ecological system in Southwestern Spain. *Ecology and Society, 16*(1), 23.

Panagos, P., Borrelli, P., Poesen, J., Ballabio, C., Lugato, E., Meusburger, K., Montanarella, L., & Alewell, C. (2015). The new assessment of soil loss by water erosion in Europe. *Environmental Science & Policy, 54*, 438–447.

Pasquale, B., David, A. R., Panos, P., Emanuele, L., Jae, E. Y., Christine, A., David, W., Luca, M., & Cristiano, B. (2020). Land use and climate change impacts on global soil erosion by water (2015-2070). *Proceedings of the National Academy of Sciences*. https://doi.org/10.1073/pnas.2001403117

Pereira, P., Barcelo, D., & Panagos, P. (2020). Soil and water threats in a changing environment. *Environmental Research, 186*, 109501.

Pereira, P., Bogunovic, I., Munoz-Rojas, M., & Brevik, E. (2018). Soil ecosystem services, sustainability, valuation and management. *Current Opinion in Environment Sustainability, 5*, 7–13.

Potter, C. S., Randerson, J. T., Field, C. B., Matson, P. A., Vitousek, P. M., Mooney, H. A., & Klooster, S. A. (1993). Terretrial ecosystem production: A process model based on global satellite and surface data. *Global Biogeochemical Cycles, 7*, 811–841.

Reed, M. S., Evely, A. C., Cundill, G., Fazey, I., Glass, J., Laing, A., Newig, J., Parrish, B., Prell, C., Raymond, C., & Stringer, L. C. (2010). What is social learning? *Ecology and Society, 15*, r1.

Reed, M. S., & Stringer, L. C. (2016). *Land degradation, desertification and climate change: anticipating, assessing and adapting to future change*. Routledge.

Reed, M. S., Stringer, L. C., Dougill, A. J., Perkins, J. S., Atlhopheng, J. R., Mulale, K., & Favretto, N. (2015). Reorienting land degradation towards sustainable land management: Linking sustainable livelihoods with ecosystem services in rangeland systems. *Journal of Environmental Management, 151*, 472–485.

Safriel, U. (2017). Land degradation neutrality in drylands and beyond – where has it come and where does it go. *Silva Fennica, 15*(1B), 1–19.

Sanchez Meador, A., Springer, J. D., Huffman, D. W., Bowker, M. A., & Crouse, J. E. (2017). Soil functional

responses to ecological restoration treatments in frequent-fire forests of the western United States: A systematic review. *Restoration Ecology, 25*, 497–508.

Sietz, D., Fleskens, L., & Stringer, L. (2017). Learning from non-linear ecosystem dynamics is vital for achieving land degradation neutrality. *Land Degradation and Development, 28*, 2308–2314.

Sims, N. C., Green, C., Newnham, G. J., England, J. R., Held, A., Wulder, M. A., Herold, M., Cox, S. J. D., Huete, A. R., Kumar, L., Viscarra Rossel, R. A., Roxburgh, S. H., & McKenzie, N. J. (2017). Good Practice Guidance. In *SDG Indicator 15.3.1, Proportion of land that is degraded over total land area* (p. 115). United Nations Convention to Combat Desertification (UNCCD).

Sousa, J. S. C., & Srbek-Araujo, A. C. (2017). Are we headed towards the defaunation of the last large Atlantic Forest remnants? Poaching activities in one of the largest remnants of the Tabuleiro forests in southeastern Brazil. *Environmental Monitoring and Assessment, 189*, 129.

Staentzel, C., Combroux, I., Barillier, A., Grac, C., Chanez, E., & Beisel, J. N. (2019). Effects of a river restoration project along the Old Rhine River (France-Germany): Response of macroinvertebrate communities. *Ecological Engineering, 127*, 114–124.

Stavi, I., & Lal, R. (2015). Achieving zero net land degradation: Challenges and opportunities. *Journal of Arid Environments, 112*, 44–51.

Sun, W., Song, X., Mu, X., Gao, P., Wang, F., & Zhao, G. (2015). Spatiotemporal vegetation cover variations associated with climate change and ecological restoration in the Loess Plateau. *Agricultural and Forest Meteorology, 209–210*, 87–99.

Taniguchi, T., & Yamanaka, N. (2017). Revegetation of a degraded ecosystem in dry environments: Experiences from China. In *Twelfth International Dryland Development Conference, "Sustainable Development of Drylands in the Post 2015 World," Alexandria, Egypt, 21–24 August 2016* (pp. 219–224). International Dryland Development Commission (IDDC).

Torday, J. S., & Miller, W. B. (2015). Man is integral with nature. *Mind Nat J, 8*(1), 37–44.

UNCCD. (2016). *Reporting Manual: Performance Review and Assessment of Implementation System (PRAIS)*. UNCCD.

United Nations. (2015). *Transforming our world: the 2030 Agenda for Sustainable Development*. Resolution adopted by the United Nations General Assembly on 25 September 2015 (A/RES/70/1).

Verburg, P., Crossman, N., Ellis, E., Heinimann, A., Hostert, P., Mertz, O., Nagendra, H., et al. (2015). *Anthropocene, 12*, 29–41.

Virapongse, A., Brooks, S., Metcalf, E., Zedalis, M., Gosz, J., Kliskey, A., & Alessa, L. (2016). A social-ecological systems approach for environmental management. *Journal of Environmental Management, 178*, 83–91.

Wang, L., Yan, H., Wang, X., Wang, Z., Yu, S., Wang, T., & Shi, Z. (2020). The potential for soil erosion control associated with socio-economic development in the hilly red soil region, southern China. *Catena, 194*, 104678.

Westley, F., Olsson, P., Folke, C., Homer-Dixon, T., Vredenburg, H., Loorbach, D., Thompson, J., Nilsson, M., Lambin, E., Sendzimir, J., et al. (2011). Tipping toward sustainability: Emerging pathways of transformation. *Ambio, 40*(7), 762–780.

Wuepper, D., Borrelli, P., & Finger, R. (2020). Countries and the global rate of soil erosion. *Nature Sustainability, 3*, 51–55.

Yang, J., & Huang, X. (2021). The 30 m annual land cover dataset and its dynamics in China from 1990 to 2019. *Earth System Science Data, 13*, 3907–3925.

Yuan, Z., Ma, D., Nie, X., Liao, Y., Huang, B., & Zhuo, M. (2020). Progress in research on prevention and control of soil erosion under forest in red soil hilly region of south China. *Acta Pedologica Sinica, 57*(1), 12–21.

Zare, M., Panagopoulos, T., & Loures, L. (2017). Simulating the impacts of future land use change on soil erosion in the Kasilian watershed, Iran. *Land Use Policy, 67*, 558–572.

Zhang, X., Liu, L., Chen, X., Gao, Y., Xie, S., & Mi, J. (2021). GLC_FCS30: global land-cover product with fine classification system at 30 m using time-series Landsat imagery. *Earth System Science Data, 13*, 2753–2776.

Zhong, B., Peng, S., Zhang, Q., Ma, H., & Cao, S. (2013). Using an ecological economics approach to support the restoration of collapsing gullies in southern China. *Land Use Policy, 32*, 119–124.

Zhu, W., Pan, Y., He, H., Yu, D., & Hu, H. (2006). Simulation of maximum light use efficiency for some typical vegetation types in China. *Chinese Science Bulletin, 51*(4), 457–463.

Zhuang, C., Jiang, C., Chen, W., Huang, W., Yang, J., Zhao, Y., & Yang, Z. (2021). Policy-driven co-evolution of the food–water–ecosystem–livelihood nexus in two ecosystem conservation hotspots in southern China. *Global Ecology and Conservation, 30*, e01789.