Spatiotemporal heterogeneity correction in land ecosystem services and its value assessment: a case study of the Loess Plateau of China

Lintao Liu (591365301@qq.com)
Gansu Agricultural University

Hengjia Zhang
Gansu Agricultural University https://orcid.org/0000-0002-1030-4644

Yao Zhang
Gansu Agricultural University

Fuqiang Li
Gansu Agricultural University

Xietian Chen
Gansu Agricultural University

Yong Wang
Gansu Agricultural University

Yingying Wang
Gansu Agricultural University

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Spatiotemporal heterogeneity correction in land ecosystem services and its value assessment: a case study of the Loess Plateau of China

Lintao Liu [a], Hengjia Zhang [a,*], Yao Zhang [b], Fuqiang Li [a], Xietian Chen [a] ,Yong Wang [a] , Yingying Wang [a]

[a] *College of Water Conservancy and Hydropower Engineering, Gansu Agricultural University, Lanzhou 730070, China*

[b] *College of Life Science and Technology, Gansu Agricultural University, Lanzhou 730070, China*

**Corresponding author. E-mail address: zhanghj@gsau.edu.cn (H.J. Zhang)*

ABSTRACT

The considerable variation in structures and functions of different ecosystems leads to highly variable ecosystem service values (ESVs). Consequently, the accurate quantification of ESVs can better assess and reflect impacts of land use and cover changes (LUCC) on ecosystem services. In the land use simulations of this study, a CA-Markov model was chosen and nine factors affecting land use change were evaluated, followed by the construction of a multi-criteria evaluation method to simulate land use scenarios between 2025 and 2030 on the Loess Plateau. Six key ecological indicators (economy, water production, net primary plant productivity, habitat quality, accessibility, and soil conservation) were used to correct for spatiotemporal heterogeneity within the terrestrial ESV equivalent weight table for China to obtain an ESV equivalent weight factor table that is applicable to the Loess Plateau. Using the newly corrected table, ESVs for the Loess Plateau region were estimated between 1995 and 2030, and the impacts of LUCC on ESVs were analyzed. The Kappa values for the 2015 land use simulation results were 80.2 and 82.6, which were greater than 0.75, indicating that the CA-Markov model simulations were accurate. Throughout the study period, the largest increases in land use type area were for built-up areas and forest lands, with built-up areas primarily derived from conversions of cultivated lands and grasslands, and forest land increases primarily coming from conversion of grasslands. ESVs increased overall by 933.97×10^8 yuan and 312.86×10^8 yuan from 1995 to 2018 and 2018 to 2030, respectively. The three largest contributors to ecosystem services among land use types were moderate grasses, shrublands, and dense grasslands. In conclusion, ESVs for the Loess Plateau steadily increased year by year from 1995 to 2030, indicating that ecological restoration projects played major roles in improving the stability and sustainability of the region's ecosystems.

Keywords: Land use change; Land use simulation; Land ecosystem service; Ecosystem ser vice values; Spatiotemporal heterogeneity correction; The Loess Plateau of China

1. Introduction

Ecosystem services refers to the various benefits that humans receive directly or indirectly from environments and are important features of regional ecological civilization and sustainable development (Costanza et al., 1997; Wang et al., 2018; Shi et al., 2021). Ecosystems provide numerous services to humans including supporting, regulating, provisioning, and cultural services (Costanza, 2014). The valuation of ecosystem services (ESVs) has become an important research focus (Snyder et al, 2019) that has significantly increased human awareness of ecosystem provisioning well-being and provided a scientific framework to better manage and sustainably develop environmental assets (Liu et al., 2021; Wang et al., 2016). However, ecosystem services are difficult to directly capture monetarily and their value is often overlooked, making it particularly important to assess ecosystem services via a scientific framework. Costanza et al. (1997) first quantified global ESVs, and the developed framework has become a well-used metric that has been used to quantify ESVs at different scales (Costanza et al., 2014; Sannigrahi et al., 2018). Costanza et al.'s (1997) ESV assessment model, in addition to being improved by others, was the basis for Xie et al. (2015) developing a standard unit ESV equivalent weight factor table that can be used to calculate terrestrial ESVs according to actual values for terrestrial ecosystems in China, and this table has been extensively used for many Chinese regions (Abulizi et al., 2016; Xie et al., 2015). The table refers to the economic value of natural food production per year for a 1 ha national average yield of farmland. The use of this equivalence factor as a reference, combined with expert knowledge and meta-analysis, can be used to determine the equivalence factor for other ecosystem services, which is useful for characterizing and quantifying the potential

contributions of different types of ecosystems to ecological service functions. However, ESVs are closely related to regional natural environments and socioeconomic conditions (Han et al., 2020). For example, functions related to raw material production, gas regulation, and nutrient cycling (Cao et al., 2017) are closely related to Net plant primary productivity (NPP). Further, functions like water supply and hydrological regulation, soil formation and retention, biodiversity protection, recreation, and culture are related to precipitation and evapotranspiration (Sharp et al., 2018), soil erosion (Sun et al., 2018), habitat quality (Li et al., 2016) and reachability (Paracchini et al., 2014), respectively. Thus, when the average unit price table is used to calculate ESVs for some Chinese regions, value assessments are clearly imprecise and do not accurately reflect actual ESVs for a region, in turn leading to inaccurate information being provided to policy makers. Therefore, studies of specific regions should consider the realities of the study area and modify natural environment parameters and socioeconomic factors according to regional ESVs and in reference to national ESVs.

Land use and cover change (LUCC) are inextricably linked to ecosystem services, and different land use types exhibit different land coverage that plays important and various roles in ecosystem service provisioning (Mendoza-González et al., 2012; Abulizi et al., 2016; Hu et al., 2020). In addition, LUCC reflects ecological processes and directly causes changes in ecosystem types, areas, and spatial distributions, in turn impacting the structures and functions of ecosystem services (Li et al., 2018). From a sustainable development perspective, human land use should be based on an accounting of ESVs to promote the rational exploitation of natural resources. Consequently, quantifying ESVs can help to better assess and reflect the impacts of LUCC on ecosystem services, and it is also an essential framework for ecological environmental protection, ecological function zoning, environmental economic accounting, and decision-making for ecological compensation (Sannigrahi et al., 2018). Land

use has been widely used to account for ESVs in recent years, but previous studies have given little consideration to the impacts of spatiotemporal heterogeneity when evaluating ESVs. Furthermore, most land use data used in early studies exhibited low precision and small study area scopes, along with lesser integration of future land use scenarios and ecosystem service assessments.

In this study, the distribution of ecosystem services was investigated in the Loess Plateau region of China, where soil erosion has been exacerbated by sparse vegetation, loose soils, periodic high-intensity rainstorms, and a long history of agricultural development (Huang and Shao, 2019; Zhao et al., 2013), thereby resulting in one of the most fragile ecosystems in the world. Moreover, the region has experienced significant LUCC in the past few decades. For example, many soil and water conservation projects in addition to ecological restoration projects have been implemented in the area after the 1970s including the construction of terraces, vegetation planting, natural vegetation restoration, and barrage construction (Fu et al., 2017; Xiu et al., 2021). The Chinese government implemented a policy of returning farmland to forestry in the region in 1999 that accelerated vegetation restoration in the area (Feng et al., 2016). Although these large-scale restoration measures have increased vegetation coverage in the Loess Plateau and significantly reduced runoff and sedimentation, the ecosystems throughout the region remain very fragile (Fu et al., 2017), and the effects of these policies on land use conversion and changes in ESVs remain unclear. Indeed, a paucity of ESV investigations in the Loess Plateau and the lack of consideration for spatiotemporal heterogeneity of ecosystem services in ESV assessments have led to a general lack of clarity in these values for the region. Thus, this region is ideal for studying the relationship between ecosystem services and land-use change.

Based on the above observations, a multi-criteria evaluation method was constructed in this study and used with the cellular automata (CA)-Markov model to simulate land use scenarios in 2025 and

2030 for the Loess Plateau. Additionally, six key ecological indicators including economy, water yield, net primary productivity of plants, habitat quality, accessibility, and soil conservation were selected to correct for the spatiotemporal heterogeneity of the Chinese terrestrial ESV equivalent weight table, and a dynamic and accurate ecosystem service value assessment method was subsequently obtained. We hypothesized that the evaluation method could be well used to assess the ESVs of the Loess Plateau from 1995–2030. Therefore, the objectives of present study were to determine: 1) analyzing the land use structure, changes, and land use interconversions in the Loess Plateau region between 1995 to 2030; 2) applying the revised ESV assessment framework to assess ESVs in this region between 1995 and 2030 while analyzing the impact of land use change on ESVs; and 3) revealing the spatiotemporal responses of different land use types and ecosystem service functions to ESVs in order to identify the mechanisms underlying their variation.

2. Study area and data source

2.1. Study area

The Loess Plateau (33°41′–41°16′ N, 100°52′–114°33′ E) is one of the four major plateaus of China, sitting at an altitude of 12–5,231 m and comprising a total area of about 64.9 × 10^4 km^2. The plateau features the most concentrated and largest loess areas of the world (Fig. 1), while also being one of the most critically fragile areas of the world due to soil erosion and environmental degradation. The Loess Plateau contains loose soils and much of its terrain is fragmented with hilly gullies. Rainfall on the plateau mostly occurs in the form of torrential downpours from July to September. The overall climate of the region is dry, with average annual precipitation and evapotranspiration of 490 mm and 350 mm, respectively, in addition to average annual temperatures of 3.6 to 14.3°C. The climate type of the plateau is classified as an Asian semi-arid continental monsoon climate zone. The Loess Plateau

area is the main hydrologically flowing region of the Yellow River and is the largest source of sediment for the lower reaches of the Yellow River, providing nearly 90% of the sediments for the lower reaches (Wang et al., 2016).

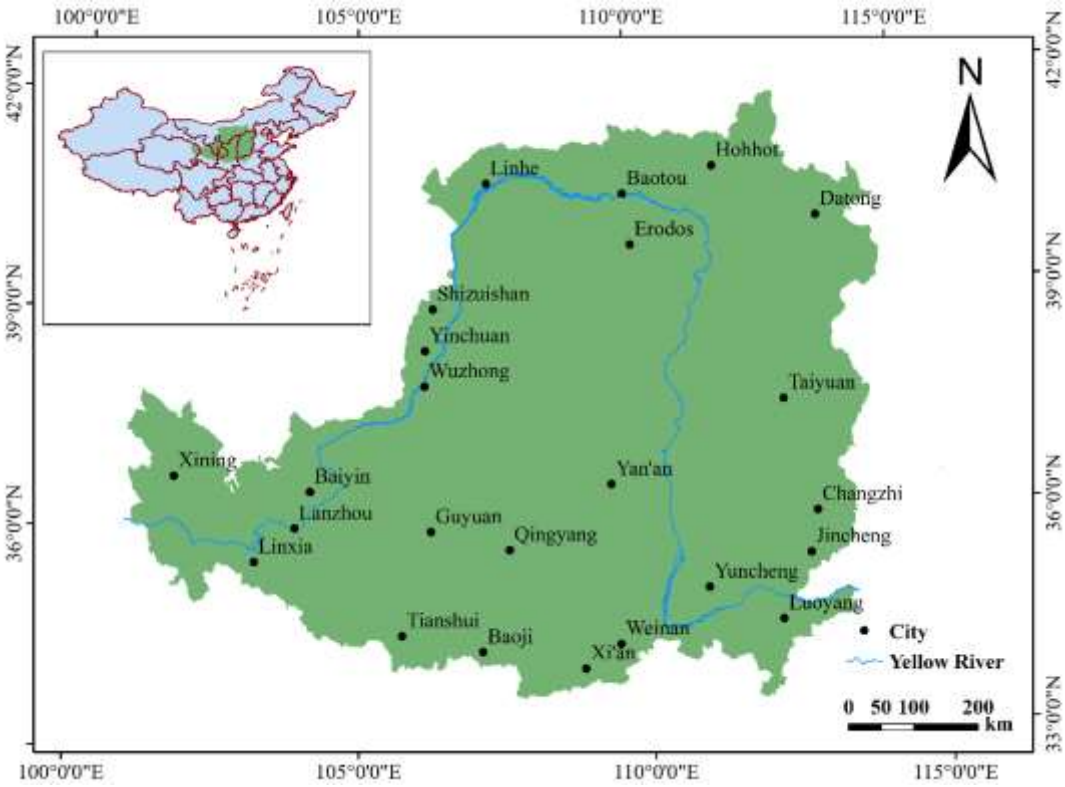

Fig. 1. Location of the study area.

2.2. Data sources

The land use data (1995, 2000, 2005, 2010, 2015, and 2018), net plant primary productivity (NPP) data (2000–2010), and precipitation data (2005–2015) used in this study were obtained from the Data Center for Resource and Environment Sciences at the Chinese Academy of Sciences (https://www.resdc.cn/), with a spatial land use data resolution of 30 m, with the other spatial resolutions being 1 km. Land use data derived from Landsat TM/ETM images were generated through visual interpretation based on national field surveys. Such data have been previously used in similar studies and exhibit an accuracy of over 90% (Chen et al., 2020). NPP data were obtained by calculating the light energy utilization model GLO_PEM, and the annual precipitation spatial interpolation dataset

was generated with daily observation data from over 2,400 meteorological stations nationwide through collation, calculation, and spatial interpolation processing. The meteorological data were generated as components of national field surveys. Elevation data were obtained from the Geospatial data cloud (https://www.gscloud.cn/), and slope data were calculated based on elevation data using the ArcGIS software program. Potential evapotranspiration data (2010–2014) were downloaded from the Global Aridity and PET Database (www.cgiar-csi.org/data/global-aridity-and-pet-database) and exhibit a spatial resolution of 1 km. The area and cost-return data for the three crops that were the focus of the study were obtained from the China Statistical Yearbook of 2010–2018, and the National Compilation of Cost-Return Information for Agricultural Products in 2010–2018, respectively. Road network data were obtained from OpenStreeMap (https://www.openhistoricalmap.org/). Distances to railroads, provincial roads, and national roads were obtained based on Euclidean distance calculations using ArcGis with a spatial resolution of 300 m. Distance from town construction, rural settlements, and deserts were obtained using ArcGis reclassification of land use data for each time period that was considered and Euclidean distance calculations at a spatial resolution of 300 m. The spatial coordinate systems used in this paper were all Krasovsky_1940_Albers.

3. Methodologies

3.1. Land use simulation

Land use simulation has become an intense area of research, with the main land use simulation methods including system dynamics, Markov models, Agent, CLUE-S simulations, CA, and CA-Markov models. CA-Markov models integrate the features of CA and Markov theory for temporal and spatial predictions, thereby enabling better spatiotemporal simulations of land change from quantitative and spatial perspectives (Sang et al., 2011). For the above reasons, CA-Markov modeling

was used in this study to simulate future land use scenarios along with nine mechanistic factors underlying land use characteristics including elevation, slope, rainfall, distance from national roads, distance from provincial roads, distance from railroads, distance from deserts, distance from rural areas, and distance from cities. The factors were also adjusted based on the actual characteristics of the study area (Fig. 2), with the specific operation steps and CA parameter settings shown in the Appendix.

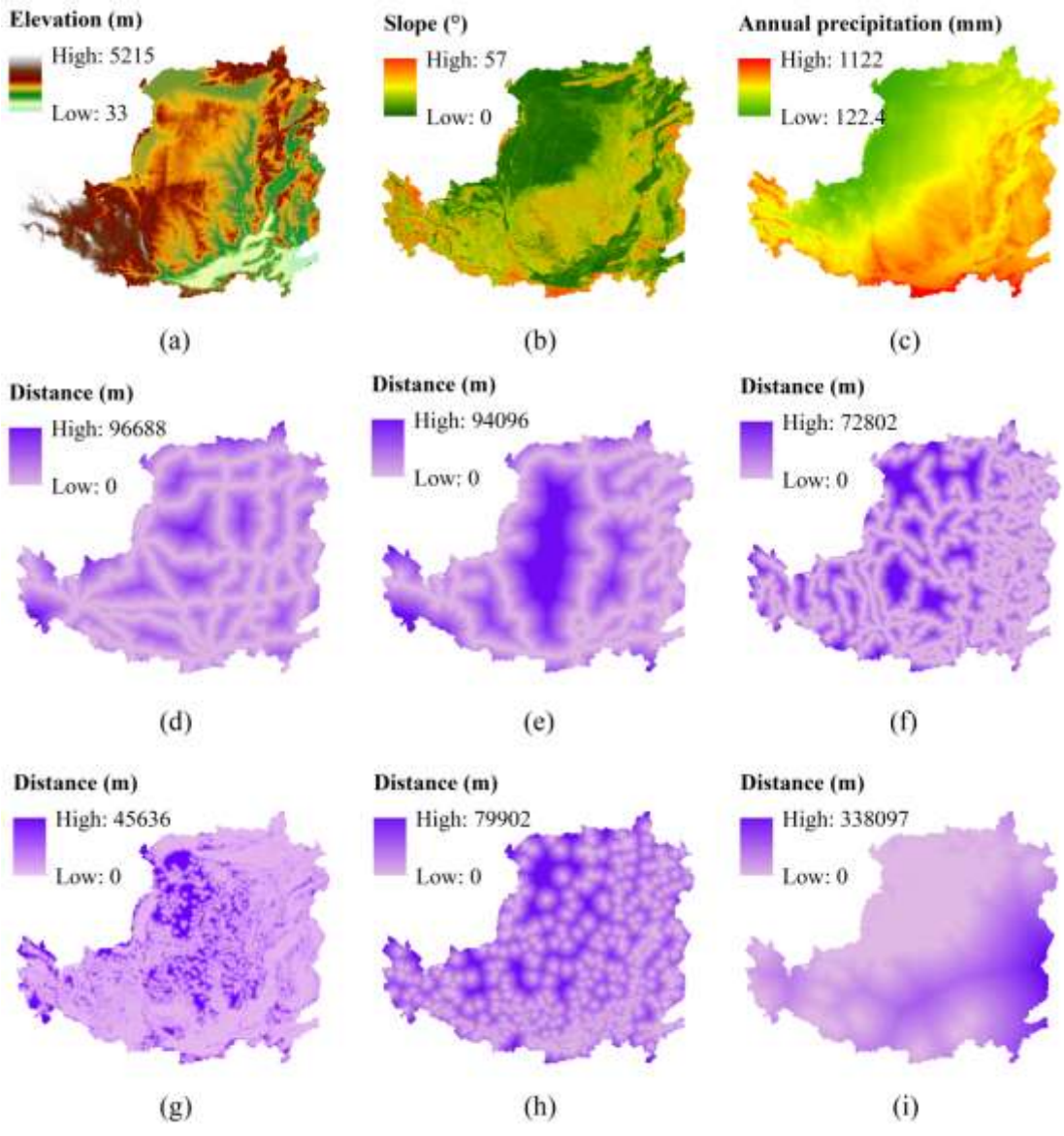

Fig. 2. Mechanistic factors underlying land use characteristics and land use simulations.

Note: (a), (b), (c), (d), (e), (f), (g), (h), and (i) indicate elevation, slope, and precipitation, in addition to distances from national roads, railways, provincial roads, urban, rural areas, and deserts in the study area, respectively.

3.1.1. CA-Markov model

The expression formulas for the CA-Markov model (Sang et al., 2011) are as follows:

$$S_{(t+1)} = P_{ij} \times S_{(t)}, \tag{1}$$

where $S_{(t)}$ and $S_{(t+1)}$ are the states of the landscape structure at t and $t+1$ times, respectively, while P_{ij} denotes the transfer state.

The expression formulas for P_{ij} are as follows:

$$P_{ij} = \begin{bmatrix} P_{11} & P_{12} & \mathrm{L} & P_{1n} \\ P_{21} & P_{22} & \mathrm{L} & P_{21} \\ \mathrm{M} & \mathrm{M} & \mathrm{L} & \mathrm{M} \\ P_{n1} & P_{n2} & \mathrm{L} & P_{nn} \end{bmatrix}, \tag{2}$$

where ($0 \le P_{ij} < 1$), $\sum_{j=1}^{n} P_{ij} = 1$ ($i, j = 1,2\Lambda\ ,n$),

$$S_{(t+1)} = f\left(S_t, N\right), \tag{3}$$

Where t and $t+1$ denote the times before and after the cellular automata, respectively; S is the discrete, finite set of states of the cellular automata; N is the domain of the cellular automata; and f is the spatial transformation rule for the cellular automata.

3.1.2. Kappa test

The expression formula for the Kappa Test model is as follows:

$$kappa = \frac{P_0 - P_c}{p_p - P_c}, \tag{4}$$

where P_0 is the proportion of correct simulations; P_c is the expected proportion of correct simulations in random scenarios; and P_p is the amount of correct simulations in the ideal classification case (i.e., 100%).

3.1.3 Degree of land use dynamism (K)

The expression formula of K (Gao et al., 2015) is as follows:

$$K = \frac{U_b - U_a}{U_a} \times \frac{1}{T} \times 100\%, \quad (5)$$

where K is the degree of land use dynamism during the study period; U_a and U_b are the areas of a land use type at the beginning and end of the study period, respectively; and T is the study period in years.

3.2. Calculation of ESVs

ESV was calculated using the following equations:

$$ESV_m = \sum_{j=1}^{m} V_{i,f} \times A_m \times D_r, \quad (6)$$

$$ESV_f = \sum_{j=1}^{f} V_{i,f} \times A_m \times D_r, \quad (7)$$

where ESV_m denotes the ecosystem service value for land-use type m ($m = 1,2\Lambda\ 12$); ESV_f denotes the value for ecosystem service function type f ($1,2\Lambda\ 11$); $V_{i,f}$ denotes the modified ESV equivalent factor table for area i; A_m is the area (ha) for land-use type m; and D_r indicates the value of ecosystem services for a modified 1 standard equivalent factor (yuan/ha).

3.3. ESV equivalent factor scale revision

Based on previous studies (Li et al., 2016; Name et al., 2014; Paracchini et al., 2014; Sun et al., 2018; Xie et al., 2015), 6 key ecological and economic (Fig. 2 (c), Fig. 3, and Fig. 4) indicators were selected to correct for the spatiotemporal heterogeneity of the 11 service functions (Table 4).

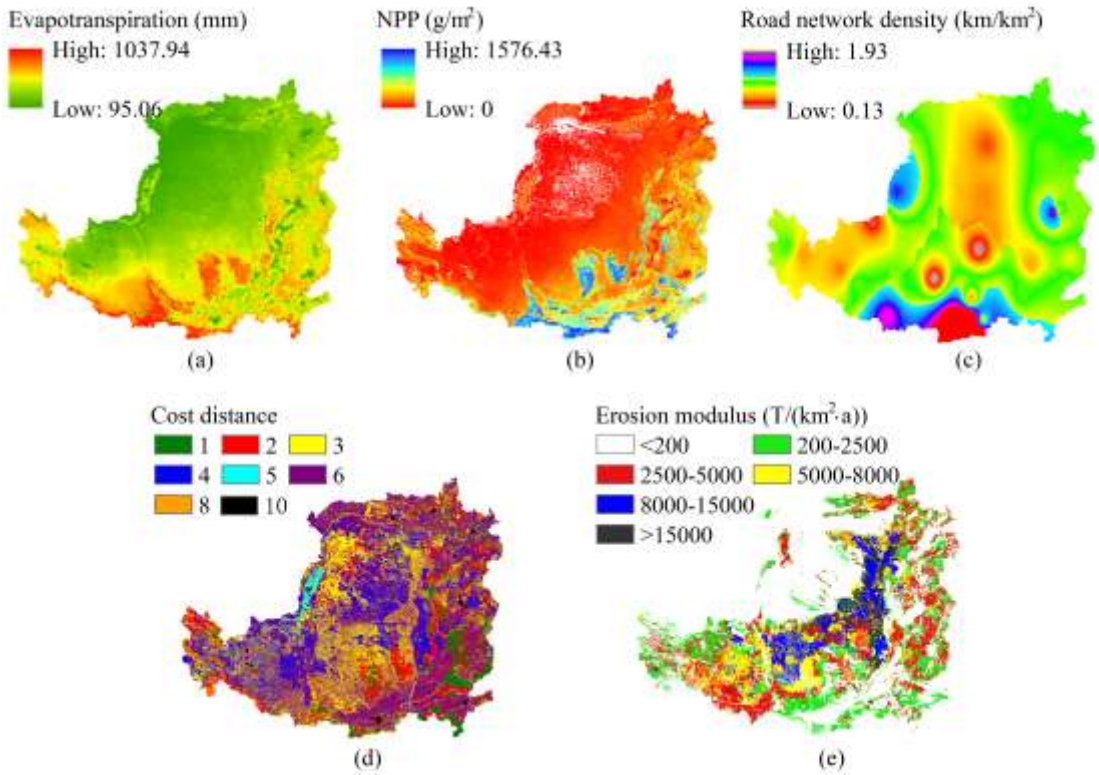

Fig. 3. Ecosystem service value correction factor for the study area.

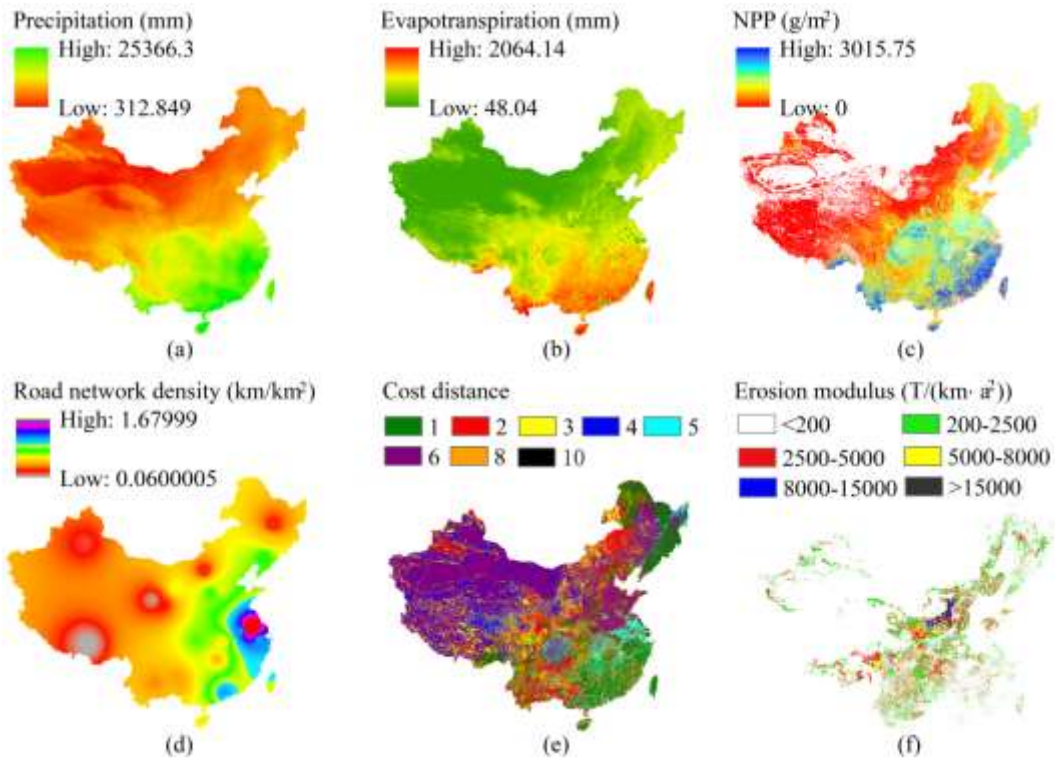

Fig. 4. Ecosystem service value correction factor for all of China.

The formula for the service functions is as follows:

$$V_{i,f} = V_f \times R_{(i,k)}, \tag{8}$$

where V_f denotes the average Chinese ecosystem service value equivalent factor scale; and $R_{(i,k)}$ denotes the corrected factor of type k ($k = 1,2\Lambda\ 6$) in region i.

3.3.1. Economic spatiotemporal correction factor

The national ESV equivalent factor table is corrected in this study with the average gross production value for the three major crops, followed by correction of a regional ESV equivalent factor table with the proportion of the three major crops grown relative to the gross production value. The economic value correction formulae were defined as follows:

$$D_r = \frac{1}{n} \times \frac{D_{2010}}{C_{2010}} \times \sum_{j=2013}^{n} C_n, \tag{9}$$

$$R_{(i,1)} = \frac{E}{\overline{E}}, \tag{10}$$

$$E = S_r \times A_r + S_w \times A_w + S_c \times A_c, \tag{11}$$

where D_{2010} and C_{2010} denote the average net profit and total value of output per hectare for the three crops in 2010, respectively; C_n denotes the average total value per hectare for the three crops in 2013–2018; S_r, S_w, and S_c denote the area sown for rice, wheat, and maize as a percentage (%) of the total area sown for the three crops in the study area in 2013–2018, respectively; and A_r, A_w, and A_c denote the total nationwide value of yield per hectare (yuan/ha) for rice, wheat, and maize from 2013 to 2018, respectively.

3.3.2. Water production spatiotemporal correction factor

Water production affects ESVs by influencing water supply and hydrological regulatory services. The contribution of water supplies from different landscapes can be estimated using the InVEST model that reflects how changes in land use patterns affect annual water production (Sharp et al., 2012). Land use structure also varies from region to region and impacts hydrological processes such as

evapotranspiration. Consequently, spatial and temporal corrections for water supply and hydrological regulations are needed for different areas to accurately assess regional ESVs. The average annual rainfall, transpiration, and evapotranspiration from 2010 to 2014 were used to calculate water yields, with the ratio of mean value of water yield in the study area (Fig. 2 (c) and Fig. 3 (a)) to the mean value for all of China (Fig. 4 (a) and (b)) used as a correction for regional water supply and hydrological regulation of ecosystem services. The water production correction formulae were defined as follows:

$$R_{(i,5)} = \frac{WY_i}{\overline{WY}}, \tag{12}$$

$$WY_i = (1 - \frac{ET_i}{R_i}) \cdot R_i, \tag{13}$$

$$\overline{WY} = (1 - \frac{ET_a}{R_a}) \cdot R_a, \tag{14}$$

where WY_i denotes the average annual water yield in the study area and $\overline{WY}$ denotes the average annual water yield nationwide; R_i and R_a denote the average annual rainfall in the study area and nationwide between 2010 and 2014, respectively; and ET_i and ET_a denote the average transpiration and evapotranspiration for the study area and nationwide from 2010 to 2014, respectively.

3.3.3. NPP spatiotemporal correction factor

Net plant primary productivity (NPP) is an important component of the surface carbon cycle and directly reflects the productive capacity of vegetation communities under natural environmental conditions while also characterizing the quality status of terrestrial ecosystems. In addition, NPP is also a major factor that determines ecosystem carbon sources/sinks and regulates ecological processes, thereby playing important roles in global change and carbon balances (Peng et al., 2016). Hence, NPP differences reflect ESV differences owing to variation among regions and land use types. In this study, the mean NPP value for the study area (Fig. 3 (b)) from 2000 to 2010 was used as a ratio to the mean

value for all of China (Fig. 4 (c)) to correct for regional gas regulation and nutrient cycling ecosystem services. The NPP correction formula was defined as follows:

$$R_{(i,4)} = \frac{N_i}{\overline{N}}, \tag{15}$$

where N_i denotes the average annual NPP for the study area and $\overline{N}$ denotes the nationwide average annual NPP.

3.3.4. Habitat quality spatiotemporal correction factor

A key goal for sustaining biodiversity is the effective conservation of species' habitats (Rew et al., 2020) that provide animals with basic environmental conditions like adequate water, food, shelter, and breeding sites. However, differences exist in the conditions provided for animals in different habitat types. For example, constructed areas provide little habitat for animals and can negatively affect their survival. In addition, the survival and reproductive success of a species partially depends on the number, condition, and spatial arrangement of habitat components (Hirzel and Lay, 2008). Further, some animals have migratory habits, wherein the type of land use and distance of the pathway varies during migration, and the resistance values encountered along the way vary in magnitude. A large resistance value refers to poor habitat quality and is not conducive to promoting biodiversity in an area. In this study, ArcGis cost distance was used to calculate the level of resistance of an area to biological migration. Based on previous analyses (Li et al., 2016), forest land was set as the most suitable habitat, while the rest of the land use types were set as cost rasters. The resistance values of land use types (Appendix) were then set as previously described (Li et al., 2016). The habitat quality correction formula was defined as follows:

$$R_{(i,2)} = 1 \Big/ \left(\frac{CD_i}{\overline{CD}}\right), \tag{16}$$

where CD_i denotes the degree of migration resistance in this study area (Fig. 3 (c)) and $\overline{CD}$

denotes the nationwide average degree of migration resistance (Fig. 4 (d)).

3.3.5. Reachability spatiotemporal correction factor

Cultural ecosystem services are defined as "the non-material benefits that people derive from ecosystems through spiritual satisfaction, cognitive development, reflection, recreation, and aesthetic experiences" (Scholte et al., 2004). Although cultural ecosystems are intangible services, they play important roles in bridging ecosystems and social systems. The Recreation Opportunity Spectrum (ROS) theory posits that the function of cultural services primarily depends on the Recreation Potential Index (RPI) and the Accessibility of Recreation Sites Index (ARSI). In turn, the RPI depends on the attractiveness and accessibility of the area. Further, accessibility reflects the real level of cultural service functions of the ecosystem. The national average road density (Fig. 4 (e)) and the average road density (Fig. 3 (d)) for the study region were calculated using ArcGis and their ratios were used to reflect the capacity for cultural supply. That is, denser average road values and more convenient transportation accessibility would lead to a stronger capacity for cultural service supply. The reachability correction formula was defined as follows:

$$R_{(i,3)} = \frac{RD_i}{\overline{RD}}, \tag{17}$$

where RD_i denotes the average road density in the study area and RD denotes the national average road density.

3.3.6. Soil conservation spatiotemporal correction factor

Soil erosion carries away large abundances of soil nutrients and destroys soil structures, leading to gradual deterioration of soil ecosystems that then directly affects soil quality, agricultural productivity, and biodiversity. Further, accelerated soil erosion leads to the loss of the soil's ability to hold water, leading to pollution of water sources and damaging water engineering facilities by increasing

sedimentation in water (Wynants et al., 2018). Consequently, soil hydraulic erosion intensity was used in this study to correct for soil conservation ecosystem services in the study area. The ratio of the mean value of soil hydraulic erosion intensity for China (Fig. 4 (f)) to the mean value of soil hydraulic erosion intensity for a given area (Fig. 3 (e)) was used as the regional spatiotemporal correction factor for soil erosion. The soil conservation correction formula was defined as follows:

$$R_{(i,6)} = 1 \Big/ \left(\frac{S_i}{\overline{S}} \right), \tag{18}$$

where S_i denotes the average erosion modulus for the study area and $\overline{S}$ denotes the nationwide average erosion modulus.

The basic framework for the study design is shown in Fig. 5.

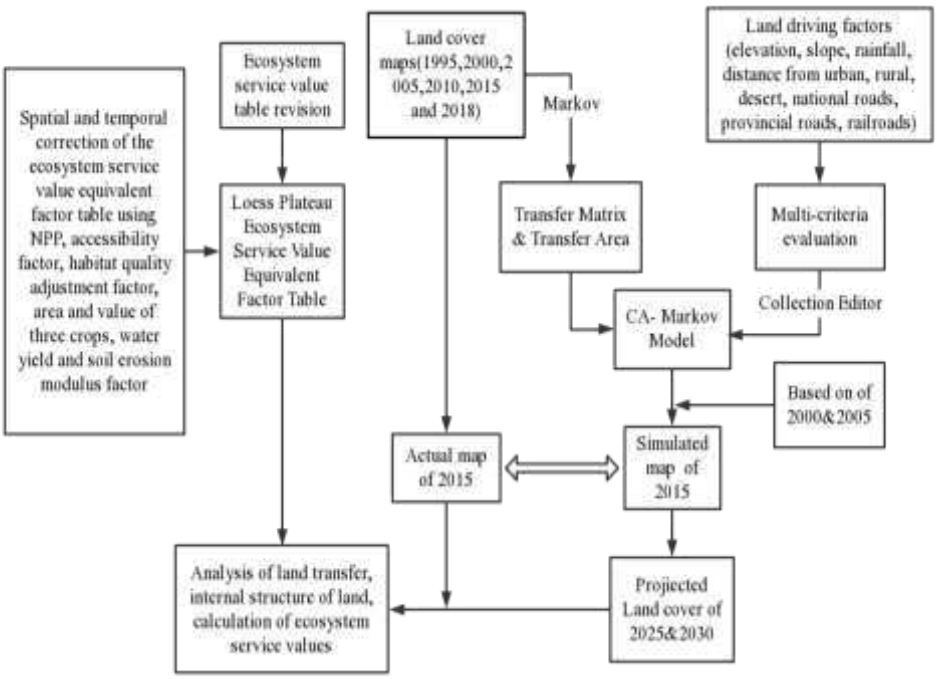

Fig. 5. Schematic showing the design framework for this study.

4. Results and analyses

4.1. Land use simulations

To verify simulation accuracy, land use was predicted for 2015 using the land use in 2000 and

2005, revealing Kappa values of 80.2% and 82.6% (Table 1), respectively. The average forecast rates for cultivated lands, forest lands, grasslands, water bodies, built-up areas, and unused lands in 2015 were 78.9%, 79.8%, 83.4%, 85.6%, 75.3%, and 80.7%, respectively. Given that these values were both > 0.75, the simulation results were appropriate and could accurately reflect future land use scenarios. Consequently, the CA-Markov model was used to simulate the 2025 and 2030 (Fig. 6) land use scenarios for the Loess Plateau.

Table 1

Accuracy of land use predictions in 2015 for different time series.

Kappa values (%)							
2015	Overall prediction	Cultivated land	Forest land	Grassland	Water body	Built-up area	Unused land
First forecast	82.6	81.5	80.2	85.2	85.8	75.4	81.6
Second forecast	80.2	78.3	79.3	82.5	85.4	75.2	79.8
Average	81.4	79.9	79.8	83.9	85.6	75.3	80.7

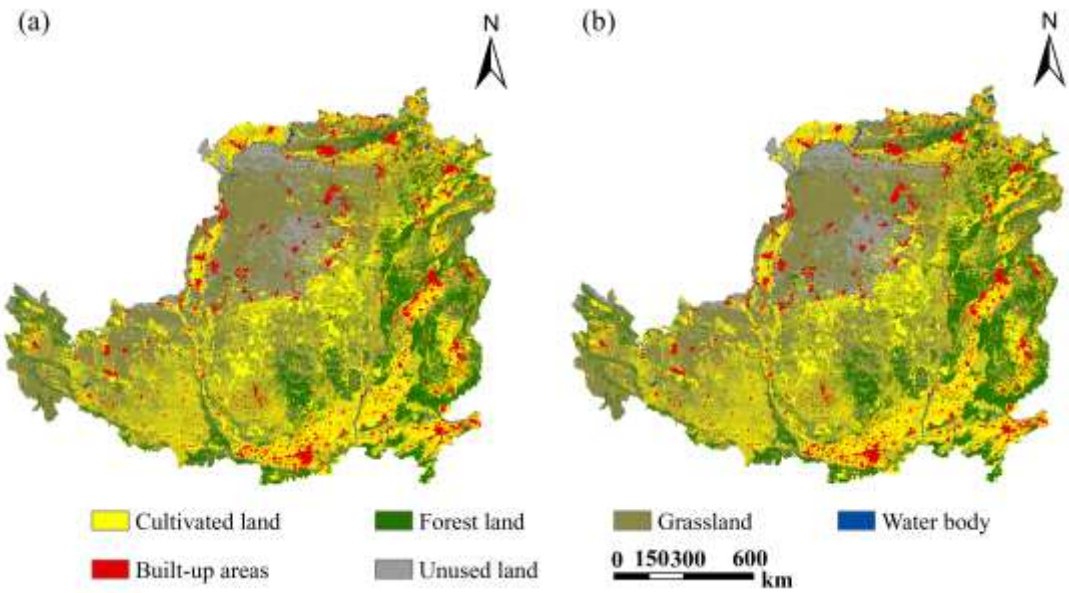

Fig. 6. Land use scenarios for 2025 (a) and 2030 (b).

4.2. Land use structure, changes, and transformation patterns

4.2.1. Analysis of land use structures

Grasslands accounted for the largest proportion of land cover in the Loess Plateau (41.7%), followed by cultivated lands (32.3%), forest lands (14.9%), unused lands (6.4%), built-up areas (3.2%), and water bodies (1.4%) (Fig. 7). Among grasslands, moderate grasslands (46.9%) accounted for the largest share (Fig. 8). In addition, dry land primarily constituted the cultivated lands within the Loess Plateau (97.3%). The area of forest land was dominated by forest and shrub lands, with the sum of the two accounting for about 78%. Among built-up areas, rural settlements comprised the largest portion (67.6%), while sandy land comprised the largest portion of unused land (71.6%), and swampland only accounted for 2.4% of unused land. Water body area primarily comprised streams, rivers, and bottomlands (74.9%).

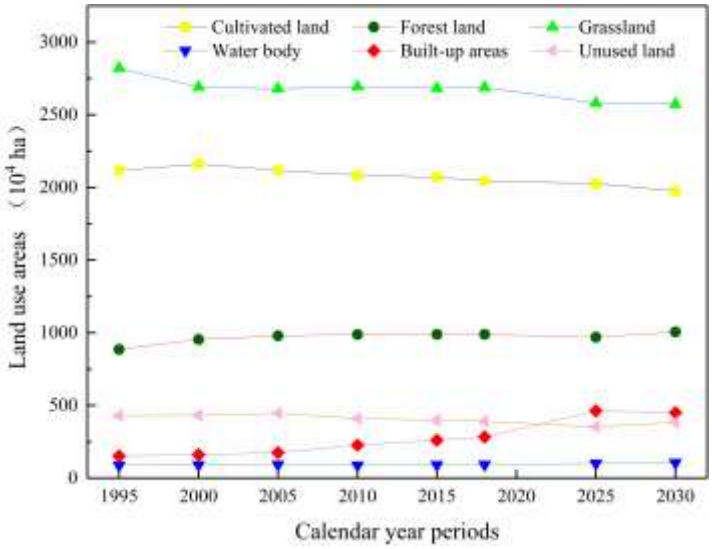

Fig. 7. First-class land use change trends in the Loess Plateau.

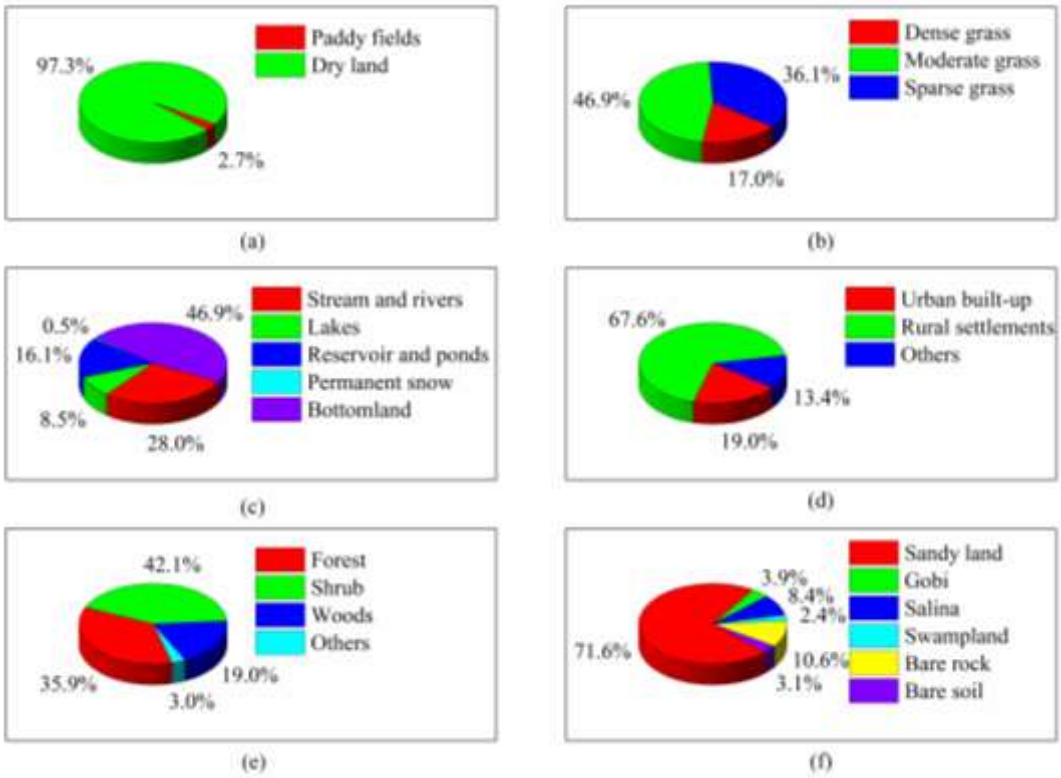

Fig. 8. Secondary land use structures in the Loess Plateau.

4.2.2. Analysis of land use dynamics

The rate of land use type changes exhibited varying characteristics among different stages during the study period (Table 2), with the most prominent changes being those for built-up areas. The K value for built-up areas was the highest among land use types (1.11–9.04%) between 1995 and 2025, indicating that built-up area types increased the most over this period. The K value for construction areas was −0.52% between 2025 and 2030, indicating that built-up areas will begin to decrease during this period. The K value for cultivated land was only positive for the period corresponding to 1995–2000, indicating that cultivated land growth only occurred during this period. Overall, the K values for built-up areas, water bodies, and forest lands were 5.59%, 0.57%, and 0.39% throughout the study period, respectively, indicating increased land uses for these land types. In contrast, the K values for unused land, grassland, and cultivated land were −0.30%, −0.25%, and −0.19%, respectively,

indicating decreased land use for these types.

Table 2

Land use dynamics for the study area between 1995 and 2030.

Land use types	K values (%)							
	1995–2000	2000–2005	2005–2010	2010–2015	2015–2018	2018–2025	2025–2030	1995–2030
Cultivated lands	0.43	−0.41	−0.32	−0.14	−0.40	−0.13	−0.51	−0.19
Forest lands	1.56	0.51	0.19	0.02	−0.01	−0.28	0.75	0.39
Grasslands	−0.93	−0.08	0.11	−0.08	0.07	−0.58	−0.06	−0.25
Water bodies	0.84	0.40	−1.07	0.54	0.71	1.29	0.88	0.57
Built-up areas	1.11	1.76	5.94	3.01	2.84	9.04	−0.52	5.59
Unused lands	0.20	0.63	−1.66	−0.59	−0.51	−1.38	1.68	−0.30

4.2.3. Land use changes and transformation patterns

Built-up areas increased from 1995 to 2018 (Fig. 7), exhibiting a net increase of 131.06 × 10^4 ha (Table 4) and this primarily occurred due to the conversion of cultivated lands and grasslands, with change values of 74.19 × 10^4 ha and 39.84 × 10^4 ha, respectively. Forest lands generally increased (net increase of 1,03.64 × 10^4 ha or 11.7%), and this primarily occurred due to the conversion of grasslands (87.98 × 10^4 ha). Net increases in watershed areas comprised 5.09 × 10^4 ha, primarily from the conversion of grassland (4.29 × 10^4 ha) and unused land (2.62 × 10^4 ha). The net increase in built-up areas was 112.15 × 10^4 ha between 2018 to 2030, representing an increase of 26.9%, with a net conversion of 54.61 × 10^4 ha and 52.21 × 10^4 ha to cultivated land and grassland, respectively. The net increases in forest lands and water bodies were smaller, at 9.17 × 10^4 and 11.8 × 10^4 ha, respectively. The increase in built-up areas, forest lands, and water bodies during these two study periods were primarily concentrated in the core metropolitan area (Fig. 9) within the southeastern region of the Loess Plateau and around the Yellow River, respectively.

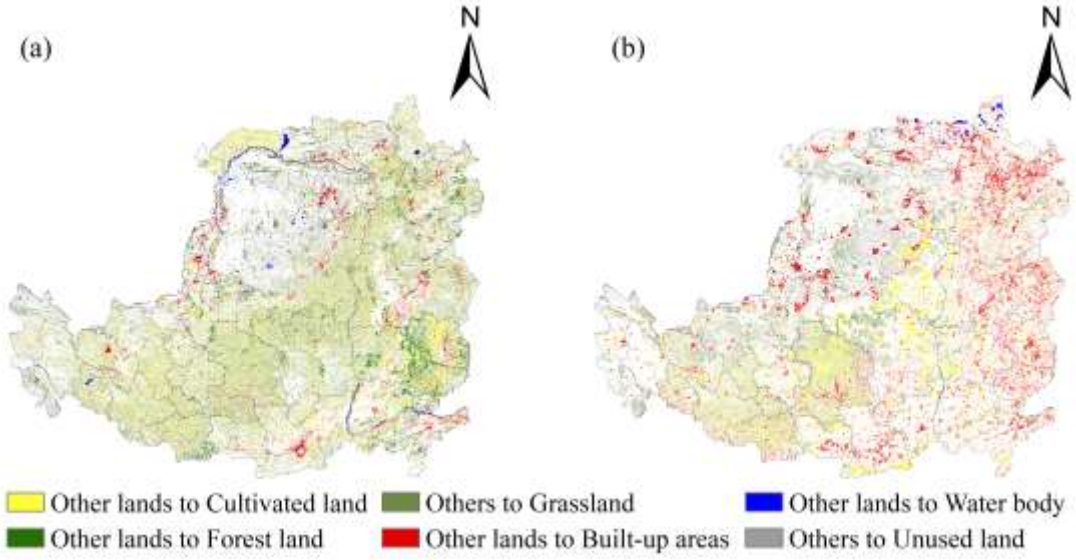

Fig. 9. Land area conversion on the Loess Plateau from 1995 to 2018 (a) and 2018 to 2030 (b).

4.3. Changes in the values of ecosystem services and their contributions

Land use reclassification data were used for ESV accounting (Table 3).

Table 3

Land use reclassification data for the Loess Plateau.

First-class classification	Secondary Classification	Source Code	Reclassification	Recoding
Cultivated lands	Paddy fields	11	Paddy fields	11
	Dry lands	12	Dry lands	12
Forest lands	Forests	21	Forests	21
	Shrubs	22	Shrubs	22
	Woods	23	Shrubs	22
	Others	24	Shrubs	22
Grasslands	Dense grasses	31	Scrubs	31
	Moderate grasses	32	Meadows	32
	Sparse grasses	33	Prairies	33
Water bodies	Streams and rivers	41	Water systems	41
	Lakes	42	Water systems	41
	Reservoirs and ponds	43	Water systems	41
	Permanent ice and snow	44	Permanent ice and snow	44
	Beaches and shores	45	Wetlands	64
	Bottomlands	46	Wetlands	64
Built-up areas	Urban built-up	51	Bare soils	65
	Rural settlements	52	Bare soils	65

	Others	53	Bare soils	65
	Sandy lands	61	Deserts	61
	Gobi	62	Deserts	61
	Salina	63	Bare soils	65
Unused land	Swamplands	64	Wetlands	64
	Bare soils	65	Bare soils	65
	Bare rocks	66	Bare soils	65
	Others	67	Bare soils	65

Note: The data source of original land use classifications comes from Liu et al. (2005).

4.3.1. Changes in ESVs between 1995 and 2030

ESVs exhibited overall increases during 1995–2030 (Fig. 10(b)), with a total increase of 1,246.83 × 10^8 yuan. In phase 1 (1995–2018), total ESVs increased by 933.97 × 10^8 yuan, with the largest increase of 532.37 × 10^8 yuan occurring between 1995 and 2000. In 1995, the total ESV was 21,118.49 × 10^8 yuan, with regulatory services comprising the largest portion (14,170.50 × 10^8 yuan; 67.1% of the total), followed by supporting services (14.9%), provisioning services (10.6%), and cultural services (7.4%). The total ESV in 2018 was 22,052.46 × 10^8 yuan and this primarily derived from an increase in regulatory services (753.88 × 10^8 yuan) and increases support, cultural, and provisioning services of 84.56 × 10^8, 54.84 × 10^8, and 40.69 × 10^8 yuan, respectively. In phase 2 (2018–2030), the total ESV increased by 312.86×10^8 yuan, while the ESV decreased by 269.75 × 10^8 yuan in 2018–2030. In phase 2, support services and cultural services decreased by approximately 46.17 × 10^8 and 9.85 × 10^8 yuan, respectively. In contrast, the values of regulatory and provisioning services increased by 366.18 × 10^8 and 2.71 × 10^8 yuan, respectively. As indicated above, the regions with the most significant changes in ecosystem services were primarily located in the southeastern areas of the Loess Plateau and around rivers.

4.3.2. Contribution of different land use types to ESVs

Different land use types differentially contributed to ESVs (Fig. 10(a)). The five land use types

with the highest contributions to total ESVs throughout the study period were moderate grasslands, water systems, shrublands, scrublands, and forestlands that accounted for 21.0%, 18.1%, 13.8%, 13.0%, and 12.0% of total ESVs, respectively. Although the area covered by water systems was only 0.8% of the study area, the total ESV contributed by water systems was 18.1%. Throughout the study period, the total ESVs increased for water system, forest, shrub, and bare soil land ecosystems, at levels of 699.33×10^8, 941.43×10^8, 467.51×10^8, and 19.55×10^8 yuan respectively. In contrast, the greatest decreases were observed for sparse grass, moderate grassland, and dry land ecosystem services, by 400.6×10^8, 267.84×10^8, and 129.34×10^8 yuan respectively.

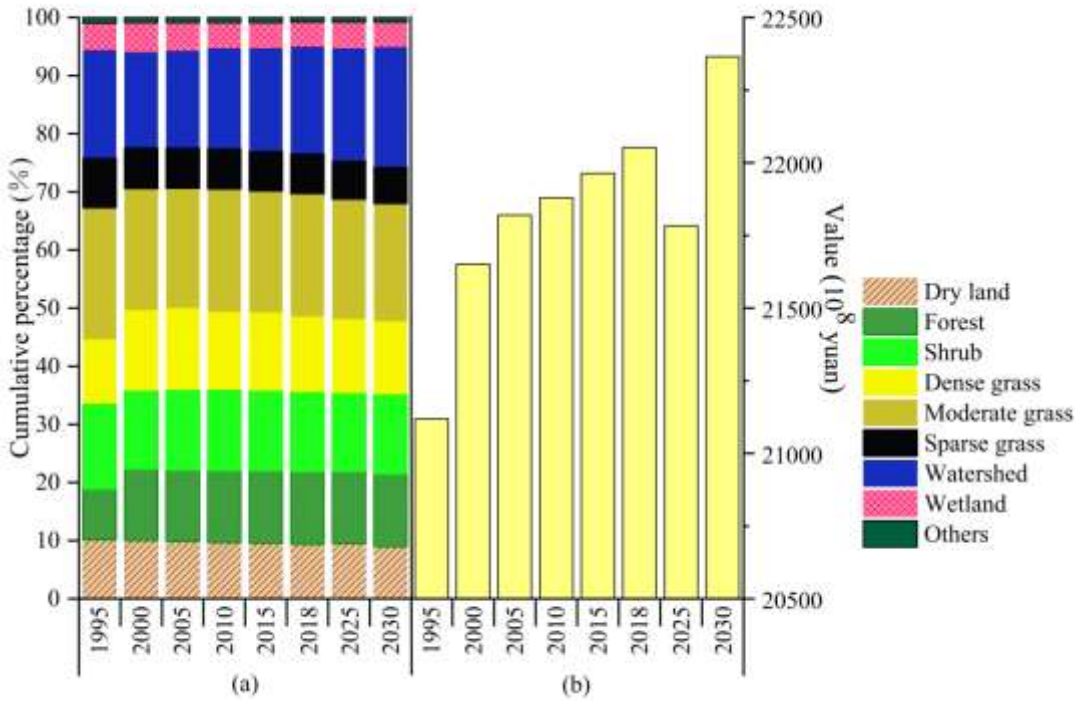

Fig. 10. Contribution of land use types to ESVs (a) and total values among different periods (b).

Note: The secondary-class land use estimates in 2025 and 2030 were calculated from the product of first-class land use types and the proportion of each secondary land use type in 2025 and 2030, while the proportions of secondary land use types were calculated from 2015 land use data via Markov modeling.

4.3.3. Contribution of ecosystem service functions to ESVs

The contributions of different ecosystem service functions to total ESV varied (Fig. 11). Across the study period, the five most influential individual ecosystem services based on their contribution to total ESV were hydrological regulation (6,597.9 × 10^8 yuan), climate regulation (5,291.15 × 10^8 yuan), biodiversity (2,172.99 × 10^8 yuan), environmental purification (1,856.02 × 10^8 yuan), aesthetic landscapes (1,612.26 × 10^8 yuan), and gas regulation (989.59 × 10^8 yuan) that together accounted for 84.84% of total ESVs. The total value of contributions from other categories of individual ecosystem services (i.e., service production, soil conservation, raw material production, water supply, and maintenance of nutrient cycles) was 3,309.1 × 10^8 yuan, representing 15.16% of the total ESV. Hydrological regulation, climate regulation, water supply, purification of the environment, recreation and culture, and biodiversity increased between 1995 and 2030 by 946.47 × 10^8, 103.57 × 10^8, 90.29 × 10^8, 71.3 × 10^8, 44.97 × 10^8, and 41.94 × 10^8 yuan, respectively. Food production decreased the most among categories (by 40.05 × 10^8 yuan), accounting for 77.4% of overall decreases.

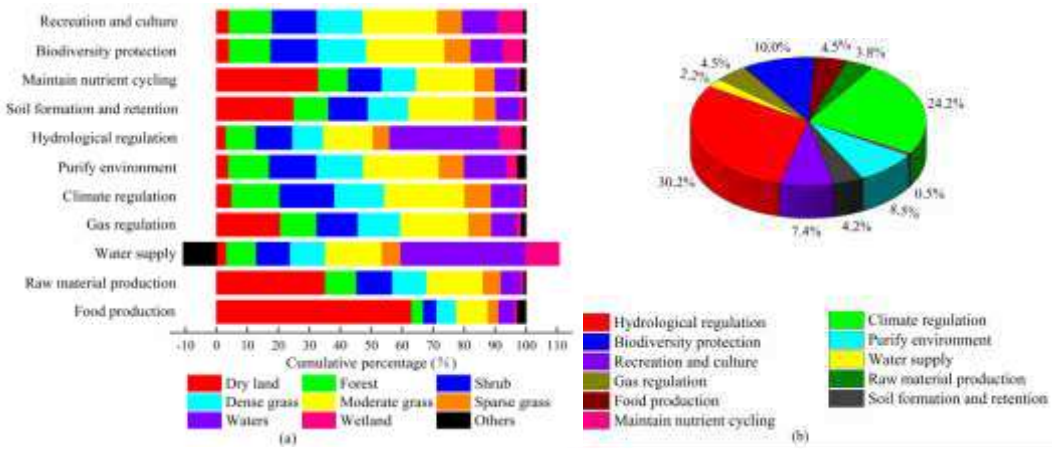

Fig. 11. Contribution of different land use types to ecosystem functions (a) and the value of various ecosystem service functions (b).

Table 4

Land use conversion area (10^4 ha).

	Land use types	Cultivated lands	Forest lands	Grasslands	Water bodies	Built-up areas	Unused lands	Total
1995 to 2018	Cultivated lands	1,664.76	56.56	270.67	14.47	100.93	8.31	2,115.71
	Forest lands	38.74	749.16	86.21	2.01	8.28	1.37	885.76
	Grasslands	284.54	174.19	2,249.20	11.40	46.40	55.20	2,820.93
	Water bodies	13.64	1.69	7.11	57.17	3.53	4.67	87.80
	Built-up areas	26.74	1.51	6.56	0.90	116.25	0.56	152.51
	Unused lands	16.83	6.30	69.09	6.93	8.19	321.48	428.82
	Total	2,045.25	989.39	2,688.84	92.88	283.57	391.58	6,491.52
2018 to 2030	Cultivated lands	1,559.97	70.05	201.97	10.44	122.86	9.13	1,974.42
	Forest lands	52.13	836.06	88.23	3.15	19.10	7.17	1,005.83
	Grasslands	234.38	98.70	2,099.70	8.36	72.60	58.25	2,571.99
	Water bodies	6.63	0.85	5.37	87.69	2.17	2.82	105.53
	Built-up areas	68.25	6.66	20.38	4.06	346.74	4.68	450.77
	Unused lands	13.24	2.68	62.05	3.01	8.46	293.43	382.86
	Total	1,934.61	1,015.01	2,477.69	116.71	571.92	375.49	6,491.42

Table 5

Modified Ecosystem Service Equivalent Factor Values (yuan/ha).

Ecosystem	Ecosystem	Cultivated land	Forest land	Grassland	Water body	Wetla	Unused land

service classification	service functions	Paddy field	Dry land	Forest	Shrub	Scrub	Meadow	Prairie	Water system	Permanent ice and snow	nd	Desert	Bare soil
Provisioning services	Food production	1.43	0.89	0.31	0.20	0.40	0.23	0.11	0.84	0.00	0.54	0.01	0.00
	Raw material production	0.09	0.42	0.69	0.45	0.59	0.35	0.15	0.24	0.00	0.53	0.03	0.00
	Water supply	−2.92	0.02	0.38	0.24	0.34	0.20	0.09	9.21	2.40	2.88	0.02	0.00
Regulating services	Gas regulation	0.49	0.30	0.96	0.63	0.87	0.51	0.23	0.34	0.08	0.84	0.05	0.01
	Climate regulation	0.60	0.38	6.84	4.45	5.48	3.18	1.41	2.41	0.57	3.79	0.11	0.00
	Environmental purification	0.18	0.11	2.03	1.35	1.81	1.05	0.46	5.84	0.17	3.79	0.33	0.11
	Hydrological regulation	3.02	0.30	5.27	3.72	4.24	2.46	1.09	113.59	7.92	26.92	0.23	0.03
Supporting services	Soil formation and retention	0.00	0.34	0.86	0.56	0.78	0.45	0.20	0.30	0.00	0.75	0.04	0.01
	Nutrient cycling maintenance	0.08	0.05	0.09	0.06	0.08	0.05	0.02	0.03	0.00	0.08	0.00	0.00
	Biodiversity protection	0.21	0.13	2.42	1.58	2.19	1.28	0.56	2.56	0.01	7.90	0.12	0.02
Cultural services	Recreation and culture	0.14	0.10	1.86	1.11	1.54	0.90	0.40	3.03	0.14	7.59	0.08	0.02

5. Discussion

5.1. Analysis of land use simulation and change

Land use data were evaluated in this study for the Loess Plateau, with land cover datasets deriving from recognized institutions or official statistic databases at a spatial resolution of 30 m and with an accuracy of over 90%. In the land use simulations of this study, a grid size of 300 m × 300 m (converted from a spatial resolution of 30 m × 30 m) was chosen and nine factors that affect land use change were evaluated, followed by the construction of a multi-criteria evaluation method (Appendix) to simulate predicted land use scenarios on the Loess Plateau. The accuracy of the CA-Markov model varied for different land use simulations (Table 1). For example, built-up areas exhibited relatively low prediction accuracy, primarily due to the close association of built-up areas with social and economic development (Cai and Wang., 2020). Social and economic development in China is influenced by national policies, and thus, policy changes significantly impact the size and location of construction lands. Kappa tests revealed that longer forecast series led to lower forecast accuracy. For example, the accuracy of the 10- and 15-year forecasts were 82.6% and 80.2%, respectively. Therefore, future forecasts should consider policy influences and the impact of forecast time series on CA-Markov model results as much as possible.

During the rapid economic development and urbanization that has occurred in the past few decades, land use in the Loess Plateau has undergone unprecedented changes. Croplands, grasslands, and unused lands decreased between 1995 and 2030, while built-up areas, water area, and wetlands increased over this time (Fig. 7). Moreover, forest lands and built-up areas increased by 50.69% and 159.41%, respectively, primarily due to conversion from grasslands and croplands. The reasons underlying these LUCCs are primarily related to policies promulgated by the Chinese government in

the region, including returning farmlands to forests and grasslands (Wang et al., 2019), banning free grazing, the Beijing–Tianjin Wind and Sand Source Control Project (Shan et al., 2015; Zhao et al., 2020), and the China Wetland Conservation Initiative (Meng et al., 2017). These ecological conservation measures have altered land use patterns in the Loess Plateau, and the regional ecosystem has gradually developed in a healthy and stable direction. Spatial distribution analysis (Fig. 9) indicated that increases in forest land and built-up areas were primarily concentrated in the southern region of the Shanxi Province and the core metropolitan area, while increases in arable land, water area, and wetlands were primarily concentrated around the Yellow River. Agricultural intensification is one of the main drivers of land use change and people have reclaimed high-quality farmland close to water sources to generate higher agricultural yields and increase investments in water conservation facilities (Liu et al., 2013). Thus, farmland and water areas have gradually expanded around the river. The accelerated urbanization rate in China after 2000 has resulted in abundant built-up areas encroaching on arable lands. The increases in built-up areas are primarily concentrated in the core metropolitan areas, also indicating that urbanization and infrastructure development in the study area are also accelerating.

5.2. Comparison with ESV changes identified in other studies

The ESV valuations of this study are much higher than those based on the amount of value per unit area for two reasons. First, the price basis for expressing the value in this study differs from other studies. Xie *et al.* (2015) previously used the average net profit per hectare metric for three major crops to develop the ES equivalent factor table. Sharp rises in grain production costs over time, coupled with the Chinese government's moderate increase in macro-control and the associated grain price subsidy policies have led to successive declines or even negative average net profits per hectare for the three

major crops. Thus, it is clearly not reasonable to use the average net profit per hectare value for the three main crops across a year to calculate ESV equivalent weight factor tables. Rather, the total value of the three main crops has remained relatively stable and it is consequently more reasonable to use this value to correct the ESV table. Second, differences in the conditions of ecological service functions among different regions are considered, and the strength of different ecosystem service functions is influenced by different ecological processes and conditions (Constanze et al., 1997). Importantly, this study corrected the spatiotemporal heterogeneity of ESVs using six key ecological indicators including the economy, water production, NPP, habitat quality, accessibility, and soil conservation, ultimately obtaining a table of ESV equivalent weighting coefficients that is applicable to the Loess Plateau (Table 5). Furthermore, some issues were identified with the NPP, precipitation, and evapotranspiration datasets due to them not being the most recent data, temporal inconsistency, poor spatial resolution, and poor accuracy, which arise from their poor accessibility owing to time and effort constraints. Consequently, there is still room for further improvement in these areas. Fortunately, the values of these parameters used herein are independent of each other for correcting the ecosystem service value tables. Thus, their temporal inconsistencies do not affect the corrected results.

ESVs in China have boomed after 2000, but assessment methods primarily include two techniques that are based on equivalent factors or physical quantities, with the former achieving rapid accounting of ESVs due to simple operation and easy comparison of results. Consequently, studies have primarily adopted the equivalent factor method for assessing ESVs. The latest assessment results (Table 5) obtained based on the above studies in China and elsewhere leads to lower values of ecosystem services of the Loess Plateau than are calculated using this table compared to the ESV tables developed by Xie (2015). For example, the value of ecosystem services of the Loess Plateau calculated in this

paper for 2018 is 22,052.5 × 10^8 yuan (Fig. 10(b)), while the value calculated using the table developed by Xie (2015) is 151.63 × 10^8 yuan higher than the above value. In particular, soil conservation, gas regulation, and maintenance of nutrient cycling ecosystem service functions are 1,921.87 × 10^8 yuan, 1,246.15 × 10^8 yuan, and 139.76 billion yuan higher in the previous study than in this study, respectively, while aesthetic landscape ecosystem service function values are 611.32 × 10^8 yuan lower than in this study. Further examination of these differences revealed that the high soil erosion modulus, low vegetation cover, and high population in the study area compared to the national averages resulted in a smaller accounting value for soil conservation, gas regulation, and the maintenance of nutrient cycling ecosystem service functions. The ecosystem value in this study was 1,013.4 × 10^8 yuan higher than that calculated by Jiang *et al.* (2016). However, the calculation method used by the latter study was subjective and did not consider the spatial and temporal variability of ESVs, thereby leading to low assessment results. Previous studies (Song and Deng., 2017; Chen et al., 2020) have assessed ESVs using assessment coefficients primarily based on national averages or global averages, but failed to consider the influence of ecological processes and conditions between different regions. Therefore, this study better reflects the actual ecosystem service values and strength of service functions in the study area by considering regional spatial and temporal heterogeneity. In addition, human perspectives on ecosystem services vary in different socio-economic contexts (Wang et al., 2019). Consequently, this study considers a correction of factors on the "supply side" of ecosystem services that does not reflect human preferences. When using the equivalent factor method in the future, socio-economic factors can be considered and corrections can be made from the "demand side" of ecosystem services. Thus, when using the equivalence factor method in the future, we can consider socioeconomic factors and make corrections from the "demand side" of ecological services.

5.3. Impacts of LUCC conversion on ESV changes

Different ecosystems exhibit differences in structure and function (Constanze et al., 1997). For example, when considering the same study area in this investigation, large differences in ESV were generated by dense, moderate, and sparse grasslands of the same region. In this study, secondary land use reclassification (Table 1) was used to more accurately reflect and reliably estimate ESVs. The ESVs in the Loess Plateau increased by 933.97×10^8 and 312.86×10^8 yuan across the study periods of 1995–2018 and 2018–2030, respectively, resulting from changes in regional economic development, ecological environments, and land use patterns. During the 1995–2018 and 2025–2030 periods, ESVs in the study area exhibited an overall steady increase. However, ESVs decreased from 2018 to 2025, primarily due to accelerated urbanization that resulted in the conversion of agricultural and grassland areas to construction lands, thereby decreasing ESVs. In many developing countries, economic benefits are the primary consideration for land resource management, while ecological benefits are often neglected, thereby increasing pressure on natural resources and ecosystems, leading to threatened regional ecological security (Horlings and Barsden, 2011). The ESVs in the Loess Plateau region primarily derive from grasslands, forest lands, and farmlands (Fig. 11(a)). Across the study period, the value-addition of ecosystem services in the region primarily originated from increases in forest, scrubland, and water system areas that contributed 37%, 18.3%, and 43.9% to the value-added total for ecosystems, respectively.

The value of regulatory services increased the most throughout the study period, primarily due to increased area of forest lands and water systems. The contribution of individual ecosystem service functions to total ESVs was highest for hydrological regulation and lowest for maintaining nutrient cycles (Fig. 11(b)), suggesting that vegetation cover in the area was low and should be allowed to

continue increasing to enhance ESVs. Water systems and wetlands provide the highest ESV per unit area of land use type and play a key role in water supply, hydrological regulation, and cultural landscapes. Thus, their protection can be effective for preventing ESV declines. Food supplies are mainly generated from cultivated lands that play important roles in food production, raw material production, gas regulation, soil formation, soil retention, and nutrient cycling. In addition, forest lands and grasslands play important roles across almost the entire range of ecosystem services. Overall, the conversion of forest lands, grasslands, watersheds, and wetlands to built-up areas and cultivated land results in significant losses of ecosystem services. Consequently, land for construction and cultivation should be rigorously planned to prevent damage to environments and loss of ESVs.

6. Conclusion

The simulation studies of this investigation indicated that cultivated lands, grasslands, and unused lands will continue to decrease in future scenarios, while built-up areas, forest lands, and water areas will continue to increase. Across the study period, built-up and forest land areas increased the most. Built-up areas primarily derived from cultivated and grassland areas, with these areas concentrated in core urban regions. Woodland areas increased due to conversion of grasslands, with increased woodland areas concentrated in the eastern and southern regions of the study area. ESVs increased overall between 1995 and 2030, increasing by a total of 1,246.63 × 10^8 yuan, while ESVs decreased from the southeast to northwest directions. Increased ESVs indicate that ecosystems are developing toward healthy and stable states, while imbalanced spatial ecological capital indicates that future development policies must consider imbalanced ecological capital between regions to ensure sustainable development. Hydrological regulation increased most, while food production land use types decreased most throughout the study period. Moderate grasslands made the highest contributions to

ESVs, with water system, forest, and shrub lands making up progressively larger proportions of the total contributions to ESVs.

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Authors Contributions

Lintao Liu: Conceptualization, Methodology, Investigation, Resources, Data curation, Writing - original draft, Visualization. Hengjia Zhang: Funding acquisition, Validation, Resources, Visualization, Supervision, Writing - review & editing. Yao Zhang: Supervision, Formal analysis. Fuqiang Li: Supervision. Xietian Chen: Software, Supervision. Yong Wang: Supervision. Yingying Wang: Supervision.

Availability of data and materials

The datasets analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical Approval and Consent to Participate

Not applicable.

Consent to Publish

Not applicable.

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