



# Assessing the contribution of ecological restoration projects to ecosystem services values in the Chinese loess plateau

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**Abstract** Large-scale ecological restoration projects (ERPs) in the Chinese Loess Plateau have been widely reported over the past decades. However, the impacts of land use caused by different ERPs on ecosystem service values (ESV) remain largely unknown in this ecologically fragile region. In this study, we assessed long-term changes in ESV under three typical scenarios of ERPs combinations on the Loess Plateau, using a modified rapid ecosystem services assessment method. From 2000 to 2020, the region experienced substantial changes in land use, with the expansion of forests and the shrinking of grasslands being the dominant characteristics. Forest restoration ( $1.09 \times 10^6$  ha) on the Loess Plateau has experienced obvious increase in ESV (6.26 billion RMB) as a result of the Grain for Green project (GfG) and the Natural Forest Conservation Program (NFCP). These

changes have led to an increase in the overall ESV by 1.74 billion RMB in the last 20 years. The ecological conservation scenario demonstrates the highest benefit potential in ESV for increasing ecological services compared to the other two scenarios, with a growth of  $1.32 \times 10^6$  ha of forest and 9.89 billion RMB, and this increasing trend will continue to be driven by the GfG in the future. We recommend regulating the spatiotemporal trade-offs relationships between forests, grasslands, and farmlands, as well as developing diverse projects for ecosystem conservation and restoration on the Loess Plateau.

**Keywords** Ecosystem services · Land use and land cover change · Value equivalent evaluation · Ecological restoration · Loess plateau

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## Introduction

To alleviate ecosystem degradation, the Chinese government has implemented a series of ecological restoration projects (ERPs) in ecologically vulnerable regions (Lu et al., 2022), which have significantly altered ecosystem services (ESs) and biodiversity at the regional scale. The ecosystem services are the indirect and direct benefits of ecosystems obtained by humanity to maintain their well-being, and mismanagement of ESs can decrease their utility (Costanza et al., 1997; Malek et al., 2018). Over the last decades, global ecosystem services and biodiversity have

degraded due to large-scale land use and coverage change (LUCC) caused by anthropic activities (Guo et al., 2020). For instance, China's rapid socio-economic development has threaten the sustainability of natural capital over the past decades (Wu et al., 2019). Bryan et al. (2018) reported sixteen pivotal scio-ecological projects to demonstrate China's response to the sustainability emergency of the national land system (e.g., soil erosion and deforestation). However, the contribution of these ERPs to the supply of ESs remains largely unknown.

A series of revegetation and nature reserve protection projects have been carried out in ecologically fragile regions of China (Ouyang et al., 2016). Among them, eleven projects are related to the Loess Plateau, and several assessments have demonstrated that these projects have altered landscape processes (e.g., an increase in "greenness") and ecosystem services across this ecological barrier area of China (Piao et al., 2019; Zhu et al., 2016). Jiang et al. (2018) assessed the ES change in the Beijing–Tianjin Sandstorm Source Region from 2000 to 2010 under the background of ecological restoration and climate variability, and the results of the study showed that ERPs play a role in enhancing soil conservation. Yang et al. (2018) assessed the changes in ESs in the Yanhe River watershed using the InVEST model, and the results showed that GfG had different degrees of influence on the changes in each ES, and all five ESs increased. However, most studies in the Loess Plateau focused on assessing the historical changes in ESV only based on the LUCC processes at coarse spatiotemporal scales (e.g., Fu et al., 2017; Han et al., 2021), and understanding the relationship between the ecosystem service values (ESV) change and the implementation of the single ecological project, such as Grain for Green Project (GfG) (Ouyang et al., 2016; Song & Deng, 2017). These studies have seldom analyzed the spatiotemporal dynamics of the LUCC-ESV nexus from the perspective of land-related socio-ecological projects, furthermore, there are gaps in the assessment of the potential ESV variation driven by these projects in a long-time series.

Spatiotemporal assessment of ESV is an effective modelling framework to underline the values of natural assets for improving human welfare (Braat & de Groot, 2012; Tezer et al., 2020), optimizing ESs supply (Wang et al., 2022), and guaranteeing ecological security (Yin et al., 2021). For example, the physical

quantity method calculates the ESV change using biophysical-processed models and empirical valuation equations (e.g., social preference), which is mainly used to assess single ecosystem service for fulfilling its relatively complex practicableness (La Notte et al., 2017). The economic valuation proposes a LUCC-based benefit transfer method by integrating economic value per unit of every ecosystem service and its total area in land-system (Xie et al., 2017), which is suitable for ESV assessment at multi-scales with its advantages of operability and simplified data requirements (Costanza et al., 2014). Although the previous studies (e.g., Fu et al., 2015; Turner et al., 2010) demonstrated that the economic valuation can not reflect actual market exchanges, the majority of existing ESs are identified as the non-rival characteristics and do not need to fit complete market conditions (Chen et al., 2022). Hence, the economic valuation method has been widely improved to regenerating revised ESV valuation models according to the actual conditions of regional land systems.

The Loess Plateau is located in arid and semi-arid zone, and is famous as a high sensitive region to climate change and land use. There is an urgent need for immediate sediment treatment of soil erosion areas (approximately  $21.37 \times 10^6$  ha) in the Loess Plateau, which poses a significant threat to the security of the downstream socio-ecological system (Yang et al., 2019). A county-level assessment demonstrates that the ESV of grassland in typical hilly-gully regions is increasing (Zhang et al., 2020). However, there is still a lack of understanding regarding how ERPs will impact the overall change in ecological assets on the Loess Plateau, as local policymakers are often more concerned with accounting for the benefits of implemented projects (Wang et al., 2019; Xian et al., 2020). The Chinese government has optimized the implementation of pre-existing ERPs since 2015, therefore, a scientific assessment of trends in total ESV on the Loess Plateau would provide decision support for potential ERPs implementation and long-term optimisation. This study assessed the long-term changes in LUCC-ESV nexus on the Loess Plateau, to contrasting and revealing how different ERPs affect the ecosystem patterns, ESs supply, and changes in their values. Specifically, this study aims to: (1) evaluate the spatiotemporal changes in LUCC and ESV on the Loess Plateau from 2000 to 2020; (2) determine the varying impacts of ERPs on the potential

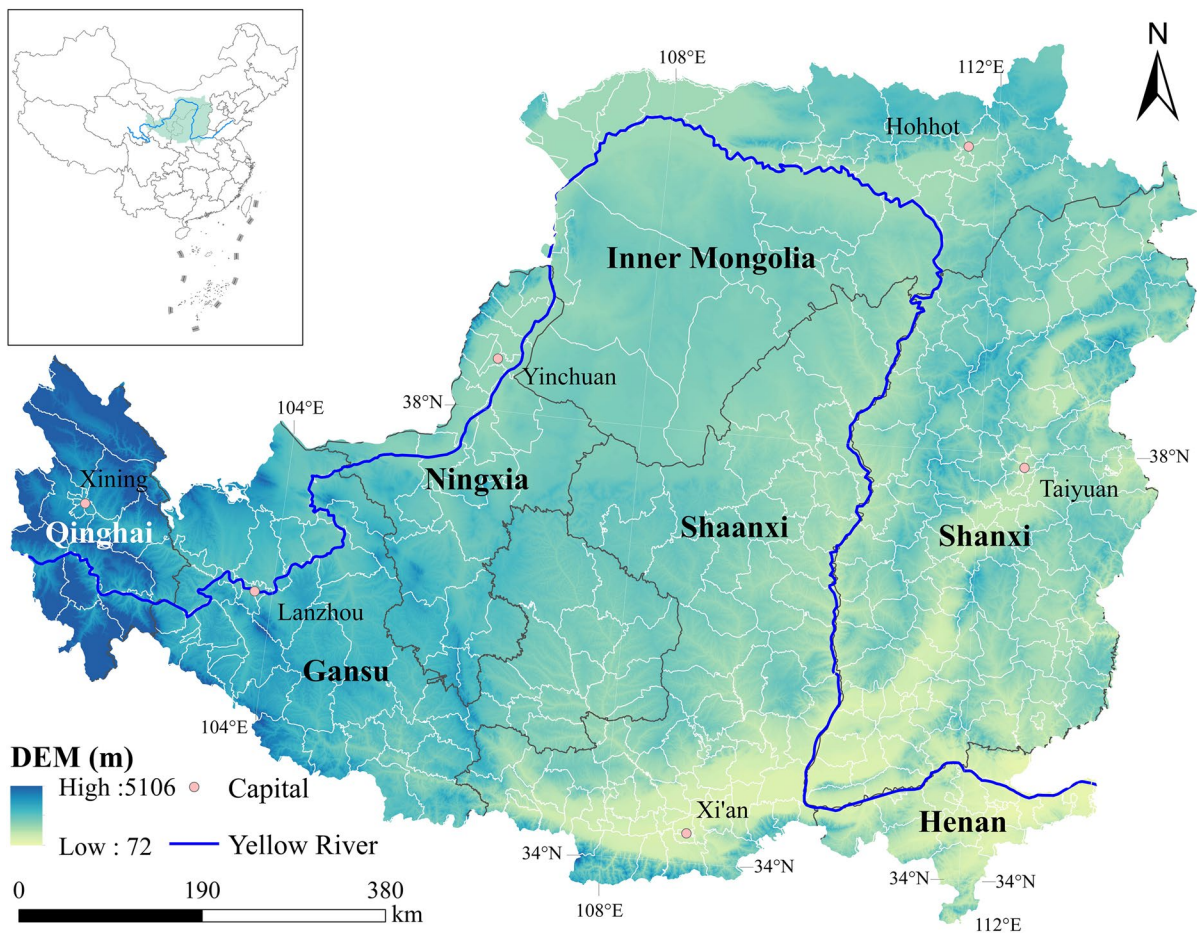
enhancement of ESV in different regions; and (3) provide ecological management recommendations to enhance ESs supply and ESV through cost-benefit analysis.

**Material and methods**

**Study area**

The Loess Plateau has a total area of approximately 640,000 km<sup>2</sup> and covers the entire provincial units of Shanxi (SX) and Ningxia (NX), as well as parts of the Shaanxi (SAX), Gansu (GS), Inner Mongolia (NM), Qinghai (QH), and Henan (HN) (Fig. 1). The climatic features in this region vary gradually from a temperate humid monsoon in the southeast to a

temperate arid climate in the northwest. The average yearly precipitation ranges from 200 to 700 mm, while mean annual temperatures range from 4.3 to 14.3 °C (Li et al., 2016). This region is not only a protective ecological barrier for maintaining ecological security in China, but also an important area for the supply of high-quality agricultural products and raw materials, biodiversity conservation, and the vital region for socio-economic development (Zhang et al., 2019). The LUCC dynamic on the Loess Plateau has undergone a drastic transformation, for example, urbanization is encroaching on part of the highly productive plain cropland and natural ecosystem, while cropland has decreased caused by the GfG project (Wang et al., 2014). Such drastic LUCC processes have led to complex ESV changes. The immediate response to the situation



**Fig. 1** Location of the Chinese Loess Plateau

involves conducting a thorough assessment of the spatiotemporal patterns of ESV on the Loess Plateau, which is crucial for promoting regional ecological preservation and sustainable socio-economic development initiatives.

#### Calculation of ecosystem services values

Xie et al. (2017) conducted a comprehensive statistical survey on the perceptions of the ESV by Chinese experts in the field of ecology and environment. Based on their findings, they proposed a national-scale ESV method that utilizes an equivalent coefficients table with a standard equivalent factor. Specifically, the standard equivalent factor is defined as “the potential natural grain value provided by 1 hm<sup>2</sup> of nationally averaged yielding farmland in the absence of human disturbance” (Xie et al., 2015). It also represents the potential value per unit area that can be provided by different ES types in each ecosystem (Xie et al., 2017). In this study, farmland, forest, grassland, water area, and barren land were selected to assess the value of each of the nine key ESs and the total regional ESV in the region based on their significant contributions to multiple ESs supply and biodiversity (Zhang et al., 2020).

$$ESV = \sum_{i=1}^5 \left( \sum_{j=1}^9 V_{ij} \right) \times S_i \quad (1)$$

$$V_i = \sum_{j=1}^9 E_{ij} \quad (2)$$

where  $V_i$  denotes the total value per unit area of land use type  $i$ ;  $E_{ij}$  signifies the value of ecosystem service  $j$  corresponding to land use type  $i$ ;  $S_i$  represents the area of ecosystem type  $i$ .

In regional-scale assessments, anthropogenic disturbances make it difficult to accurately measure the economic value of food production that farmland ecosystems can provide under natural conditions (Jiang et al., 2020). Therefore, the net profit per unit area of grain production on farmland (including wheat, maize, and rice) was used as a standard equivalent factor for ESV assessment. Regional adjustments were made to the 2010 national standard equivalence factor table. The biomass factor adjustment factor ( $C = NPP_r / NPP_c$ ) was calculated from the regional  $NPP_r$  (134.65 MgC/km<sup>2</sup>, Xu et al., 2016) and national  $NPP_c$  (265.43 MgC/km<sup>2</sup>, Liu et al., 2021) in 2010,

and the  $C$  value was compared to the  $E_{ij}$ . To improve the precision of the correction coefficients, the percentage of the total sown area of the grains and the average net profit per unit area (RMB/hm<sup>2</sup>) of each administrative region were weighted and summed, and this sum was then multiplied by the corrected  $E_{ij}$  to obtain the corrected  $V_{ij}$  (Table S2). In this case, the net grain profit data for each administrative region were obtained from the Cost–Benefit Statistic Yearbook of China’s Agricultural Products in 2010 (<https://kns.cnk-i.net/kns8/defaultresult/index>). In addition, the constant price calculations were used to make the final calculation of the total monetary values for the historical period comparable. The consumer price index (CPI) was obtained from the China Statistical Yearbook (2000–2015) and the values for each year were converted to constant prices (RMB) based on the year 2000.

$$Price_b = Price_t \times 100 / (CPI_t \times E_{t-1}) \quad (3)$$

where  $Price_t$  is the value in year  $t$ ;  $E_{t-1}$  is the cumulative correction factor for year  $t-1$ ,  $CPI_t$  is the national CPI for year  $t$ ,  $Price_b$  is the constant price in year  $t$  when converted to the base year. The tools for calculation of ESV and mapping are ArcMap 10.7 and Origin 2022.

#### Scenarios of ecological restoration projects

Three typical ERPs were selected as the basic types for scenario design, including GfG, Natural Forest Conservation Program (NFCP), and Sandification Control Program for the Loess Plateau (SCP). Among them, the GfG project has a broad geographical scope of implementation and impacts a significant number of individuals, the NFCP and SCP play a crucial role in managing the prevalent flooding and sandstorm disasters in this area. Based on the functions, coverage and socio-economic parameters of these ERPs (Table S1), three LUCC scenarios in 2030 were designed to simulate the potential impacts of implementing different numbers and types of ecological restorations on the ESV of the Loess Plateau. The baseline scenario represents the trend of historical vulnerability and no projects were conducted in the future, and the spatial pattern of LUCC in 2030 was simulated using a CA model followed by Wang et al. (2022). Due to the substantial investment in

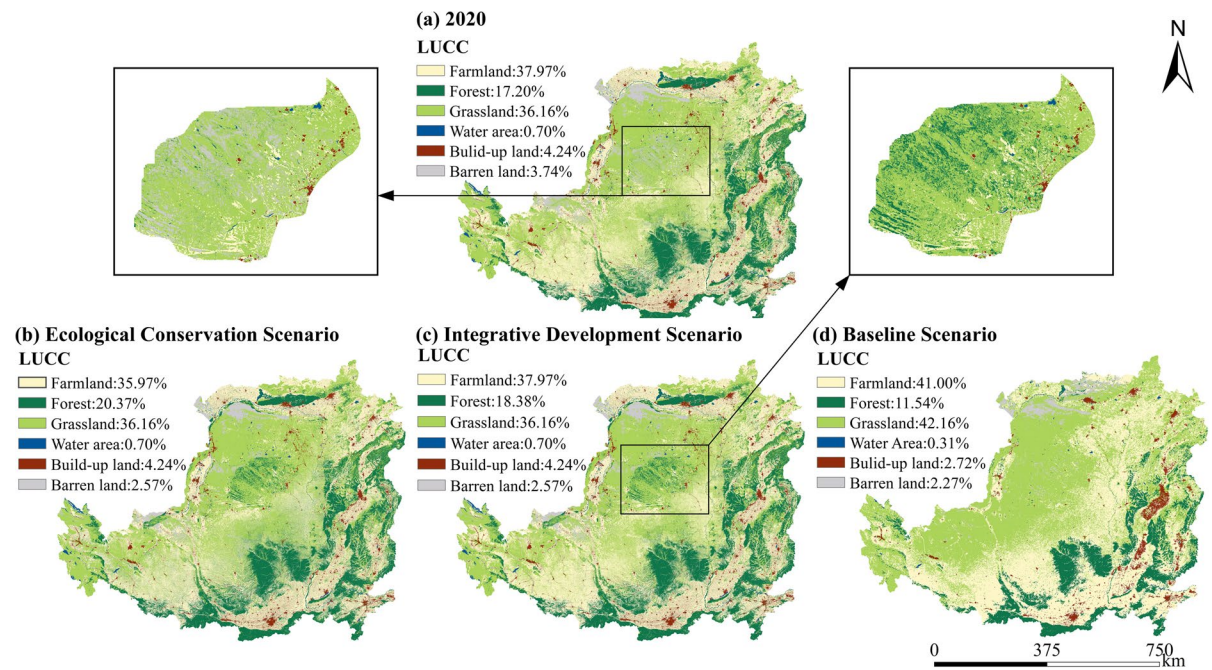
GfG project and considering the eco-socio-economic advantages, the integrative development scenario solely encompasses the combined effects of SCP and NFCP. The ecological conservation scenario represents a combination of SCP, NFCP, and GfG, prioritizing eco-environmental protection and the value of eco-efficiency compensation (Table 1). The LUCC

maps for the integrative development and ecological conservation scenarios in 2030 were created based on the baseline map in 2020 using GIS mapping techniques. It was assumed that the LUCC types in these scenarios were converted according to the land use management rules established through the goals of ERPs (Fig. 2).

**Table 1** The descriptions of different combination scenarios in ecological restoration projects on the Loess Plateau

Scenario	Combinations of ecological projects and their investment costs
Ecological conservation	GfG: Subsidy for returning farmland to forestry, 24,000 yuan/ha (Bryan et al., 2018). SCP includes public welfare forest construction (4500 yuan/ha), closed-country forestry (1050 yuan/ha), fly-sown afforestation (1800 yuan/ha), medium and young forest nurturing management (1800 yuan/ha), artificial afforestation for reserve resource cultivation (4500 yuan/ha), and forest renovation cultivation (3000 yuan/ha) (Bryan et al., 2018; Liu et al., 2013) NFCP includes artificial afforestation (4500 yuan/ha), fly-sown afforestation (including post-fly management and care, 1800 yuan/ha) and closed forestry (1050 yuan/ha) (Bryan et al., 2018; State Forestry Administration of China, 2012a, 2012b, 2012c, 2019, 2020) The areas of GfG, SCP and NFCP cover approximately 6.43E+07 ha in the study area
Integrative development	The areas of SCP and NFCP cover approximately 5.99E+07 ha in the study area

Abbreviations: *GfG* Grain for Green project; *SCP* the Sandification Control Program for areas in the vicinity of Beijing-Tianjin; *NFCP* the Natural Forest Conservation Program



**Fig. 2** Spatial distribution of land use on the Loess Plateau in 2020 and for different scenarios

Data source

The LUCC dataset for the historical period (2000–2020) was obtained from GlobeLand30 (<http://www.globallandcover.com/>). The GlobeLand30 product has been widely used in ESs assessment, demonstrating a higher overall accuracy of 83.50–85.72% compared to similar products (Chen et al., 2021). Elevation and slope data were obtained from the Geospatial Data Cloud (<http://www.gscloud.cn>). All raster data were resampled at a uniform spatial resolution of 30 m × 30 m to meet the needs of fine-scale analysis at the county level. The boundary data for ERPs were obtained from National Ecosystem Science Data Center, National Science & Technology Infrastructure of China (<http://www.nesdc.org.cn>), provided by Shao et al. (2022).

Results

Changes in historical LUCC-ESV

The overall trend of land-use conversion indicates a shift from farmland and grassland to forest and

build-up land on the Loess Plateau during the historical period (Fig. 3). The proportions of farmland (39.37%-37.97%) and grassland (38.63%-36.15%) in the study area are decreasing, but they continue to be the dominant land use types. The area covered by forests is showing an increasing trend (15.52%-17.2%). The interconversions of the different land use types on the Loess Plateau show significant variations (Fig. 4). Approximately 2.10% of farmland has been converted to forest, while 6.72% has been converted to grassland. Moreover, 5.39% of farmland has been converted to build-up land. Grassland has experienced multiple types of degradation, including encroachment from forest (8.42%), farmland (8.31%), barren land (2.04%), and built-up land (1.35%). By 2020, the new built-up land will primarily be obtained through the conversion of farmland and grassland.

The total ESV corresponding to the nine types of ESs in the region increased from 0.17 billion RMB from 2000 to 2020 (Fig. 5). Specifically, erosion prevention accounts for the largest proportion of the total ESV (16.53%-16.79%), and other ESs types with a high proportion of total ESV include habitat

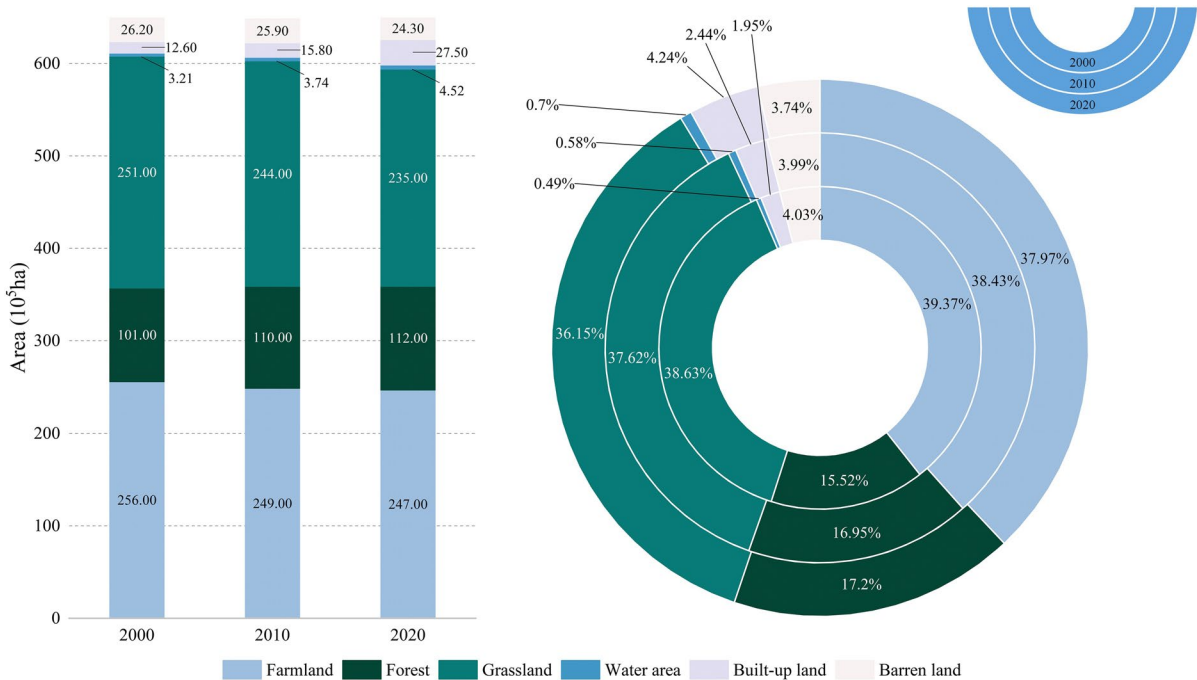
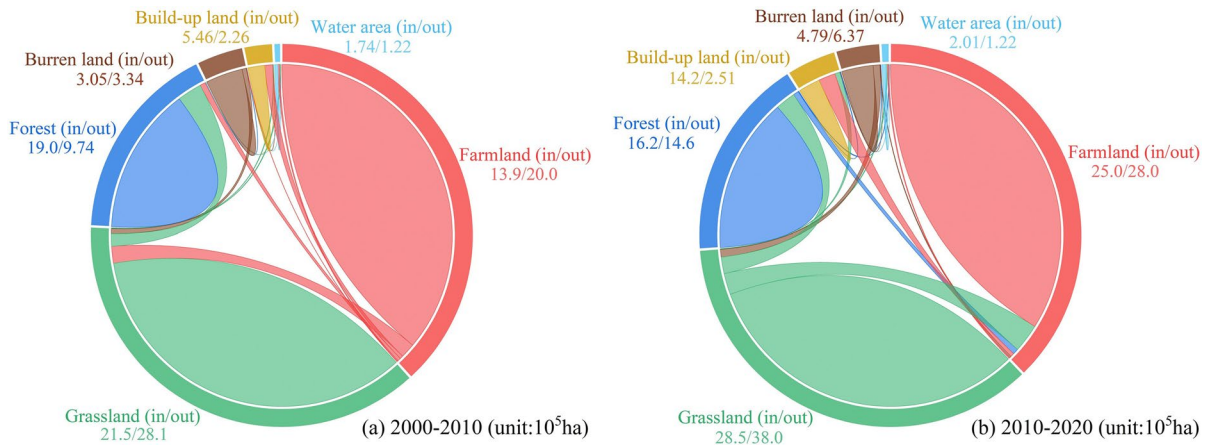
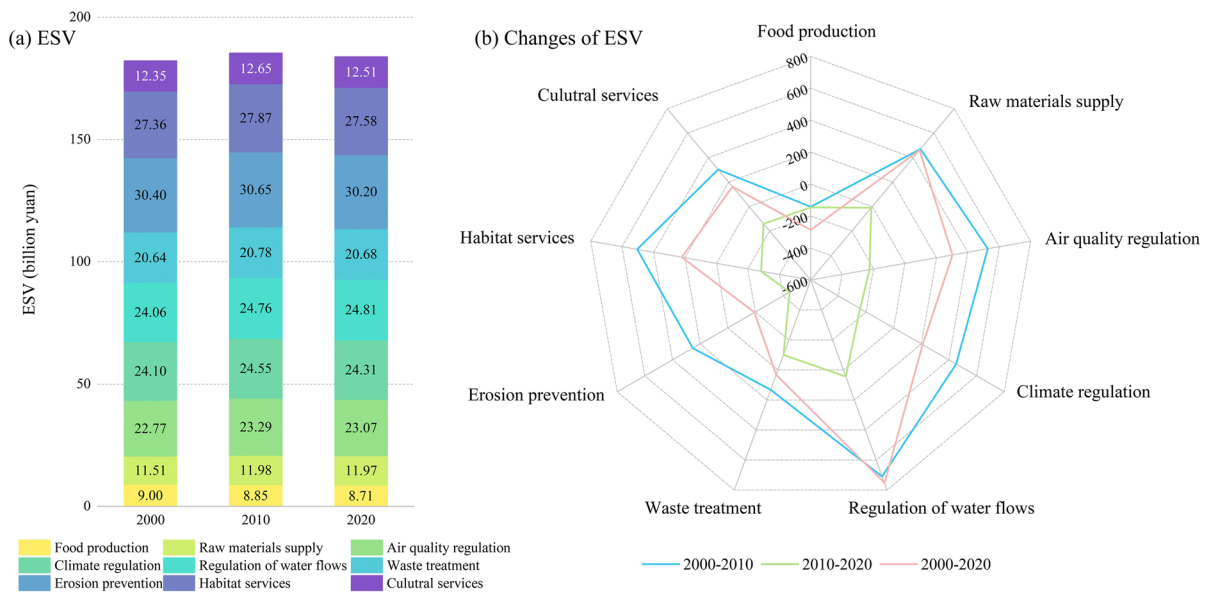


Fig. 3 Area and percentage of different land use types on the Loess Plateau from 2000 to 2020



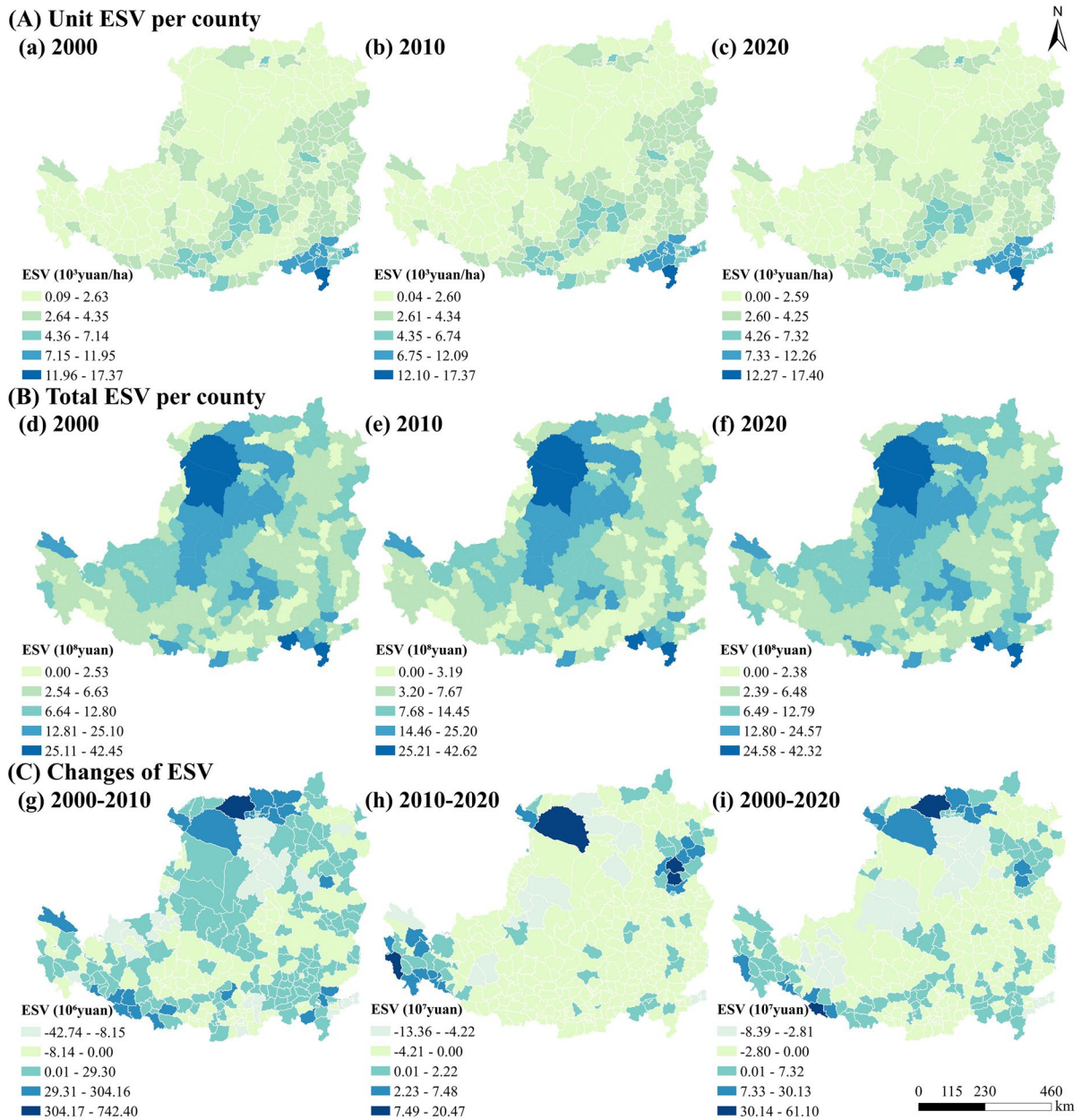
**Fig. 4** Land use conversion on the Loess Plateau from 2000 to 2020



**Fig. 5** Changes in ESV on the Loess Plateau from 2000 to 2020

services (15.10%–15.13%), regulation of water flows (13.32%–13.58%), and climate regulation (13.29%–13.33%). Furthermore, the values of nine services all increased in this region from 2000–2010, but all decreased from 2010–2020, with food production and air quality regulation being the two most obvious types. Complex changes in ESV were observed resulting from LUCC process over the historical period, which should be taken into account for land use trade-offs.

At the county level, there were substantial differences in the relative levels of ESV and the cumulative effect of total ESV (Fig. 6). From 2000 to 2010, the counties with low unit ESV (<2630 RMB/ha) were primarily located in the western part of the plateau (e.g., southern NM). In 2000, NM had the largest area with low value per unit ESV ( $1.35 \times 10^7$  ha), accounting for 95.56% of the total number of counties with low value per unit on the Loess Plateau. By 2010, the number of counties with low value per unit had



**Fig. 6** Distribution of unit ESV, total ESV and their changes in the Loess Plateau from 2000 to 2020

decreased, however, the proportion of counties with low unit ESV increased in the period of 2010–2020. Overall, the proportion of counties with low value per unit ESV (<2630 RMB/ha) on the Loess Plateau ranged from 52.16% to 55.73% in 2000–2020.

The majority of the total ESV on the Loess Plateau comes from counties within the high

unit value range. For instance, 80.00–95.56% of counties in NM fall into the low unit value range (1977.19–2181.83 RMB/ha), and they contribute only 16.11–16.82% of the total ESV in this region. From 2000 to 2020, a total of 260 counties experienced a decline in their total ESV, with an average annual decline of  $1.29 \times 10^8$  RMB. Among them,



Hongsibao district in NX had the largest decrease of 4.19 million RMB per year. In addition, 133 counties showed an increasing trend in total ESV, with an average annual increase of  $2.15 \times 10^8$  RMB, and the county with the largest increases were Urad Front Banner in NM (30.55 million RMB per year). The increase in total ESV between 2000 and 2010 (196 counties covering 3.20 million ha) was higher

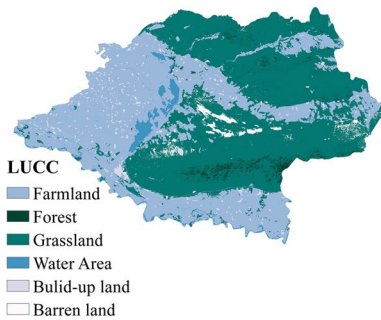
than the increase between 2010 and 2020 (84 counties covering 1.26 million ha).

Changes in ESV due to revegetation from 2000 to 2020

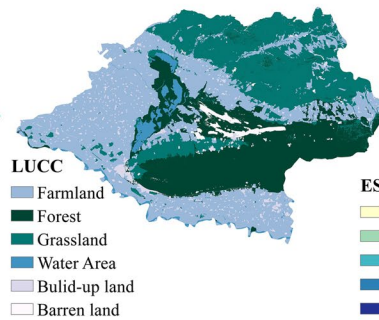
From 2000 to 2020, there is clear spatiotemporal heterogeneity in the ESV of counties affected by

**(A) Urad Front Banner**

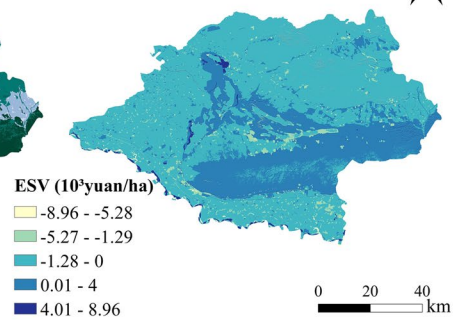
**(a) 2000**



**(b) 2020**

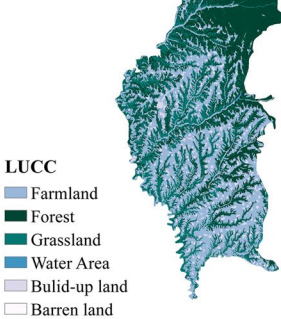


**(c) 2000-2020**

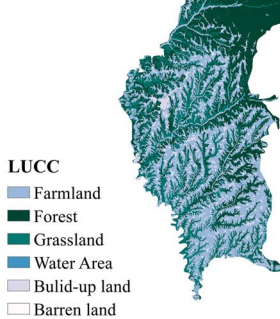


**(B) Luo chuan county**

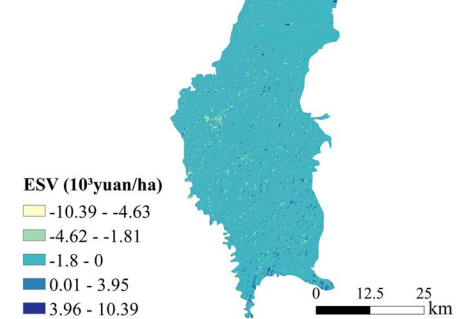
**(d) 2000**



**(e) 2020**

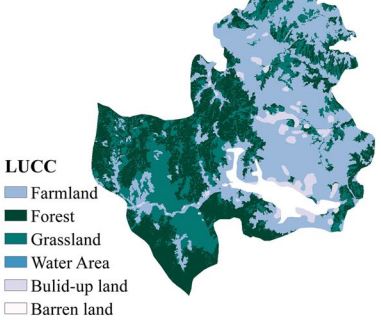


**(f) 2000-2020**

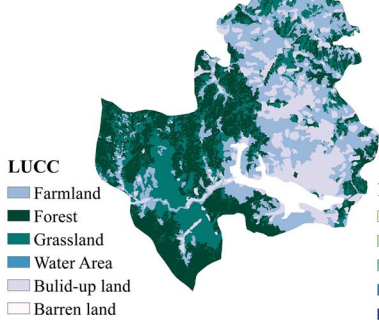


**(C) Jiao district of Yangquan city**

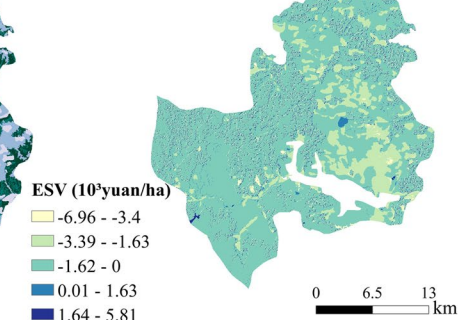
**(g) 2000**



**(h) 2020**



**(i) 2000-2020**



**Fig. 7** Revegetation area and corresponding changes in ESV in three typical counties from 2000 to 2020

different ERPs. GfG has the highest coverage and number of people affected (401 counties,  $1.32 \times 10^8$  people), followed by NFCP and SCP (Table S1). As a result of these ERPs, the forest area increased by 10.82%, the farmland area decreased by 3.56%, and 7.15% of the barren land was converted to other types of land in the study area. For instance, the Urad Front Banner in NM is a typical area where all three types of projects overlap (Fig. 7), resulting in 12.31% conversion of farmland to vegetation. Additionally, the proportion of forest area increased by 24.58%, while 50% of the grassland underwent conversion to forest (43.23%), farmland (6.55%), and barren land (1.30%), respectively. Moreover, the additional build-up land (45.16%) mainly replaced farmland. Luochuan county in SAX is a typical area that has been affected by the GfG and NFCP, resulting in minimal overall ESV changes. Over the past 20 years, the county has experienced a decrease of 0.62% in its farmland area, which has primarily been converted into additional grassland (3.89%) and built-up land (3.51%). However, the county has only a minor increase of 0.41% in ESV. The "Jiaoqu" in SX represents regions that have not been covered by these projects. This area has experienced a decrease of 11.16% in its farmland area from 2000 to 2020, and the built-up land area has observed a substantial increase (3.81%-17.17%).

Consequently, this region has witnessed a pronounced reduction in ESV, with an annual decrease of  $8.00 \times 10^5$  RMB.

On a provincial scale (Fig. 8), NM achieved the highest level of vegetation restoration from 2000 to 2020, accounting for 32.62% of the total restored vegetation area on the Loess Plateau, followed by SX (19.70%) > GS (18.31%) > SAX (17.09%) > NX (7.40%), and QH (2.58%). HN had the smallest area of restored vegetation (2.31%). The intensity of vegetation restoration efforts also led to significant differences in the changes in ESV. NM contributed 54.27% of the total increase in ESV on the Loess Plateau. GS (21.14%) and QH (17.83%) followed with the next highest ESV growth rates, while SX contributed 6.76%. The remaining provinces and regions experienced a declining trend in total ESV. Notably, SAX had the most significant decrease (-0.39 billion RMB), accounting for 44.09% of the ESV decrease in the study area.

Changes in ESV under different scenarios

At the county level, the baseline scenario demonstrates the ESV changes of the Loess Plateau in the absence of the ERPs' continuation. From 2020 to 2030, there will be an increase in the proportion of

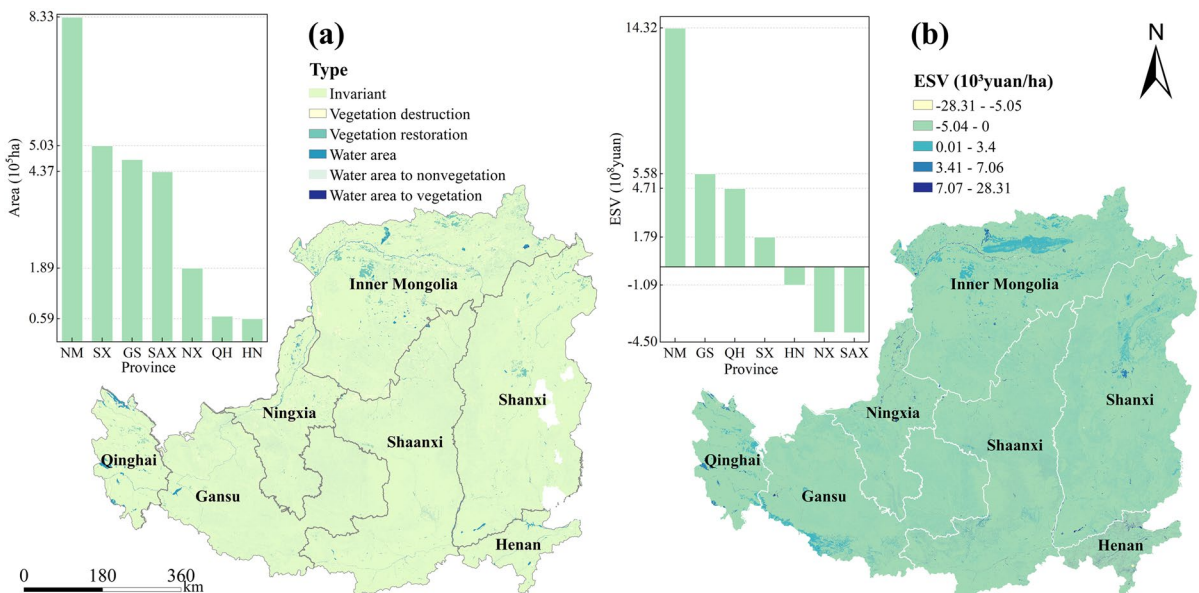
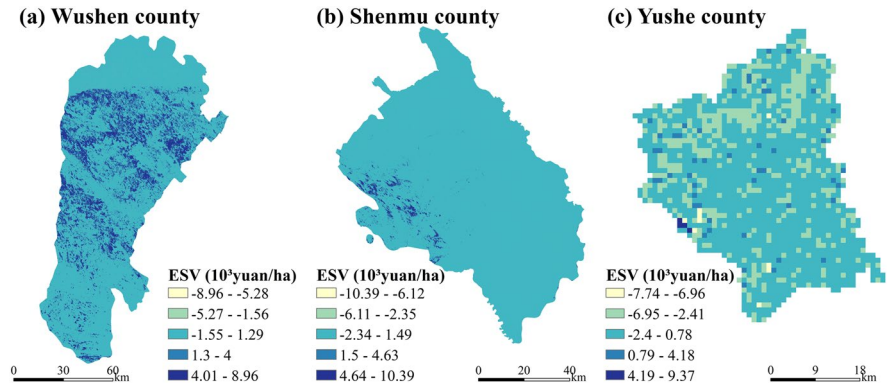


Fig. 8 Revegetation area and corresponding ESV changes at the provincial scale on the Loess Plateau in 2000–2020

**Fig. 9** Changes in ESV in three typical counties under different scenarios from 2020 to 2030



grassland (42.16%) and a decrease in forest coverage (30%), and this reduction in forest area will primarily be due to its conversion to farmland (23.57%) and grassland (20.26%). For example, the proportion of forest area in the Yushe county of SX will decrease from 33.31% to 10.20% (Fig. 9). In contrast, farmland will expand from 14.59% to 34.50%, with new farmland replacing grassland (48.32%) and forest (20.28%). The encroachment of farmland on forests will lead to a reduction in the county’s ESV, with an average annual reduction rate of  $1.50 \times 10^9$  RMB.

In the integrative development scenario, the ERPs aim to transform the Mu Us Desert, as well as the barren hills and barren land of the Upper and Middle Yellow River project areas, into forests. This will result in a forest area of 18.38% by 2030, all of which will be converted from barren land. However, the area share of farmland and grassland decreases, leading to a decrease in ESV of food production to  $8.76 \times 10^9$  RMB compared to the baseline scenario. For instance, the forest area in Shenmu county in SAX is projected to increase from 2.02% in 2020 to 3.61% in 2030 (Fig. 9), primarily through the conversion of barren land, leading to an increase in ESV ( $7.30 \times 10^8$  RMB).

In the ecological conservation scenario, there would be a reduction of 5.25% in farmland and the complete conversion of that land into forest, accounting for 64.06% of the new forest area. Although this scenario would result in decreased food production, there would be an increase in vegetation that would lead to further growth in other ESs. Especially, the proportion of forest area in Wushen county, NM (Fig. 9), would notably rise from 3.36% in 2020 to 20.35% in 2030. Around 77.61% of the additional forested land would be obtained through revegetation

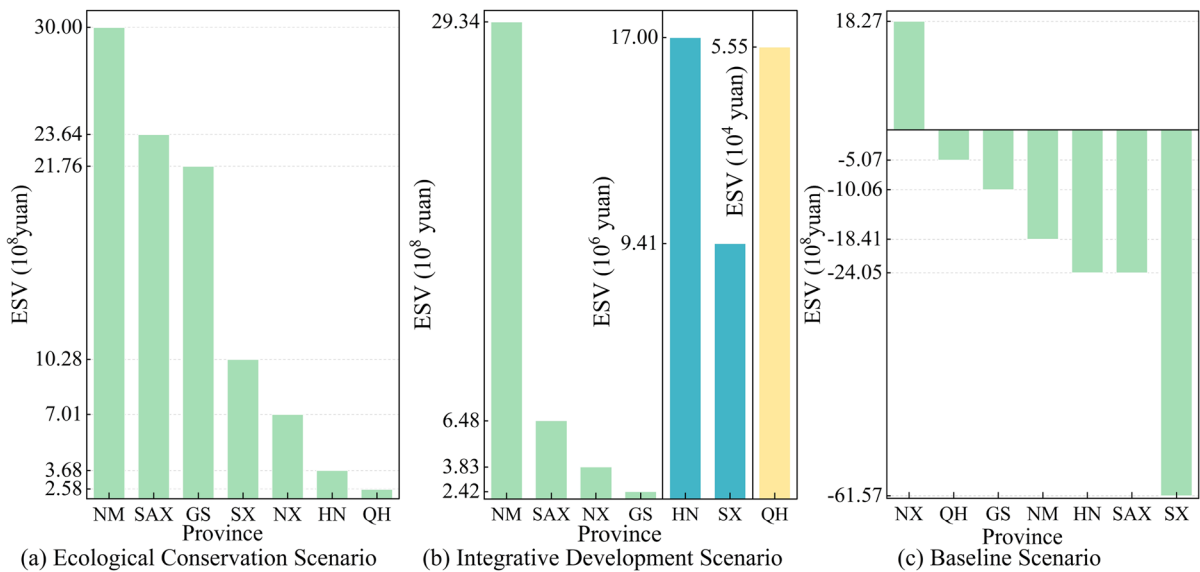
and farmland retreatment. These measures are expected to enhance the county’s future ESV by 1.05 billion RMB.

At the provincial level, the total ESV for the integrative development scenario and the ecological conservation scenario increases by  $4.23 \times 10^8$  RMB and  $9.89 \times 10^9$  RMB respectively from 2020 to 2030. In contrast, the baseline scenario decreases by 1.25 billion RMB. Under the ecological conservation scenario, NM experiences the largest increase in total ESV, approximately 3.00 billion RMB (30.33%), followed by SAX (23.90%) and GS (21.99%) respectively. The other provincial units contribute less than 10.39% (Fig. 10). In the integrative development scenario, NM accounts for 58.85% of the total vegetation restored on the Loess Plateau (Fig. 10), followed by SAX (16.57%) and GS (10.59%), while QH restores the lowest percentage of the area (0.51%). In the baseline scenario, NM still performs best in terms of vegetation recovery (25.67%, Fig. 10), followed by GS (20.78%) and SX (18.68%), while HN has the lowest percentage of area recovered (0.49%). SX decreasing by 6.16 billion RMB (42.99%), while other provinces decrease by 3.54% to 16.80%.

**Discussion**

Drivers of land use change

Since the implementation of the ERPs, the Loess Plateau has been experiencing large-scale drastic land use changes. As the policy of ERPs are more inclined to reduce cropland to restore forest land (Wang et al., 2020) and the problem of insufficient attention to grassland protection, this has led to a



**Fig. 10** ESV changes at the provincial scale on the Loess Plateau for different scenarios

sharp reduction in the area of farmland and grassland in the Loess Plateau and making the trade-off between forests and farmland more prominent (Wang et al., 2019). Additionally, grassland degradation will result in a shortage of livestock products in the region. While farming expansion has been limited, advancements in agricultural technology and intensification have helped mitigate the risk to food supply security (Wang et al., 2022). From 2000 to 2020, 1.09 million hectares of new forest were added to the study area, with the largest contribution coming from NM (4.74 million hectares), benefitting directly from ERPs based on the supporting of China's forestry policy. NM has become a key province for implementing ecological restoration projects in China over the past 20 years (Tian et al., 2015). However, the precise extent of vegetation restoration in different ecological projects needs further definition on the Loess Plateau, especially considering the potential overlap of projects in NM and SN.

The increase in grassland and forest over the past 20 years in NX has remained relatively low, likely due to the fragile natural environment and relatively low level of socio-economic development in the area (Liang et al., 2021). The decline in forest and grassland area, coupled with the expansion of farmland and built-up land, has created a clear trade-off,

resulting in a total reduction in ESV of 2.71 million RMB. Although there has been a slight increase in food production in the region during the scenario period, there has been a significant reduction in all eight service categories, especially habitat services by 17.91%. The overall degradation of the ecosystem and decline in ESV will diminish the area's key ecological functions in terms of soil–water conservation and biodiversity. We recommend implementing a more synergistic ecological management strategy for such key areas experiencing ESV changes.

Changes in the LUCC of the Loess Plateau reflect important human impacts on the ecosystem over time, and in addition, climate change has been identified as one of the main drivers affecting the LUCC. Topography and slope have a significant effect on the conversion of unused land to grassland and the interconversion of grassland, forest and farmland, which may be related to the policies of ERPs in China (Zhou et al., 2020). Overall, drivers of land use change remains complex (Liu et al., 2021).

#### Impact of ecological projects on ESV

In the integrative development scenario, ERPs will cover 364 counties and affect  $1.16 \times 10^8$  people on the Loess Plateau. The ecological conservation scenario increases the area covered by ecological projects

to 401 counties and a population of  $1.32 \times 10^8$ , with greater potential for ESV improvement in NM, SAX, and NX. The additional vegetation in the last 20 years provided an additional ESV of 2.32 billion RMB, indicating that the NFCP and GfG projects significantly increased the ESs supply in the study area, consistent with Li et al (2016). The ecological conservation scenario demonstrates the highest potential for vegetation restoration, with  $1.32 \times 10^6$  hectares of farmland targeted for reforestation. However, there is uncertainty regarding the actual net benefits of these restoration projects in terms of ESV. This uncertainty stems from a combination of factors, including project investment, water constraints, climate change, and ecosystem management practices (Cao et al., 2019).

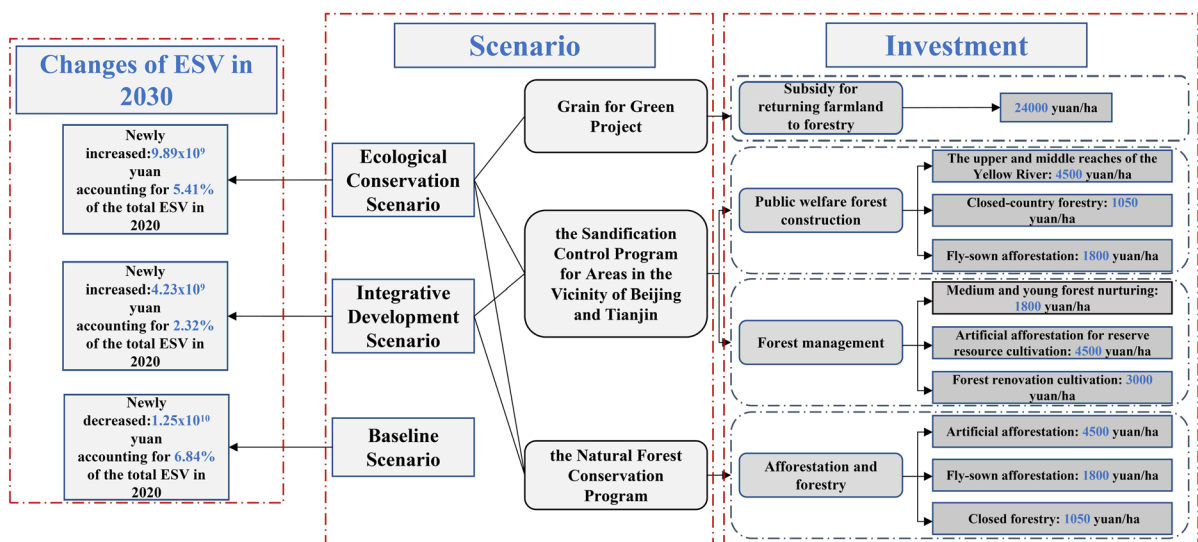
Low survival rates of ongoing vegetation restoration on the Loess Plateau (Bai et al., 2019) may result in ESV overestimation for forests. It is challenging to accurately assess the impacts of diverse restoration efforts at the regional level. Previous studies have found that large-scale revegetation in arid-semi-arid regions could intensify transpiration and exacerbate water scarcity (e.g., Feng et al., 2016; Ge et al., 2020), potentially posing long-term challenges to ecosystem stability. Thus, a balance between ERPs on the Loess Plateau and the carrying capacity of regional water resources necessitates further exploration. The

comparison of scenarios demonstrates that modifying the scope of the GfG leads to more significant ESV changes, and the GfG project can play a vital role in ESV growth on the Loess Plateau.

### Impact of ESV changes on ecological management

Nexus change between ecological restoration and ESV can be utilized for ecological management. A more precise assessment of ESs benefits would aid in determining the net benefits of specific ecological projects using revegetation scenarios for the synergistic ecological management. For example, regional eco-compensation schemes can be designed through a cost-benefit analysis of ecological assets in forest and grassland (Ma et al., 2020). We Summarized the implementation objectives and potential compensation mechanisms of typical ERPs (Fig. 11). Since the spatial scope of the implementation of ERPs is not clear, this study only provides the unit price of each investment and does not calculate the total investment. It still was found that the investment intensity of the three projects in terms of subsidiarity for returning farmland to forest, public welfare forest construction, forest management, and afforestation are closely associated with ESV benefits.

In addition, the rapid growth of planted forests typically leads to higher consumption of soil water



**Fig. 11** Investment and benefits of ecological restoration projects in the Loess Plateau (modified from Bryan et al., 2018; Liu et al., 2013; and State Forestry Administration of China, 2012a, b, c, 2019, 2020)

(Piao et al., 2019; Tuswa et al., 2019), meanwhile, the delayed replenishment of precipitation in arid and semi-arid regions may result in the drying of topsoil, erosion, and wind erosion (Jiang et al., 2016). Therefore, it is crucial to carefully select areas for vegetation restoration and improve existing engineering techniques for ESV enhancement. For instance, reducing the density of tree planting can create adequate space for utilizing understorey resources (Wu & Chen, 2022). This study also demonstrates that water bodies and wetlands contribute significantly to the enhancement of ESs functions, including biodiversity conservation, cultural value, recreational value, and climate regulation. It is recommended that agricultural water quotas on the Loess Plateau be rigorously assessed and controlled, and future ERPs should prioritize the systematic restoration of wetland and lake ecosystems.

### Uncertainty

The unit value-based ESV estimation method used in this study can be used to quickly assess changes in regional ESs. However, Richardson et al. (2015) point out that there is uncertainty in the complex relationship between ecosystem characteristics and services, and that the final ESV does not accurately reflect intermediate inputs of goods and services. We suggest developing a value assessment method based on the supply–demand process of ESs, which can compensate for the limitations of ESV assessment. For example, by incorporating consumers' willingness to pay for ecological goods and services, the methodology can be modified to ensure a reasonable ESV, such as by introducing a net profit on food at constant prices. The correction-based ESV method is applicable to assessing ESV in the study area, but further testing is needed to examine the uncertainty in ESV resulting from changes in NPP accuracy. Additionally, improving the data resolution and accuracy of LUCC classification can reduce the uncertainty of the assessment results.

### Conclusions

This study aims to analyze the changes in LUCC-ESV nexus affected by ERPs on the Loess Plateau. The findings indicate that the region witnessed

a decline in farmland ( $-9.10 \times 10^5$  ha), grassland ( $-1.61 \times 10^6$  ha) and barren land ( $-1.87 \times 10^5$  ha) from 2000 to 2020, with the corresponding ESV loss of 1.81 billion RMB, 3.95 billion RMB and 547 million RMB. Meanwhile, an increasing trend in the areas and ESV in other land use types. Notably, the ERPs played a crucial role and accounted for 1.32 times the total ESV increase (2.32 billion RMB). The ecological conservation scenario shows the best performance for enhancement of ESV, especially in the NM province. Conversely, the baseline scenario showed a decrease in ESV. The study provides valuable scientific insights into ecosystem service assessment, which can inform ecological management planning and decision-making. Based on these findings, several recommendations are proposed for the ecological management of the Loess Plateau, including strengthening synergistic conservation and restoration efforts for forest and grass ecosystems, assessing the adverse effects of large-scale afforestation on the region, and enhancing conservation and restoration initiatives for lakes and wetland ecosystems.

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**Data availability** Data that support the findings of this study are available from the corresponding author upon reasonable request.

### Declarations

**Ethics approval and consent to participate** Not applicable.

**Consent for publication** Not applicable.

**Disclaimer** 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.

**Competing interests** The authors declare no competing interests.

## References

- Bai, X. J., Wang, B. R., An, S. S., et al. (2019). Response of forest species to C:N: P in the plant-litter-soil system and stoichiometric homeostasis of plant tissues during afforestation on the Loess Plateau, China. *Catena*, *183*, 104186.
- Braat, L. C., & De Groot, R. (2012). The ecosystem services agenda: Bridging the worlds of natural science and economics, conservation and development, and public and private policy. *Ecosystem Services*, *1*(1), 4–15.
- Bryan, B. A., Gao, L., Ye, Y., et al. (2018). China's response to a national land-system sustainability emergency. *Nature*, *559*(7713), 193–204.
- Cao, S. X., Zhang, J., & Su, W. (2019). Difference in the net value of ecological services between natural and artificial forests in China. *Conservation Biology*, *33*(5), 1076–1083.
- Chen, H., Costanza, R., & Kubiszewski, I. (2022). Land use trade-offs in China's protected areas from the perspective of accounting values of ecosystem services. *Journal of Environmental Management*, *315*, 115178.
- Chen, J., Chen, L., Chen, F., et al. (2021). Collaborative validation of GlobeLand30: Methodology and practices. *Geospatial Information Science*, *24*(1), 134–144.
- Costanza, R., d'Arge, R., de Groot, R., et al. (1997). The value of the world's ecosystem services and natural capital. *Nature*, *387*, 253–260.
- Costanza, R., de Groot, R., Sutton, P., et al. (2014). Changes in the global value of ecosystem services. *Global Environmental Change*, *26*, 152–158.
- Feng, X. M., Fu, B. J., Piao, S. L., et al. (2016). Revegetation in China's Loess Plateau is approaching sustainable water resource limits. *Nature Climate Change*, *6*, 1019–1022.
- Fu, B., Zhang, L., Xu, Z., et al. (2015). Ecosystem services in changing land use. *Journal of Soils and Sediments*, *15*(4), 833–843.
- Fu, Q., Li, B., Hou, Y., et al. (2017). Effects of land use and climate change on ecosystem services in Central Asia's arid regions: A case study in Altay Prefecture, China. *Science of the Total Environment*, *607–608*, 633–646.
- Ge, J., Pitman, A., Guo, W. D., et al. (2020). Impact of revegetation of the Loess Plateau of China on the regional growing season water balance. *Hydrology & Earth System Sciences*, *24*(2), 515–533.
- Guo, Y., Zheng, H., Wu, T., et al. (2020). A review of spatial targeting methods of payment for ecosystem services. *Geography and Sustainability*, *1*(2), 132–140.
- Han, X., Yu, J., Shi, L., et al. (2021). Spatiotemporal evolution of ecosystem service values in an area dominated by vegetation restoration: Quantification and mechanisms. *Ecological Indicators*, *131*(7713), 108191.
- Jiang, C., Nath, R., Labzovskii, L., et al. (2018). Integrating ecosystem services into effectiveness assessment of ecological restoration program in northern China's arid areas: Insights from the Beijing-Tianjin Sandstorm Source Region. *Land Use Policy*, *75*, 201–214.
- Jiang, C., Wang, F., Zhang, H. Y., et al. (2016). Quantifying changes in multiple ecosystem services during 2000–2012 on the Loess Plateau, China, as a result of climate variability and ecological restoration. *Ecological Engineering*, *97*(1), 258–271.
- Jiang, D., Ma, W., Zhou, F., et al. (2020). Spatiotemporal changes of ecosystem service value in Dalou Mountain area at township scale. *Research of Environmental Sciences*, *33*, 2713–2723.
- La Notte, A., Maes, J., Dalmazzone, S., et al. (2017). Physical and monetary ecosystem service accounts for Europe: A case study for in-stream nitrogen retention. *Ecosystem Services*, *23*, 18–29.
- Li, S., Liang, W., Fu, B., et al. (2016). Vegetation changes in recent large-scale ecological restoration projects and subsequent impact on water resources in China's Loess Plateau. *Science of the Total Environment*, *569–570*, 1032–1039.
- Liang, Y., Hashimoto, S., & Liu, L. (2021). Integrated assessment of land-use/land-cover dynamics on carbon storage services in the Loess Plateau of China from 1995 to 2050. *Ecological Indicators*, *120*, 106939.
- Liu, M. Z., Jia, Y. G., Zhao, J. J., et al. (2021). Revegetation projects significantly improved ecosystem service values in the agro-pastoral ecotone of northern China in recent 20 years. *Science of the Total Environment*, *788*, 147756.
- Liu, Y. P., Zhang, G. H., Yang, Y. J., et al. (2013). Strategic adjustment of the second phase planning of the Jing-Jin wind and sand source control project. *Forestry Investigation and Planning*, *38*(6), 92–95.
- Lu, N., Tian, H., Fu, B., et al. (2022). Biophysical and economic constraints on China's natural climate solutions. *Nature Climate Change*, *12*, 847–853.
- Ma, Z. H., Xia, C. Q., & Cao, S. X. (2020). Cost-benefit analysis of China's natural forest conservation program. *Journal for Nature Conservation*, *55*, 125818.
- Malek, Z., Zumpano, V., & Hussin, H. (2018). Forest management and future changes to ecosystem services in the Romanian Carpathians. *Environment, Development & Sustainability*, *20*(3), 1275–1291.
- Ouyang, Z. Y., Zheng, H., Xiao, Y., et al. (2016). Improvements in ecosystem services from investments in natural capital. *Science*, *352*(6292), 1455–1459.
- Piao, S. L., Wang, X. H., Park, T., et al. (2019). Characteristics, drivers and feedbacks of global greening. *Nature Reviews Earth & Environment*, *1*, 14–27.
- Richardson, L., Loomis, J., Kroeger, T., et al. (2015). The role of benefit transfer in ecosystem service valuation. *Ecological Economics*, *115*, 51–58.
- Shao, Q. Q., Liu, S. C., Ning, J., et al. (2022). Assessment of ecological benefits of key national ecological projects in China in 2000–2019 using remote sensing. *Acta Geographica Sinica*, *77*(9), 2133–2153.
- Song, W., & Deng, X. (2017). Land-use/land-cover change and ecosystem service provision in China. *Science of the Total Environment*, *576*, 705–719.

- State Forestry Administration of China. (2012a). *The management measures for the archives of natural forest resource protection projects*. China Forestry Publishing House.
- State Forestry Administration of China. (2012b). *The management measures for forest management and protection of natural forest resource protection projects*. China Forestry Publishing House.
- State Forestry Administration of China. (2012c). *The verification measures for the second phase of natural forest resource protection projects*. China Forestry Publishing House.
- State Forestry Administration of China. (2019). *The plan for the system of natural forest protection and restoration*. China Forestry Publishing House.
- State Forestry Administration of China. (2020). *The general plan for the protection and restoration of important ecosystems in China (2021–2035)*. China Forestry Publishing House.
- Tezer, A., Turkay, Z., Uzun, O., et al. (2020). Ecosystem services-based multi-criteria assessment for ecologically sensitive watershed management. *Environment, Development & Sustainability*, 22(3), 2431–2450.
- Tian, H. J., Cao, C. X., Chen, W., et al. (2015). Response of vegetation activity dynamic to climatic change and ecological restoration programs in Inner Mongolia from 2000 to 2012. *Ecological Engineering*, 82(1), 276–289.
- Turner, R. K., Morse-Jones, S., Fisher, B., et al. (2010). Ecosystem valuation: A sequential decision support system and quality valuation issues. *Annals of the New York Academy of Sciences*, 1185(1), 79–101.
- Tuswa, N., Bugar, R. D. H., Mapeto, T., et al. (2019). The impacts of commercial plantation forests on groundwater recharge: A case study from George (Western Cape, South Africa). *Physics and Chemistry of the Earth*, 112, 187–199.
- Wang, B., Liang, Y., & Peng, S. (2022). Harnessing the indirect effect of urban expansion for mitigating agriculture-environment trade-offs in the Loess Plateau. *Land Use Policy*, 122, 106395.
- Wang, X. J., Zhang, B. Q., Xu, X. F., et al. (2020). Regional water-energy cycle response to land use/cover change in the agro-pastoral ecotone, Northwest China. *Journal of Hydrology*, 2020(580), 124246.
- Wang, Y., Zhao, J., Fu, J., et al. (2019). Effects of the Grain for Green Program on the water ecosystem services in an arid area of China—using the Shiyang River basin as an example. *Ecological Indicators*, 104, 659–668.
- Wang, Z., Jiao, J., Su, Y., et al. (2014). The efficiency of large-scale afforestation with fish-scale pits for revegetation and soil erosion control in the steppe zone on the hill-gully Loess Plateau. *CATENA*, 115, 159–167.
- Wu, J., & Chen, J. (2022). Coupling logic and implementation paths of agroforestry and high-quality agricultural development. *Journal of Northwest A&F University (Social Science Edition)*, 22(4), 153–160.
- Wu, X., Wang, S., Fu, B., et al. (2019). Socio-ecological changes on the Loess Plateau of China after Grain to Green Program. *Science of the Total Environment*, 678, 565–573.
- Xian, J. L., Xia, C. Q., & Cao, S. X. (2020). Cost-benefit analysis for China's Grain for Green Program. *Ecological Engineering*, 151, 105850.
- Xie, G. D., Zhang, C. X., Zhang, C. S., et al. (2015). The value of ecosystem services in China. *Resources Science*, 37(9), 1740–1746.
- Xie, G. D., Zhang, C. X., Zhen, L., et al. (2017). Dynamic changes in the value of China's ecosystem services. *Ecosystem Services*, 26(Part A), 146–154.
- Xu, Q., Yang, R., & Ren, Z. (2016). Analysis on the natural factors affecting NPP in Loess Plateau. *Agricultural Research in the Arid Areas*, 34(4), 244–250.
- Yang, S. Q., Zhao, W. W., Liu, Y. X., et al. (2018). Influence of land use change on the ecosystem service trade-offs in the ecological restoration area: Dynamics and scenarios in the Yanhe watershed, China. *Science of the Total Environment*, 644(1), 556–566.
- Yang, Y. F., Wang, B., Wang, G. L., et al. (2019). Ecological regionalization and overview of the Loess Plateau. *Acta Ecologica Sinica*, 39(20), 7389–7397.
- Yin, C., Zhao, W., Cherubini, F., et al. (2021). Integrate ecosystem services in socio-economic development to enhance achievement of sustainable development goals in the post-pandemic era. *Geography and Sustainability*, 1(2), 68–73.
- Zhang, J., Qu, M., Wang, C., et al. (2020). Quantifying landscape pattern and ecosystem service value changes: A case study at the county level in the Chinese Loess Plateau. *Global Ecology and Conservation*, 23, e01110.
- Zhang, Y., Zhao, X. L., Zuo, L. J., et al. (2019). The impact of land use change on ecosystem services value in Loess Plateau. *Remote Sensing for Land and Resources*, 31(3), 132–139.
- Zhou, Y., Li, X. H., & Liu, Y. S. (2020). Land use change and driving factors in rural China during the period 1995–2015. *Land Use Policy*, 99, 105048.
- Zhu, Z. C., Piao, S. L., Myneni, R. B., et al. (2016). Greening of the earth and its drivers. *Nature Climate Change*, 6, 791–795.

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