Spatial–temporal heterogeneity in the influence of landscape patterns on trade-offs/synergies among ecosystem services: a case study of the Loess Plateau of northern Shaanxi

Jinxin Shi[1] · Xiaoying Liang[1,2] · Zheng Wei[1] · Huiqiang Li[1]

Abstract

Exploring the role of landscape patterns in the trade-offs/synergies among ecosystem services (ESs) is helpful for understanding ES generation and transmission processes and is of great significance for multiple ES management. However, few studies have addressed the potential spatial–temporal heterogeneity in the influence of landscape patterns on trade-offs/synergies among ESs. This study assessed the landscape patterns and five typical ESs (water retention (WR), food supply (FS), habitat quality (HQ), soil retention (SR), and landscape aesthetics (LA)) on the Loess Plateau of northern Shaanxi and used the revised trade-off/synergy degree indicator to measure trade-offs/synergies among ESs. The multiscale geographically weighted regression (MGWR) model was constructed to determine the spatial–temporal heterogeneity in the influence of landscape patterns on the trade-offs/synergies. The results showed that (1) from 2000 to 2010, the increase in cultivated land and the decrease in forestland and grassland increased landscape diversity and decreased landscape heterogeneity and fragmentation. During 2010—2020, the change range decreased, the spatial distribution was homogeneous, and the landscape diversity and fragmentation in the northwestern area increased significantly. (2) The supply of the five ESs continued to increase from 2000 to 2020. During 2000—2010, FS—SR, FS—LA and SR—LA were dominated by synergies. From 2010 to 2020, the proportion of trade-off units in all relationships increased, and HQ—FS, HQ—SR and HQ—LA were dominated by trade-offs. (3) Landscape patterns had complex impacts on trade-offs/synergies, and the same landscape variable could have the opposite impact on specific trade-offs/synergies in different periods and areas. The results of this study will inform managers in developing regional sustainable ecosystem management strategies and advocating for more research to address ecological issues from a spatial–temporal perspective.

Keywords Landscape pattern · Trade-off and synergy · Multiscale geographically weighted regression (MGWR) · Spatial–temporal heterogeneity · The Loess Plateau of Northern Shaanxi (LPNS)

Introduction

Ecosystem services (ESs) refer to various ecological, social and economic benefits and values that humans directly or indirectly obtain from ecosystems (Daily 1997; Costanza et al. 1998; MEA 2005). In recent decades, the stability and

✉ Xiaoying Liang
liangxy@nwu.edu.cn

1 College of Urban and Environmental Science, Northwest University, Xi'an 710127, China

2 Shaanxi Key Laboratory of Earth Surface System and Environmental Carrying Capacity, Xi'an 710127, China

function of ecosystems have been affected by human activities, posing a threat to the sustainable supply of ESs (Foley et al. 2005; Turner et al. 2007; Wang et al. 2022a). Therefore, it is imperative to restore and strengthen the effective management of ecosystems. Relatedly, landscape patterns and their spatial heterogeneity are considered crucial factors because they directly affect the type, quantity, and distribution of ESs (Lovett et al. 2005; Turner et al. 2013; Liu et al. 2018a). At present, many research results have been obtained on the influence of landscape patterns on individual ESs. For example, the influence of landscape pattern change on water-related ESs had significant category differences, annual variations and spatial differences (Qiu and Turner 2015; Li et al. 2021; Xia et al. 2021); in urban landscapes, forestland had a significant promoting effect on regulation services and

support services, while construction land mainly had a negative effect (Wang et al. 2019); and compared with landscape configuration, the complexity of landscape composition had a stronger effect on crop yield (Nelson and Burchfield 2021). The above results show that landscape patterns mainly affect the supply of ESs by changing ecosystem structure and ecological processes.

However, there are complex and variable interactions and interdependence among ESs, which pose challenges to resource allocation and management decisions (Bennett et al. 2009; Howe et al. 2014). The relationships among ESs are usually divided into trade-offs, synergies and nonrelated. When the increase in one ES is accompanied by a decrease in another ES, it is called a trade-off; when two ESs simultaneously increase or decrease, it is called synergy; other relationships are nonrelated or are compatible (Li et al. 2013; Qiu and Turner 2013; Lee and Lautenbach 2016). Studies have shown that landscape patterns not only have impacts on individual ESs but also play an important role in the relationships among ESs (Rieb and Bennett 2020; Qiu et al. 2021; Lyu et al. 2022). For example, in urban landscapes, low connectivity is closely associated with a large trade-off between nutrient retention and carbon storage, as well as a large trade-off between habitat quality and pollinator abundance (Karimi et al. 2021); landscape fragmentation and land use intensity have a positive impact on the synergy between pollination and nitrogen retention (Lavorel et al. 2022). These results suggest that changes in ecosystem structure and ecological processes caused by landscape patterns may simultaneously affect multiple ESs, leading to trade-offs and synergies among ESs. Therefore, exploring the spatial–temporal heterogeneity in the influence of landscape patterns on trade-offs/synergies among ESs is helpful for understanding the generation and transmission processes of ESs, which is of great significance for multiple ES management.

Nevertheless, most of the above studies used regression analysis, correlation analysis and other global statistical methods to quantify the relationship between variables. The global model presupposes that the relationship between variables is homogeneous, ignoring the potential spatial nonstationarity, which makes it difficult to accurately evaluate the relationship between variables in local areas. The multiscale geographically weighted regression (MGWR) model can be used to determine the spatial heterogeneity in a relationship between variables and provide more scale-related information about different variables (Oshan et al. 2019). Therefore, this study introduced the MGWR model to determine the heterogeneous relationships between landscape patterns and ES trade-offs/synergies.

The Loess Plateau of northern Shaanxi (LPNS) is in the upper reaches of the Yellow River, which is a typical ecotone with water shortages, serious soil erosion, low vegetation

coverage and prominent man-land interactions. Since the implementation of the Grain for Green Project (GFG) in 1999, the landscape pattern in the area has changed dramatically, and the ecological environment and the potential supply capacity of ESs have improved to some extent (Bao et al. 2016; He et al. 2023; Wang et al. 2023). However, the changes may also have led to significant changes in trade-offs and synergies among ESs. For example, Wang et al. (2022c) and Wu et al. (2022) showed that the number and intensity of trade-offs among ESs in northern Shaanxi increased from 2000 to 2015, and the synergy relationships decreased or even reversed into trade-offs during that period. Some scholars have also conducted in-depth exploration on the driving mechanism of ES trade-offs/synergies in the LPNS, and found that cultivated land, forest land and grassland in land use/land cover (LULC) are the main factors influencing of ES trade-offs/synergies. The above studies enriched the theoretical results on the driving mechanism of ES trade-offs/synergies in the LPNS and revealed the global relationship between ES trade-offs/synergies and drivers from a static perspective, but failed to further identify the differences in the spatial and temporal distribution of this relationship.

The main aims of this research were (1) to quantify the change characteristics of the LPNS landscape pattern from 2000 to 2020; (2) to determine the spatial heterogeneity of trade-offs/synergies among various ESs in the LPNS from 2000 to 2020; and (3) to explore the spatial–temporal heterogeneity of the influence of landscape patterns on trade-offs/synergies. The results of this study can provide information for managers implementing spatially targeted ecological restoration measures in the future.

## Materials and methods

Study area

The LPNS is in the middle of the Loess Plateau in China and the northern part of Shaanxi Province (107°30′ ~ 111°15′E, 34°10′ ~ 39°35′N), including the cities of Yulin and Yan'an, with a total area of 79967 km^2 (Fig. 1). The terrain is high in the west and low in the east, and the area has a temperate arid and semiarid monsoon climate. The average annual precipitation is 400 ~ 600 mm, increasing from the northwest to the southeast. The average annual evaporation is 900 ~ 1200 mm, decreasing from north to south. The landforms are complex and diverse, with the northwestern part dominated by the wind-sand grass shoal area and the central and southern parts dominated by the loess hilly-gully area. Most of the study area is covered by loess, with low vegetation coverage, a vulnerable ecology, serious land degradation and soil erosion (Liu et al. 2020).

Fig. 1 The Loess Plateau of Northern Shaanxi
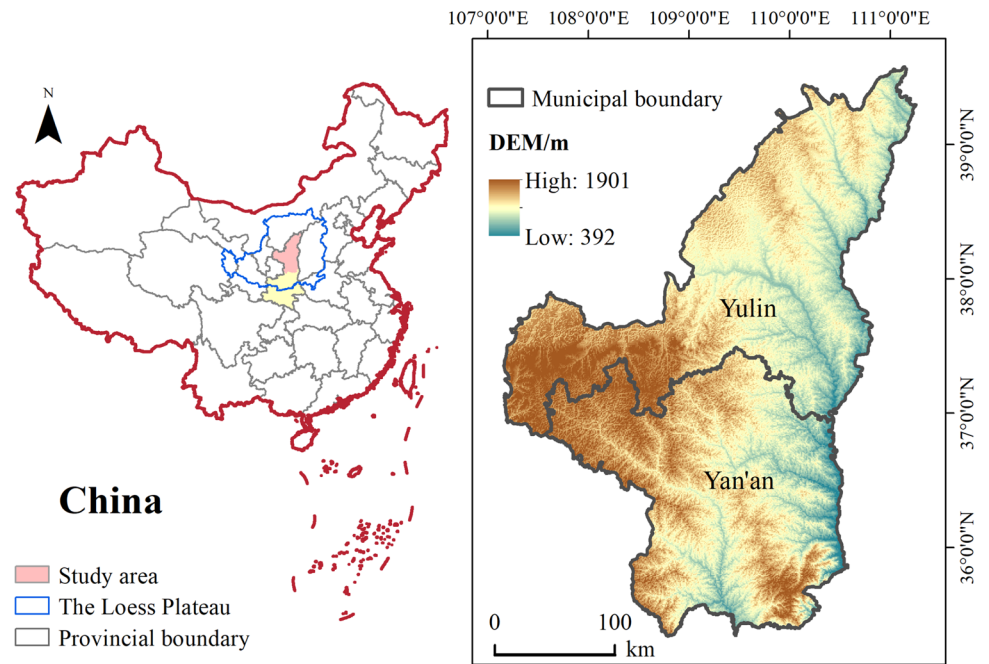
The LULC of the LPNS is dominated by cultivated land, forestland and grassland, the proportion of which has changed significantly since the implementation of the GFG in 1999 (Fig. 2). From 2000 to 2010, the scale of the GFG was large, the proportion of cultivated land decreased from 35.6 to 31.7%, and the area decreased by 3158 km^2; the proportion of forestland increased from 13.8 to 15.3%, and the area increased by 1194 km^2; the proportion of grassland increased from 43.7 to 46.0%, and the area increased by 1889 km^2. From 2010 to 2020, the scale of the GFG gradually decreased, and the range of LULC change decreased. The proportions of cultivated land, forestland and grassland showed a slight decline with the advancement of urbanization, and the change fluctuated between 0.1% and 0.3%. However, the development of forestland and grassland in abandoned lands is becoming increasingly mature, and ecological benefits are gradually emerging. Given this context, the changes in landscape patterns and ESs in the study area provided excellent conditions for exploring the spatial heterogeneity relationships between landscape patterns and
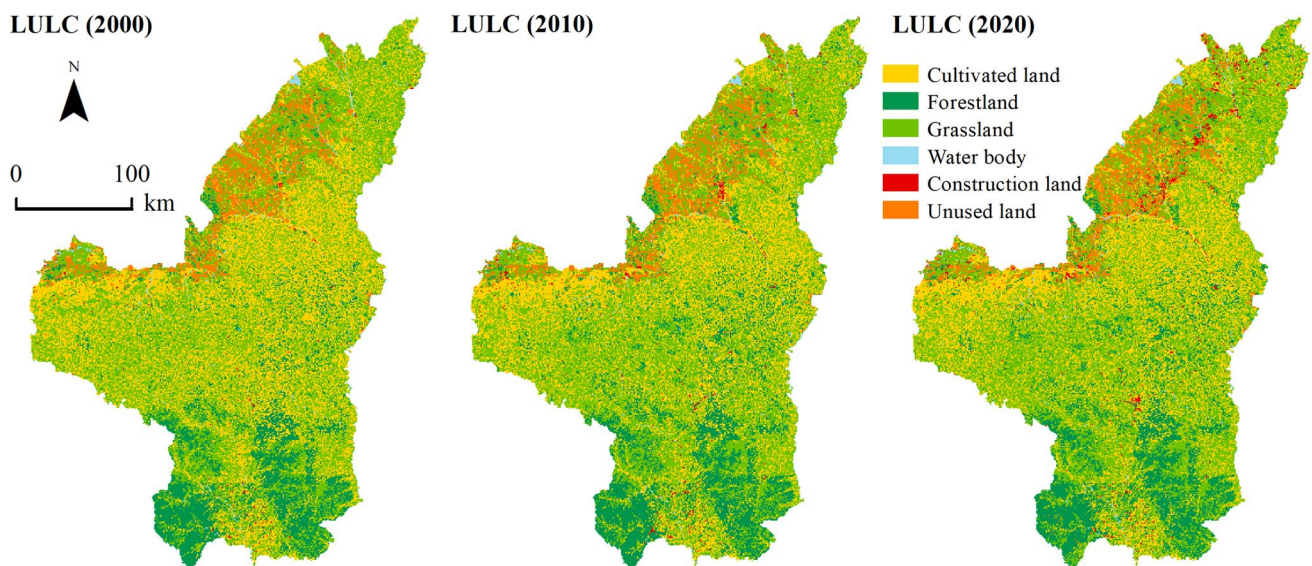
Fig. 2 Land Use/Land Cover for the Loess Plateau of Northern Shaanxi

ES trade-offs/synergies to provide reasonable suggestions for the sustainable development of arid and semiarid ecotones.

Data sources and processing

Based on the LULC data, topographic data, meteorological data, soil data, vegetation index and grain yield data in 2000, 2010 and 2020, the changes in typical ESs were evaluated to explore the spatial heterogeneity relationships between landscape patterns and ES trade-offs/synergies. All data were converted to the same spatial coordinate system and spatial resolution (1 km × 1 km) for the calculation of ESs. More details about the multisource data are shown in Table 1.

Methods

Quantification of landscape patterns

Landscape metrics are important methods for quantifying landscape patterns. In this study, three levels of metrics were selected: shape index (SHAPE) and patch density (PD) at the patch level; percentage of landscape (PLAND) at the class level (PLAND only includes the three largest LULC types in the study area: cultivated land, forestland and grassland); and largest patch index (LPI), patch richness (PR), contagion index (CONTAG), connectance index (CONNECT) and interspersion and juxtaposition index (IJI) at the landscape level. The selection of these metrics mainly considered the following four factors: (1) starting from the integrity of landscape patterns, such as landscape diversity, heterogeneity and fragmentation (Su and Fu 2012; Tanner and Fuhlendorf 2018; Zhang et al. 2020a); (2) referring to the metrics used frequently in the literature (Lamy et al. 2016; Badora and

Wróbel 2020; Chen et al. 2021; Ran et al. 2023); (3) priority should be given to metrics that are easy to understand and calculate to improve the repeatability of research; and (4) variance inflation factor (VIF) < 10 screening to reduce multicollinearity. All landscape metrics were calculated using FRAGSTATS v4.2 (McGarigal et al. 2012) with a spatial resolution of 1 km.

Ecosystem services assessment

Combined with the actual situation of water shortage, severe soil erosion and a vulnerable ecological environment in the study area and the availability of data, five typical ESs, water retention (WR), food supply (FS), habitat quality (HQ), soil retention (SR) and landscape aesthetics (LA), at a 1 km spatial resolution were calculated. The specific calculation methods are shown in Table 2 and 3.

Quantitative measure of trade-offs and synergies among ESs

The trade-off/synergy degree (TSD) indicator can reflect the spatial pattern of the trade-offs/synergies among ESs (Zhao and Li 2022). Given this information, the normalization process was used to revise it to prevent meaningless samples caused by its original algorithm and simultaneously unify its value range from -1 to 1 to enhance the comparability of different trade-offs/synergies. It can be described as follows:

$$TSD_{i-j} = \begin{cases} 0, (\Delta ES_{i,t2-t1} \times \Delta ES_{j,t2-t1} = 0) \\ \sqrt{(\Delta ES_{i,t2-t1}^2 + \Delta ES_{j,t2-t1}^2)/2}, (\Delta ES_{i,t2-t1} \times \Delta ES_{j,t2-t1} > 0) \\ -\sqrt{(\Delta ES_{i,t2-t1}^2 + \Delta ES_{j,t2-t1}^2)/2}, (\Delta ES_{i,t2-t1} \times \Delta ES_{j,t2-t1} < 0) \end{cases}$$
$$(1)$$

Table 1 Details and sources for the datasets used in this study

Data	Year	Detail	Source
Land use/land cover	2000, 2010, 2020	Raster, 30 m	Environmental and Ecological Science Data Center for West China (http://westdc.westgis.ac.cn/)
Digital elevation model (DEM)	2000	Raster, 30 m	Earth Science Data Systems (ESDS) Program (https://earthdata.nasa.gov/esds/)
Precipitation, potential evapotranspiration	2000, 2010, 2020	Raster, 1 km	National Earth System Science Data Center (http://www.geodata.cn)
Soil texture	1995	Raster, 1 km	Data Center for Resources and Environmental Sciences (https://www.resdc.cn/)
Soil organic carbon content, bulk density	2017	Raster, 250 m	National Earth System Science Data Center (http://www.geodata.cn)
Root depth	2017	Raster, 250 m	The Soil and Terrain Database (SOTER) Programme (https://data.isric.org)
Normalized difference vegetation index (NDVI)	2000, 2010, 2020	Raster, 1 km	Earth Science Data Systems (ESDS) Program (https://earthdata.nasa.gov/esds/)
Food yield	2000, 2010, 2020	Spreadsheet, county	Yan'an Statistical Yearbook, Yulin Statistical Yearbook

Table 2 Methods and process for quantifying ecosystem services

Ecosystem service	Model or principle	Assessment process
Water retention (WR)	The water conservation evaluation model based on InVEST (Yu et al. 2012)	$WR = min\left(1, \frac{249}{V}\right) \times min(1, 0.3 \times TI) \times min\left(1, \frac{K_s}{300}\right) \times Y$, WR = water retention (mm), V = velocity coefficient (Bao et al. 2016), TI = topographic index, K_s = soil saturated hydraulic conductivity (cm/d), Y = water yield (mm)
Food supply (FS)	Food crop yields have strong linear relationship with NDVI (Peng et al. 2016)	The food supply of each pixel is distributed according to the proportion of the NDVI value of each cultivated land pixel relative to the overall NDVI value of the county's cultivated land (ton/km^2)
Habitat quality (HQ)	Habitat quality module of InVEST (Wang et al. 2022b)	$HQ = H\left[1 - \left(\frac{D}{D+K}\right)\right]$, HQ = habitat quality, H = habitat suitability, D = degree of habitat degradation, K = half-saturation constant, Z = default parameter of the normalized constant model
Soil retention (SR)	Sediment retention module of InVEST (Hu et al. 2014)	$SR = R \times K \times LS \times (1 - P \times C)$, SR = soil retention [t/(hm^2 · a)], R = rainfall erosivity index [MJ · mm/(hm^2 · h · a)] (Liu et al. 2018b), K = soil erodibility factor [t · hm^2 · h/(hm^2 · MJ · mm)], LS = slope length and steepness factor, P = conservation practice factor, C = cover and management factor
Landscape aesthetics (LA)	The biophysical characteristics of landscapes (Frank et al. 2013)	The evaluation index system of landscape aesthetics is constructed from naturalness, heterogeneity, terrain complexity and accessibility of landscape, and the weight of each index is determined by using the analytic hierarchy process (expert scoring). The basic calculation methods are shown in Table 3

Table 3 Assessing indices of landscape aesthetics

Criteria	Index	Assessment process	Weight
Naturalness	Vegetation cover (+)	$FVC = \frac{NDVI - NDVI_{soil}}{NDVI_{veg} - NDVI_{soil}}$, FVC = vegetation cover, $NDVI_{veg}$ and $NDVI_{soil}$ = NDVI values with cumulative distribution frequencies of 95% and 5%	0.382
	Percentage of water area (+)	$P = \frac{W}{A}$, P = percentage of water area in a county, W = water area of a county (km^2), A = total area of a county (km^2)	0.160
Heterogeneity	Shannon's Diversity Index (+)	Using the moving window method, with a window radius of 500 m and a grid size of 1 km × 1 km	0.250
Terrain complexity	Degree of relief (+)	$R = \frac{Mean(H)}{1000} + \frac{\left\{[Max(H) - Min(H)] \times \left[1 - \frac{P(A)}{A}\right]\right\}}{500}$, R = degree of relief (Zhou et al. 2012), H = Elevation within the window (m), $P(A)$ = area of flat land (km^2) (slope $\leq 5°$), A = total area (km^2)	0.101
Accessibility	density of road network (+)	$D = \frac{\sum_{n=1}^{j} L_j \times w_j}{A}$, D = density of road network of a county (km/km^2), L_j = length of class j road in a county (km), w_j = weight of class j road in a county, A = total area of a county (km^2)	0.043
	Distance from main road (-)	Near Analysis of ArcGIS 10.8	0.064

"+" represents positive indicator, "−" represents negative indicator

where $\Delta ES_{i,t2-t1}$ and $\Delta ES_{j,t2-t1}$ refer to the variation in ES values for types i and j from $t1$ to $t2$, respectively, and are calculated as follows:

$$\Delta ES_{t2-t1} = ES_{t2}\prime - ES_{t1}\prime \qquad (2)$$

where $ES_{t1}\prime$ and $ES_{t2}\prime$ represent the normalized values of ES at $t1$ and $t2$, respectively. To reflect the trend of ESs over time, the normalization process was performed simultaneously for the data from three periods, and the mathematical expression is as follows:

$$ES_{t1}' = \frac{ES_{t1} - \min(ES_{t1}, ES_{t2})}{\max(ES_{t1}, ES_{t2}) - \min(ES_{t1}, ES_{t2})} \tag{3}$$

where ES_{t1} and ES_{t2} represent the observed values of ES at $t1$ and $t2$, respectively. As shown in Eq. (1), when $TSD_{i-j} = 0$, there is nonrelated between ES_i and ES_j; when $TSD_{i-j} > 0$, there is synergy between ES_i and ES_j; and when $TSD_{i-j} < 0$, there is a trade-off between ES_i and ES_j. The absolute value of TSD_{i-j} reflects the strength of the trade-offs/synergies.

Before exploring the spatial heterogeneity relationships between landscape patterns and ES trade-offs/synergies, it is necessary to use global Moran's I to detect the spatial dependence of trade-offs/synergies, and its value ranges from -1 to 1. After the significance test, Moran's I > 0 indicates that the trade-off/synergy is positively correlated in space; Moran's I < 0 indicates that the trade-off/synergy is negatively correlated in space; and Moran's I = 0 indicates that the trade-off/synergy is randomly distributed in space. The greater the absolute value of Moran's I is, the stronger the correlation.

Identifying relationships between landscape patterns and ES trade-offs/synergies

Multiscale geographically weighted regression is an extension of geographically weighted regression (GWR), which eliminates the single bandwidth assumption and allows different processes to operate on different spatial scales. It is effective in estimating parameter surfaces with different levels of spatial heterogeneity (Fotheringham et al. 2017). The MGWR model can be presented as follows:

$$y_i = \sum_{j=0}^{m} \beta_{bw_j}(u_i, v_i)x_{ij} + \varepsilon_i \tag{4}$$

where y_i indicates the estimated TSD value at sample i; β_{bw_j} indicates the regression coefficient of independent variable j; bw_j indicates the bandwidth of independent variable j; (u_i, v_i) indicates the spatial coordinate of sample i; x_{ij} indicates the value of independent variable j at sample i; and ε_i indicates the random error term for sample i.

Based on the actual performance of the MGWR model, the spatial resolution of the dependent variables (TSD) and the independent variables (landscape metric variation) involved in the calculation in this study was 3 km.

Results

Landscape pattern variation

Due to the implementation of the GFG, the LPNS experienced a decrease in cultivated land and an increase in forestland and grassland from 2000 to 2020, resulting in significant changes in the landscape pattern (Fig. 3), mainly in terms of increased landscape diversity and heterogeneity and reduced landscape complexity and fragmentation.

Specifically, the changes in 2000—2010 were significant and mainly concentrated in the central part of the loess hilly-gully area. LPI and CONTAG showed an upward trend, while SHAPE, PD and CONNECT showed a downward trend, indicating that the dominant patches gradually expanded; in addition, the small and complex patches coalesced into relatively isolated and simple-shaped large patches, thus improving the fragmentation of the landscape. However, these results also caused some obstacles to the connectivity between landscapes. The increase in PR and IJI indicated that the landscape types in the area were enriched and more evenly distributed spatially, the landscape was diversified, and the heterogeneity was weakened. At the class level, cultivated land was concentrated from the northeastern and central southern areas to the central northern, western and southern areas, while forestland and grassland expanded significantly.

From 2010 to 2020, the change range of most areas in the study area was small and evenly distributed. In the northwestern area, PR, PD, and IJI showed an upward trend, while LPI, PLAND_G, SHAPE and CONTAG showed a downward trend. In essence, the erosion of grassland through the expansion of construction land (Fig. 1) led to fragmentation of the landscape while enhancing the diversity of the landscape and reducing heterogeneity. In addition, SHAPE in the southeastern mountains increased significantly, indicating that the reduction in the intensity of human activities caused by the GFG had a positive impact on the restoration of the ecological environment.

Ecosystem services variation

From 2000 to 2020, WR, FS, HQ, SR, and LA all showed significant upward trends in the study area. There was significant spatial–temporal heterogeneity in the trends during the first 10 years and the second 10 years (Fig. 4). Among the ESs, FS was mainly related to the distribution of cultivated land, while other ESs had a strong spatial correlation with forestland.

As shown in Fig. 4, from 2000 to 2010, the implementation of the GFG and the increase in rainfall in the study area caused the WR in the southern mountainous area to have a significant upward trend, while the northwestern area also increased slightly. Due to the change in the proportion of cultivated land (Fig. 3), the high value areas of FS (92 ~ 459) were concentrated in the northwestern and central northern areas. The increase in forestland directly promoted the increase in HQ in the central and northeastern areas, but the spatial distribution was more
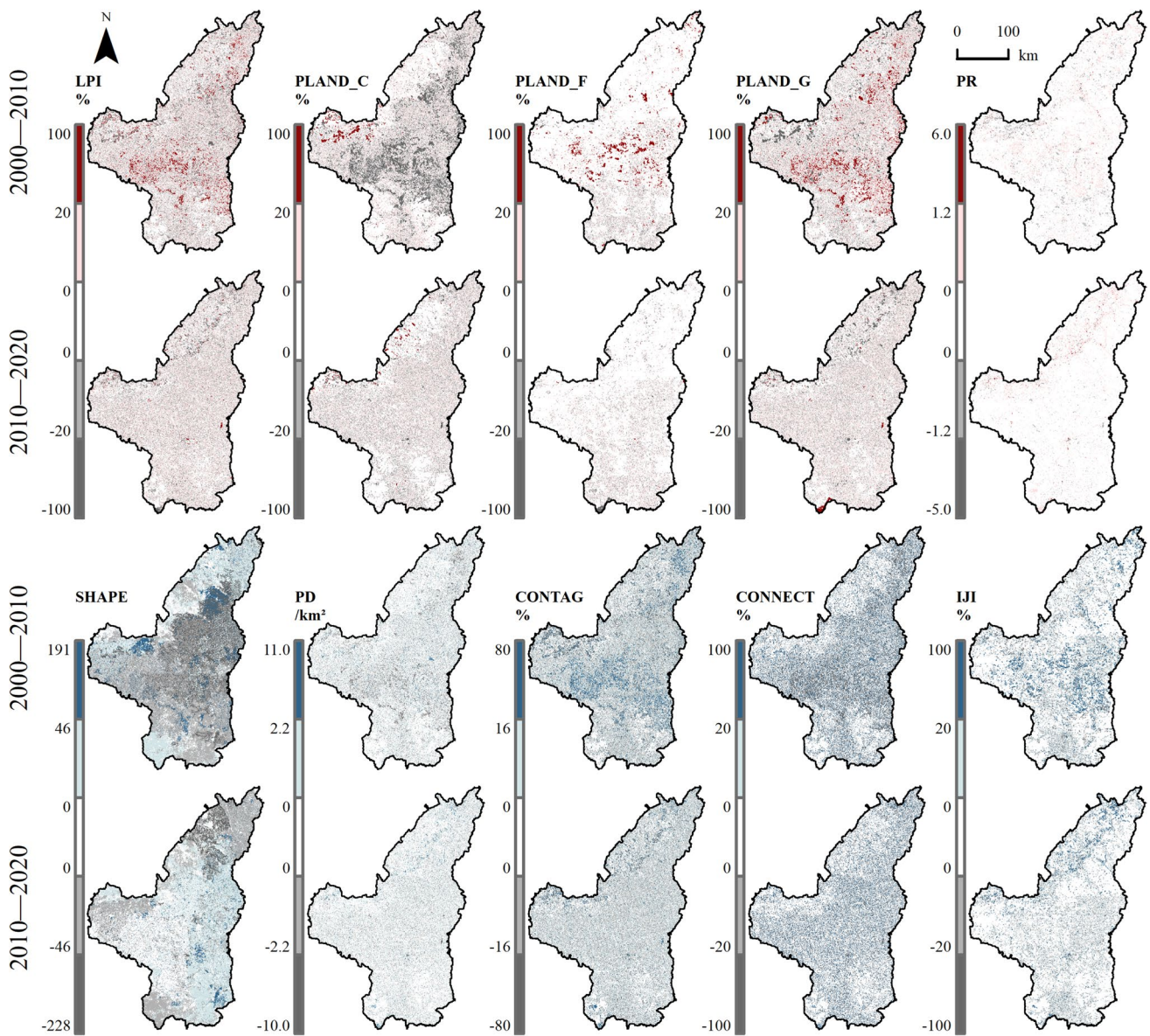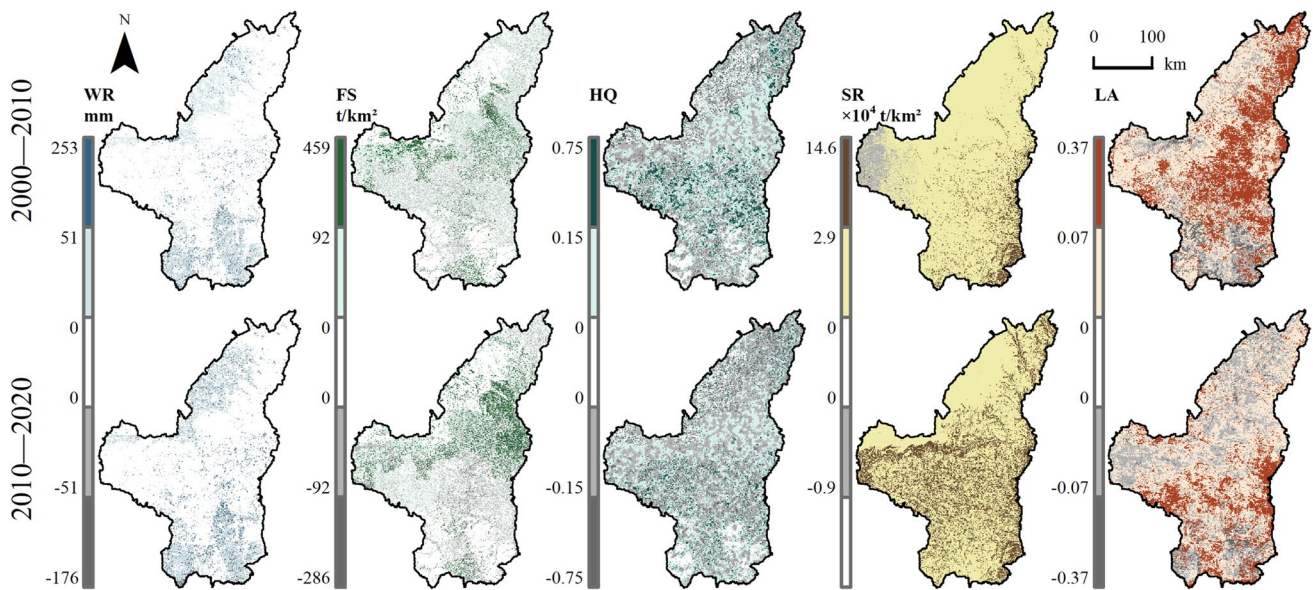
Fig. 3 Spatial patterns and changes in landscape metrics in 2000—2010 and 2010—2020. (PLAND_C: percentage of cultivated land, PLAND_F: percentage of forestland, PLAND_G: percentage of grassland)

dispersed; however, most areas showed a downward trend. The rising trend of SR was obvious, and the high value area (2.9 ~ 14.6) was mainly concentrated in the southeastern border area; the western loess tableland area decreased slightly. The LA in the study area increased significantly overall, while the declining trend in the southeastern mountainous areas was more obvious.

From 2010 to 2020, the GFG entered the advance stage, and the ecological benefits were gradually reflected. Due to the management of some unused land in the northwestern area, the vegetation was repaired to a certain extent, and the increase in WR strengthened. With the increase

in agricultural demand and productivity, the increasing trend of FS was more obvious, and the high-value area expanded to the eastern area. At the same time, the central and southern areas were affected by the GFG, showing a certain degree of downward trend. The forestland and grassland in the central, western and northeastern areas gradually matured, which greatly enhanced the soil retention capacity. At the same time, due to the influence of altitude, SR increased significantly in the ridge zone from the central to the western area. The overall downward trend of HQ and LA increased, and the upward trend in the central area weakened.

Fig. 4 Spatial patterns and changes in the ecosystem services in 2000—2010 and 2010—2020. (FS: food supply, WR: water retention, SR: soil retention, HQ: habitat quality, LA: landscape aesthetics)

Spatial–temporal patterns of trade-offs/synergies among ESs

A geographic grid was used to calculate the TSD at a 3 km spatial resolution to explain the spatial distribution and intensity of the trade-offs/synergies among the ESs, and the dominant relationship was determined based on the proportion of trade-off units and synergy units.

In general, the distribution of trade-offs/synergies among the ESs showed different degrees of heterogeneity in time and space (Fig. 5). The trend over time showed consistency; that is, the proportion of trade-off units showed an upward trend, and the proportion of synergy units showed a downward trend (Fig. 6). Specifically, the interactions between WR and other ESs were weak, and their trade-off and synergy units accounted for less than 50%, mainly based on synergies, concentrated in the northwestern wind-sand grass shoal area and the southern mountainous area. However, the spatial patterns of the trade-offs/synergies between FS and SR, HQ, and LA were opposite. From 2000 to 2010, FS—HQ was dominated by trade-offs, while FS—SR and FS—LA were dominated by synergies, mainly concentrated in the central and northern areas; during 2010—2020, the trade-offs/synergies in the eastern area were enhanced because of the significant increase in FS, and the synergistic relationship of FS—SR on the ridge zone was enhanced at the same time. In 2000—2010, HQ—SR and HQ—LA were dominated by synergies, mainly concentrated in the forestland in the central and southern areas. However, in 2010—2020, with the decreasing trend of HQ in the area becoming increasingly obvious, the synergistic relationship

changed to a trade-off relationship, and the dominant relationships of HQ—SR and HQ—LA reversed. From 2000 to 2010, SR—LA was dominated by synergy, and the western and southern areas showed a trade-off trend. From 2010 to 2020, the degree of synergy in the central western area and the eastern border area increased with increasing LA, but the trade-off relationship in the northwestern area expanded due to the decline in LA.

Table 4 shows that there were positive spatial autocorrelations in the relationships among the five ESs, and the autocorrelations showed a decreasing trend with time. Among them, SR—LA had the highest Moran's I and the strongest spatial autocorrelation, while WR—FS had the lowest Moran's I and the weakest spatial autocorrelation.

Spatial–temporal heterogeneity of relationships between landscape patterns and ES trade-offs/synergies

Based on the relationships among the ESs, this study selected three representative ES pairs, namely, the trade-off-based FS—HQ, the synergy-based SR—LA, and the nonrelated-based WR—FS, to explore the heterogeneous relationships between landscape metrics and trade-offs/synergies through the MGWR model. According to the two parameters (Adj R^2 and corrected Akaike information criterion (AICc)) provided by the model, the fitting effect of the model was characterized. The larger the Adj R^2 and the smaller the AICc were, the better the fitting effect of the model. Table 5 shows that the landscape metrics had the best fitting effect with SR—LA, while the fitting effect with
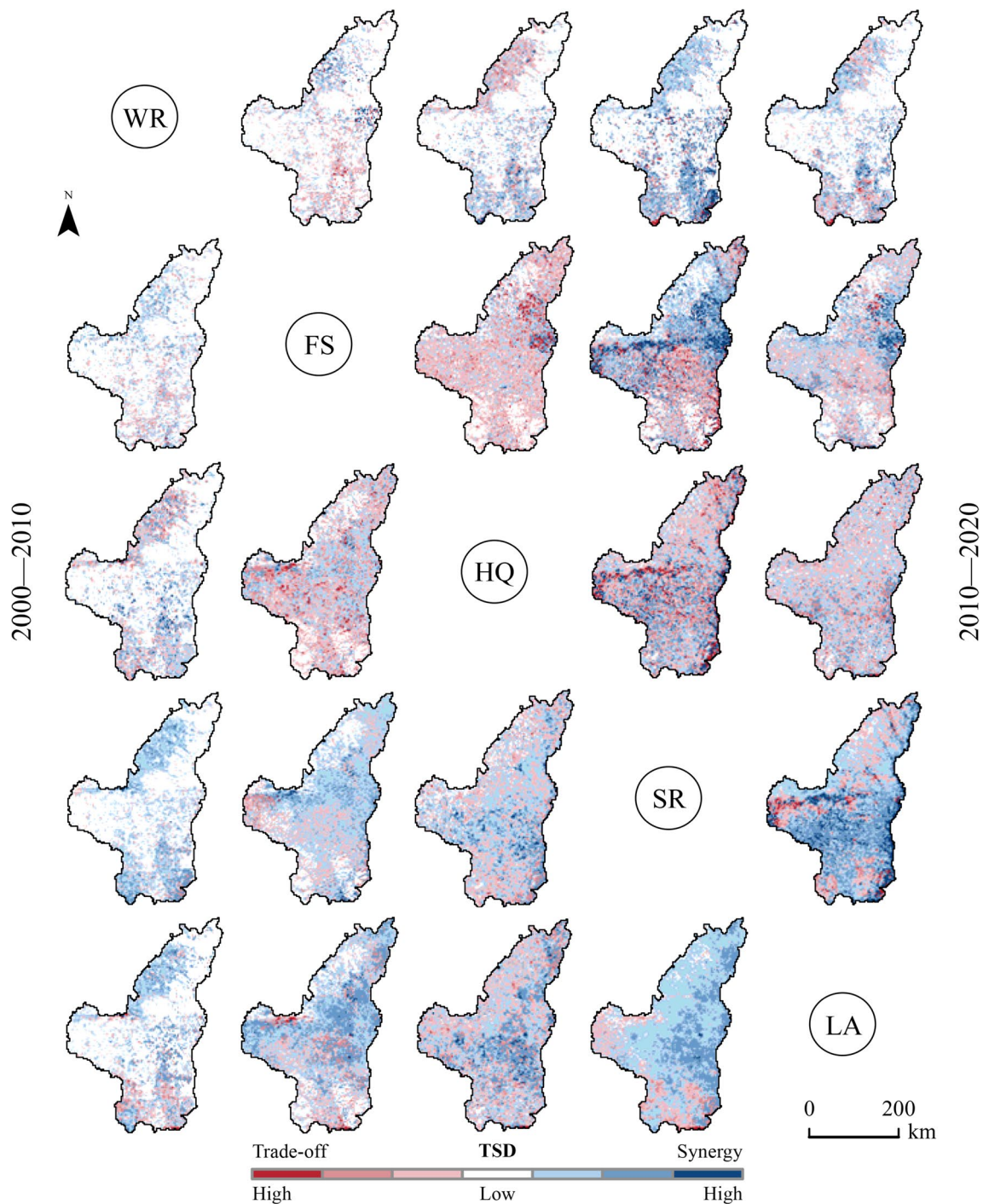
Fig. 5 Spatial patterns of the trade-offs/synergies among the ecosystem services in 2000—2010 and 2010—2020

WR—FS was poor. Figure 7 shows that the absolute value of the MGWR standard residual |*Residual*| <2.5 in most areas of the study area, indicating that the results of the model were robust (Zhang et al. 2020b; Xue et al. 2022a).

The spatial nonstationary relationships between variables were described by the regression coefficients; that is, the positive regression coefficient and the increase in the independent variable or the negative regression coefficient and the decrease in the independent variable promoted the synergy between ESs, while the positive regression coefficient and the decrease in the independent variable or the negative regression coefficient and the increase in the independent variable promoted the trade-off between ESs. According to the results of the MGWR model, when

Fig. 6 Proportion of the trade-offs/synergies among the ecosystem services in 2000—2010 and 2010—2020

**Table 4** Spatial patterns of relationships among the ecosystem services

Type	2000–2010			2010–2020		
	Moran's I	Z-score	P-value	Moran's I	Z-score	P-value
WR—FS	0.097	12.894	0.000	0.087	11.535	0.000
WR—HQ	0.158	21.047	0.000	0.166	22.127	0.000
WR—SR	0.388	51.622	0.000	0.187	24.893	0.000
WR—LA	0.292	38.877	0.000	0.179	23.877	0.000
FS—HQ	0.209	27.774	0.000	0.145	19.368	0.000
FS—SR	0.317	42.249	0.000	0.255	33.905	0.000
FS—LA	0.319	42.507	0.000	0.257	34.171	0.000
HQ—SR	0.374	49.819	0.000	0.208	27.683	0.000
HQ—LA	0.320	42.634	0.000	0.174	23.138	0.000
SR—LA	0.670	89.201	0.000	0.535	71.173	0.000

the absolute value of the regression coefficient was large ($|\beta| > 0.1$), the influence of the independent variable on the relationship between ESs was obvious. Figure 8 shows that

there was spatial–temporal heterogeneity in the impacts of landscape patterns on trade-offs/synergies among ESs; that is, the same landscape metric had different influence

Table 5 Fitting performance of the multiscale geographically weighted regression model

Type	WR—FS		FS—HQ		SR—LA	
	2000–2010	2010–2020	2000–2010	2010–2020	2000–2010	2010–2020
Adj R^2	0.111	0.123	0.227	0.126	0.694	0.517
AICc	25136.687	25033.722	24386.055	25215.518	16391.795	20084.235

Fig. 7 Spatial distribution of the standard residuals
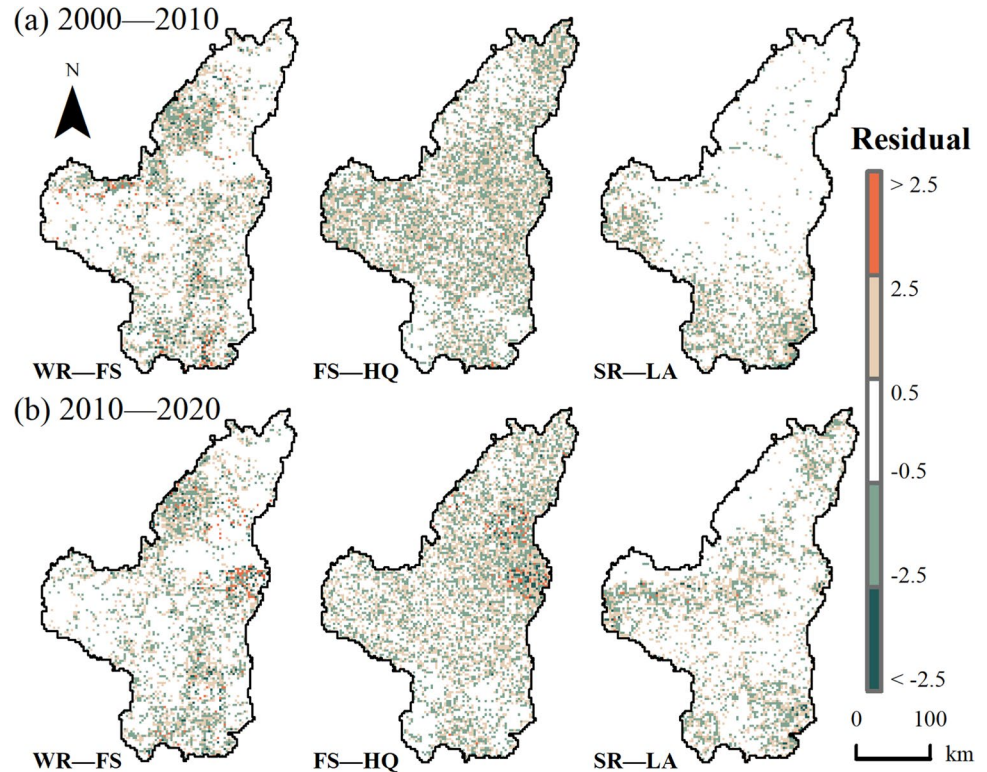
directions and intensities on trade-offs/synergies in different periods and areas.

Specifically, from 2000 to 2010, WR—FS was dominated by the nonrelated factors and mainly affected by landscape metrics such as LPI, PLAND_C and PLAND_F, among which PLAND_C had the most significant impact. Both LPI and PLAND_C had positive effects, while PLAND_F had both positive and negative effects and showed certain spatial heterogeneity (Fig. 8a1, b1 and c1). FS—HQ was dominated by trade-offs and mainly affected by PLAND_C, PLAND_F, PLAND_G, PR and CONTAG. Among them, PLAND_F and PLAND_G had a greater impact (Fig. 8c2 and d2), and positive and negative effects coexisted, with strong spatial heterogeneity. SR—LA was dominated by synergy, which was mainly affected by PLAND_C, PR and SHAPE. Among them, PLAND_C had the strongest impact, and the positive and negative effects coexisted with its effects on SR—LA occurred at a smaller spatial scale, showing strong spatial heterogeneity (Fig. 8b3); the influence of PR and SHAPE was stronger (Fig. 8e3 and f3), with the former mainly having a positive

influence and the latter mainly having a negative influence, and the spatial heterogeneity was weak.

From 2010 to 2020, WR—FS was mainly nonrelated and was affected by PLAND_C and PLAND_G (Fig. 8b4 and d4), positive and negative effects coexisted, the degree of influence was strong, and both showed strong spatial heterogeneity. The trade-off relationship between FS and HQ was enhanced, which was mainly affected by PLAND_C, PLAND_F and PLAND_G, and the positive and negative effects coexisted. Among them, the influence degree and spatial heterogeneity of PLAND_C were strongest (Fig. 8b5), and those of PLAND_F and PLAND_G were weakest (Fig. 8c5 and d5). The synergistic relationship between SR and LA weakened, which was mainly affected by LPI, PLAND_C and PR, and the degree of influence was weak. Among them, the positive and negative effects of LPI and PLAND_C coexisted (Fig. 8a6 and b6), and there was a certain spatial heterogeneity; PR was mainly positive (Fig. 8e6), and the spatial heterogeneity was weak.

Overall, the heterogeneity in the influence of landscape pattern on trade-offs/synergies among the ESs was mostly
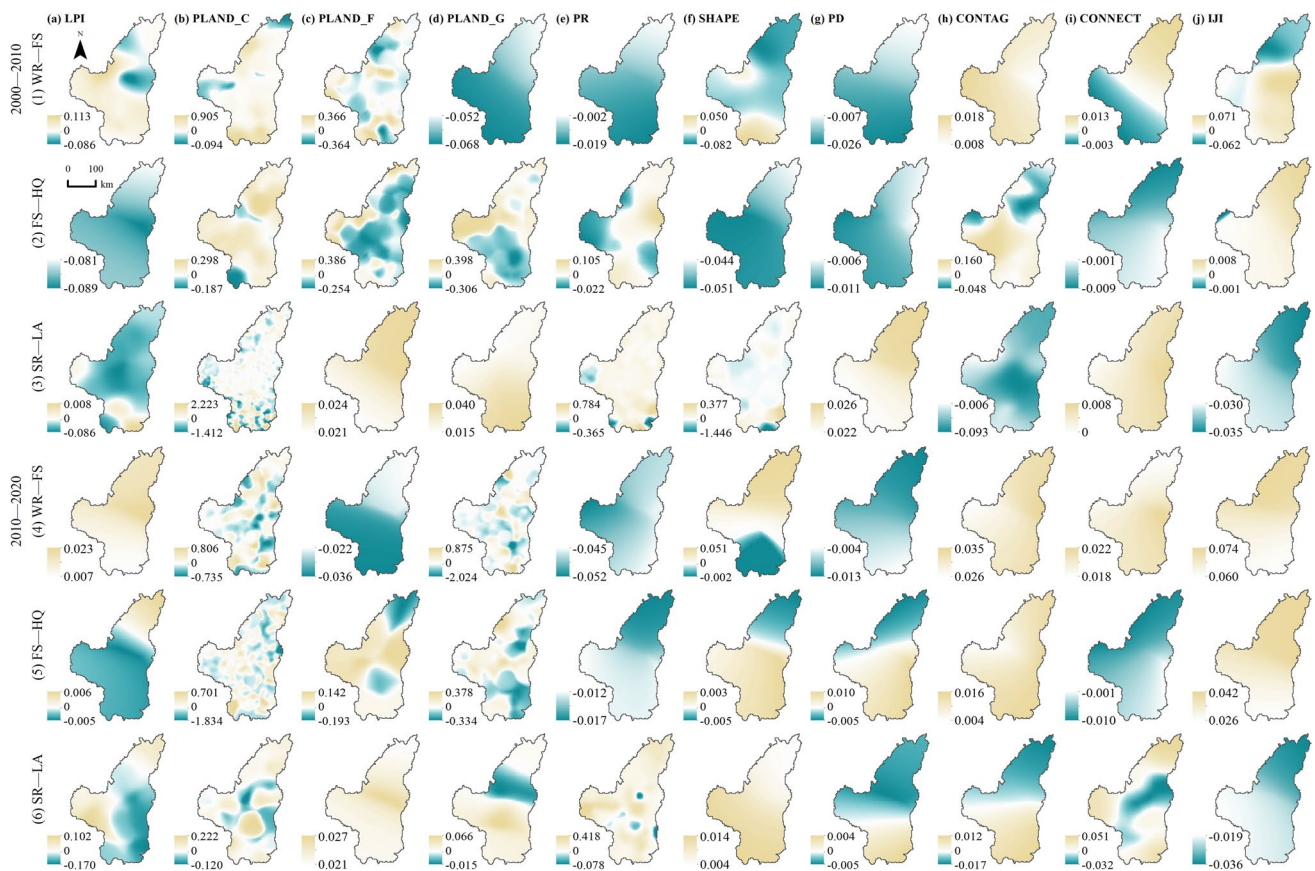
Fig. 8 Quantitative effects of landscape metrics on depicting trade-offs and synergies through the multiscale geographically weighted regression model

attributed to the different directions of changes in landscape metrics, which led to different forms of trade-offs/synergies. For example, from 2000 to 2010, PLAND_F in the central and northern parts of the study area had negative impacts on WR—FS and FS—HQ, while it showed a positive impact in the western area (Fig. 8c1 and c2). This finding might have been due to the increase in PLAND_F in the central and northern areas, which led to the decrease in FS and the increase in WR and HQ; a slight decrease in PLAND_F in the western area promoted an increase in FS and a decrease in WR and HQ (Fig. 4). Therefore, the increase and decrease in PLAND_F in different areas led to different types of trade-offs between WR—FS and FS—HQ. In this process, the relationships between landscape patterns and single ESs did not change. However, under the trade-off/synergy, the heterogeneity in the influence of landscape metrics on individual ESs might have been obscured by homogeneous regression coefficients. For example, from 2000 to 2010, the regression coefficients in the northwestern and southern areas were positive (Fig. 8b1 and b2), but the northwestern area was dominated by unused land. The increase in PLAND_C increased not only crop yield but also vegetation

coverage to a certain extent, which had positive impacts on WR and HQ. The southern area was dominated by forestland and grassland, and the change in PLAND_C had negative impacts on WR and HQ. This interregional difference in impacts might have depended more on the difference in the landscape matrices.

Discussion

Relationships between landscape pattern and ES trade-offs/synergies

Based on the dominant relationship among the ESs, three groups of ES pairs were selected: nonrelated dominant (WR—FS), trade-off dominant (FS—HQ), and synergy dominant (SR—LA). The MGWR model revealed the complex spatial–temporal relationships between landscape patterns and ES pairs, providing a more detailed explanation. From the perspective of model parameters, the fitting effect of the model seemed to be related to spatial autocorrelation (Table 5). The larger Moran's I was, the larger the Adj R^2.

This finding may indicate that the local regression model had a better fitting effect on variables with stronger spatial autocorrelation. Although the existing research results support this conclusion (Zhang et al. 2020b), more relevant studies need to be compared to verify it.

There was strong spatial–temporal heterogeneity in the response of the three group relationships to the landscape pattern. In 1999, the large-scale implementation of the GFG began in the LPNS. From 2000 to 2010, the LULC changed significantly, mainly in terms of the decrease in PLAND_C and the increase in PLAND_F and PLAND_G (Fig. 3). These changes led to an increase in vegetation coverage; enhanced the ability to intercept rainfall, block surface runoff and inhibit soil evaporation; and weakened the erosion from rainfall on the surface, thereby reducing soil erosion and promoting the trade-offs of WR—FS and FS—HQ and the positive synergy of SR—LA (Fig. 8b, c and d). From 2010 to 2020, the implementation rate of the GFG slowed significantly. The change in LULC was mainly observed in the slight increase and decrease in cultivated land and grassland at a smaller spatial scale (Fig. 3), and the change was widespread over a wide range of areas. Therefore, PLAND_C and PLAND_G had complex and significant effects on the relationships among ESs and showed strong spatial heterogeneity. The complexity may have been caused by many factors. For example, FS is usually closely related to the area of cultivated land. However, for ecotones, appropriate natural landscapes could increase biodiversity and species abundance, thereby increasing crop yield (Seppelt et al. 2016). Therefore, PLAND_G also had a certain role in promoting FS. Compared with that of grasslands, the soil reinforcement of crops is weaker, and the increase in PLAND_C is often accompanied by a decrease in SR. However, in some areas of the study area, sloping cultivated land was transformed into terraces through engineering measures

(Xue et al. 2011), which reduced the slope of cultivated land and weakened the erosion effect of rainfall and runoff from soil (Arnáez et al. 2015), thus promoting the increase in SR.

At present, the ecological environment governance in the northwestern part of the study area is an urgent problem that needs to be addressed. Greater vegetation coverage can effectively slow the movement of surface runoff and increase the infiltration of water flow. Thus, expanding the area of forestland may be the most direct and effective solution. However, based on the strong evapotranspiration in this area, it must be considered that a greater canopy of forestland would result in stronger plant transpiration (Sun et al. 2006; Xue et al. 2022b). In contrast, the transpiration of grasslands is weaker, which can better enable water conservation and soil erosion reduction. Therefore, on the basis of ensuring a red line of cultivated land, appropriately expanding the proportion of grasslands in the landscape and adjusting the spatial configuration of cultivated land and grasslands may be feasible measures for promoting the coordinated development of food security and the ecological environment in the study area.

Difference in the influence between landscape composition and landscape configuration

Studies have shown that trade-offs/synergies among ESs may vary depending on landscape composition (Qiu et al. 2021) and landscape configuration (Rieb and Bennett 2020). Therefore, this study considered the differences between the two in the selection of landscape metrics. LPI, PLAND_C, PLAND_F, PLAND_G and PR were used to characterize landscape composition, and SHAPE, PD, CONTAG, CONNECT, and IJI were used to characterize landscape configuration. Comparing the regression coefficients, it was found that the influence of landscape composition on the
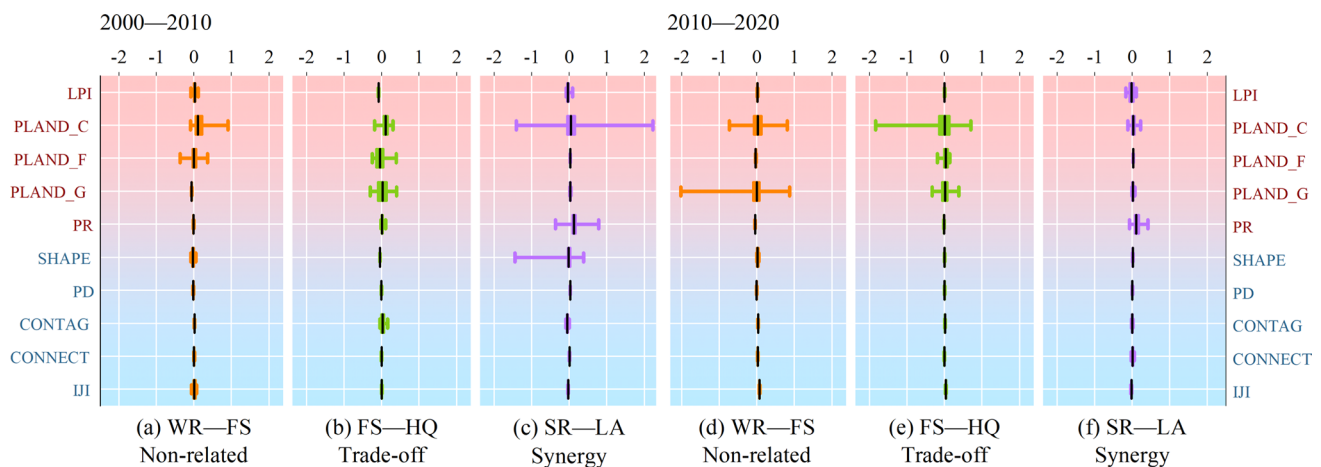
Fig. 9 Box plots for regression coefficients. Notes: The landscape composition and configuration variables are marked in red and blue, respectively

interaction among Ess was significantly greater than that of landscape configuration, which was consistent with the results of existing studies (Lamy et al. 2016; Lavorel et al. 2022; Shi et al 2023).

In this paper, the distribution characteristics of the regression coefficients between landscape metrics and trade-offs/synergies were statistically presented in box plots, which visually reflected the differences in the effects of landscape composition and landscape configuration. Overall, compared with landscape configuration, the quartiles and extreme values of the regression coefficients corresponding to landscape composition showed a larger distribution range (Fig. 9). From the perspective of time, during 2000—2020, the impact of landscape composition on the nonrelated-dominated WR—FS and trade-off-dominated FS—HQ increased with time (Fig. 9a, b, d and e), and the impact on synergy-dominated SR—LA decreased over time (Fig. 9c and f). Among them, WR—FS and FS—HQ were mainly affected by PLAND_C, PLAND_F and PLAND_G, and SR—LA was more affected by PLAND_C and PR. Comparing the two periods, the impact of landscape configuration on the relationships among Ess was stronger in 2000—2010. CONTAG had a weak effect on FS—HQ and SR—LA, WR—FS had a slight response to SHAPE and IJI, and SHAPE had the most significant effect on SR—LA. The relationships among the Ess in 2010—2020 were not sensitive to changes in landscape configuration.

Overall, PLAND_C and PLAND_G from 2000 to 2020 had a greater impact on the three groups of relationships among Ess. This might have been due to the large proportion and changes in cultivated land, forestland and grassland in the LPNS, which had an important contribution to the change in the regional landscape pattern. As important landscape matrices, their spatial–temporal changes changed not only the size of the supply units of relevant Ess but also the transmission of ecological processes between landscapes through changes in landscape configuration, thus affecting the generation and Interactions of the eSs.

Conclusions

This study quantified the landscape pattern and five typical eSs (WR, FS, HQ, SR, and LA) in the LPNS and used the revised TSD indicator to map patterns of trade-offs and synergies among the eSs. The MGWR model revealed the spatial–temporal heterogeneity in the influence of landscape patterns on the trade-offs/synergies.

The results showed that the LULC change in the LPNS was significant from 2000 to 2010, mainly observed as a decrease in cultivated land and an increase in forestland and grassland, which led to the enhancement of landscape diversity and the weakening of landscape heterogeneity and

fragmentation. HQ and LA increased significantly. From 2010 to 2020, the change range decreased, the spatial distribution was more uniform, and the landscape diversity and fragmentation in the northwestern area increased significantly. WR, FS and SR increased significantly. From 2000 to 2020, the trade-offs/synergies related to WR were weak. FS—SR, FS—LA and SR—LA were dominated by synergies. The proportion of trade-off units in all relationships had an upward trend in 2010—2020, and HQ—FS, HQ—SR and HQ—LA were dominated by trade-offs. Landscape patterns had complex impacts on trade-offs/synergies, and the same landscape variable might have the opposite impact on specific trade-offs/synergies in different periods and areas. The results of this study will inform managers in developing regional sustainable ES management strategies while advocating for more research to address ecological issues from a spatial–temporal perspective.

Author contribution Jinxin Shi: Conceptualization, Methodology, Software, Data processing, Writing–- Original Draft. Xiaoying Liang: Conceptualization, Methodology, Writing–- Review and editing, Supervision. Zheng Wei: Review & Editing. Huiqiang Li: Review & Editing.

Data Availability All data included in this study are available upon request by contact with the corresponding author.

Declarations

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

References

Arnáez J, Lana-Renault N, Lasanta T, Ruiz-Flaño P, Castroviejo J (2015) Effects of farming terraces on hydrological and geomorphological processes. A review. Catena 128:122–134. https://doi.org/10.1016/j.catena.2015.01.021

Badora K, Wróbel R (2020) Changes in the Spatial Structure of the Landscape of Isolated Forest Complexes in the 19th and 20th Centuries and Their Potential Effects on Supporting Ecosystem Services Related to the Protection of Biodiversity Using the Example of the Niemodlin Forests (SW Poland). Sustainability 12(10):4237. https://doi.org/10.3390/su12104237

Bao YB, Li T, Liu H, Ma T, Wang HX, Liu K, Shen X, Liu XH (2016) Spatial and temporal changes of water conservation of Loess Plateau in northern Shaanxi province by InVEST model. Geogr Res 35(04):664–676. https://doi.org/10.11821/dlyj201604006

Bennett EM, Peterson GD, Gordon LJ (2009) Understanding relationships among multiple ecosystem services. Ecol Lett

12(12):1394–1404. https://doi.org/10.1111/j.1461-0248.2009.01387.x

Chen WX, Zeng J, Chu YM, Liang JL (2021) Impacts of Landscape Patterns on Ecosystem Services Value: A Multiscale Buffer Gradient Analysis Approach. Remote Sens 13(13):2551. https://doi.org/10.3390/rs13132551

Costanza R, de Groot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, O'neill RV, Paruelo J, Raskin RG, Sutton P, Van Den Belt M (1998) The value of the world#s ecosystem services and natural capital. Ecol Econ 25(1):3–15. https://doi.org/10.1016/S0921-8009(98)00020-2

Daily GC (1997) Nature's Service: Societal Dependence on Nature Ecosystem, 4th edn. Island Press, Washington, DC

Foley JA, DeFries R, Asner GP, Barford C, Bonan G, Carpenter SR, Chapin FS, Coe MT, Daily GC, Gibbs HK, Helkowski JH, Holloway T, Howard EA, Kucharik CJ, Monfreda C, Patz JA, Prentice IC, Ramankutty N, Snyder PK (2005) Global Consequences of Land Use. Science 309(5734):570–574. https://doi.org/10.1126/science.1111772

Fotheringham AS, Yang WB, Kang W (2017) Multiscale Geographically Weighted Regression (MGWR). Ann Am Assoc Geogr 107(6):1247–1265. https://doi.org/10.1080/24694452.2017.1352480

Frank S, Fürst C, Koschke L, Witt A, Makeschin F (2013) Assessment of landscape aesthetics—validation of a landscape metrics-based assessment by visual estimation of the scenic beauty. Ecol Ind 32:222–231. https://doi.org/10.1016/j.ecolind.2013.03.026

He JY, Jiang XH, Lei YX (2023) Effects of ecological engineering on spatio-temporal changes of key ecosystem services on the Loess Plateau: A case study in the Yanhe River Basin, China. Acta Ecologica Sinica 43(12):1–12. https://doi.org/10.5846/stxb202205121332

Howe C, Suich H, Vira B, Mace GM (2014) Creating win-wins from trade-offs? Ecosystem services for human well-being: A meta-analysis of ecosystem service trade-offs and synergies in the real world. Glob Environ Chang 28:263–275. https://doi.org/10.1016/j.gloenvcha.2014.07.005

Hu S, Cao MM, Liu Q, Zhang TQ, Qiu HJ, Liu W, Song JX (2014) Comparative study on the soil conservation function of InVEST model under different perspectives. Geogr Res 33(12):2393–2406. https://doi.org/10.11821/dlyj201412016

Karimi JD, Harris JA, Corstanje R (2021) Using Bayesian Belief Networks to assess the influence of landscape connectivity on ecosystem service trade-offs and synergies in urban landscapes in the UK. Landsc Ecol 36(11):3345–3363. https://doi.org/10.1007/s10980-021-01307-6

Lamy T, Liss KN, Gonzalez A, Bennett EM (2016) Landscape structure affects the provision of multiple ecosystem services. Environ Res Lett 11(12):124017. https://doi.org/10.1088/1748-9326/11/12/124017

Lavorel S, Grigulis K, Richards DR, Etherington TR, Law RM, Herzig A (2022) Templates for multifunctional landscape design. Lands Ecol 1–22. https://doi.org/10.1007/s10980-021-01377-6

Lee H, Lautenbach S (2016) A quantitative review of relationships between ecosystem services. Ecol Ind 66:340–351. https://doi.org/10.1016/j.ecolind.2016.02.004

Li JH, Zhou KC, Xie BG, Xiao JY (2021) Impact of landscape pattern change on water-related ecosystem services: Comprehensive analysis based on heterogeneity perspective. Ecol Ind 133:108372. https://doi.org/10.1016/j.ecolind.2021.108372

Li T, Liang XY, Zhang J, Geng Y, Geng TW, Shi JX (2023) Ecosystem service trade-of and synergy relationship and its driving factor analysis based on Bayesian belief network: a case study of the Loess Plateau in northern Shaanxi Province. Acta Ecol Sin 43(16):6758–6771. https://doi.org/10.5846/stxb202205041231

Li SC, Zhang CY, Liu JL, Zhu WB, Ma C, Wang J (2013) The trade-offs and synergies of ecosystem services: Research progress,

development trend, and themes of geography. Geogr Res 32(8):1379–1390. http://www.dlyj.ac.cn/CN/Y2013/V32/I8/1379

Liu LY, Bian ZQ, Ding SY (2018a) Effects of landscape spatial heterogeneity on the generation and provision of ecosystem services. Acta Ecol Sin 38(18):6412–6421. https://doi.org/10.5846/stxb201801160119

Liu XN, Pei S, Chen L, Liu CL (2018) Study on Soil Conservation Service of Ecosystem Based on InVEST Model in Mentougou District of Beijing. Res Soil Water Conserv 25(6):168–176. https://doi.org/10.13869/j.cnki.rswc.2018.06.025

Liu D, Chen H, Geng TW, Zhang H, Shi QQ (2020) Spatiotemporal changes of regional ecological risks in Shaanxi Province based on geomorphologic regionalization. Prog Geogr 39(2):243–254. https://doi.org/10.18306/dlkxjz.2020.02.006

Lovett GM, Jones CG, Turner MG, Weathers KC (2005) Ecosystem Function in Heterogeneous Landscapes. Springer, New York

Lyu RF, Zhao WP, Tian XL, Zhang JM (2022) Non-linearity impacts of landscape pattern on ecosystem services and their trade-offs: A case study in the City Belt along the Yellow River in Ningxia, China. Ecol Indic 136:108608. https://doi.org/10.1016/j.ecolind.2022.108608

McGarigal K, Cushman SA, Ene E (2012) FRAGSTATS v4: spatial pattern analysis program for categorical and continuous maps. Computer software program produced by the authors at the University of Massachusetts, Amherst. Available at: the following web site: http://www.umass.edu/landeco/research/fragstats/fragstats.html

Millennium Ecosystem Assessment (2005) Ecosystems and Human Well-Being: Synthesis. Island Press, Washington, DC

Nelson KS, Burchfield EK (2021) Landscape complexity and US crop production. Nature Food 2(5):330–338. https://doi.org/10.1038/s43016-021-00281-1

Oshan TM, Li ZQ, Kang W, Wolf LJ, Fotheringham AS (2019) MGWR: A Python Implementation of Multiscale Geographically Weighted Regression for Investigating Process Spatial Heterogeneity and Scale. ISPRS Int J Geo Inf 8(6):269. https://doi.org/10.3390/ijgi8060269

Peng J, Chen X, Liu YX, Lu HL, Hu XX (2016) Spatial identification of multifunctional landscapes and associated influencing factors in the Beijing-Tianjin-Hebei region, China. Appl Geogr 74:170–181. https://doi.org/10.1016/j.apgeog.2016.07.007

Qiu JX, Turner MG (2013) Spatial interactions among ecosystem services in an urbanizing agricultural watershed. Proc Natl Acad Sci 110(29):12149–12154. https://doi.org/10.1073/pnas.1310539110

Qiu JX, Turner MG (2015) Importance of landscape heterogeneity in sustaining hydrologic ecosystem services in an agricultural watershed. Ecosphere 6(11):1–19. https://doi.org/10.1890/ES15-00312.1

Qiu JX, Queiroz C, Bennett EM, Cord AF, Crouzat E, Lavorel S, Maes J, Meacham M, Norström AV, Peterson GD, Deng R, Turner MG (2021) Land-use intensity mediates ecosystem service trade-offs across regional social-ecological systems. Ecosyst People 17(1):264–278. https://doi.org/10.1080/26395916.2021.1925743

Ran PL, Hu SG, Frazier Amy E, Yang SF, Song XY, Qu SJ (2023) The dynamic relationships between landscape structure and ecosystem services: An empirical analysis from the Wuhan metropolitan area, China. J Environ Manag 325:116575. https://doi.org/10.1016/j.jenvman.2022.116575

Rieb JT, Bennett EM (2020) Landscape structure as a mediator of ecosystem service interactions. Landsc Ecol 35:2863–2880. https://doi.org/10.1007/s10980-020-01117-2

Seppelt R, Beckmann M, Ceauşu S, Cord AF, Gerstner K, Gurevitch J, Kambach S, Klotz S, Mendenhall C, Phillips HRP, Powell K, Verburg PH, Verhagen W, Winter M, Newbold T (2016) Harmonizing biodiversity conservation and productivity in the context of

increasing demands on landscapes. Bioscience 66(10):890–896. https://doi.org/10.1093/biosci/biw004

Shi JX, Liang XY, Li HQ, Wei Z (2023) Impact of landscape pattern on ecosystem service trade-offs in the Loess Plateau of Northern Shaanxi. Acta Ecol Sin 43(21):1–15. https://doi.org/10.20103/j.stxb.202211053163

Su CH, Fu BJ (2012) Discussion on Links Among Landscape Pattern, Ecological Process, and Ecosystem Services. Chin J Nat 34(5):277–283. https://doi.org/10.3969/j.issn.0253-9608.2012.05.005

Sun G, Zhou GY, Zhang ZQ, Wei XH, McNulty SG, Vose JM (2006) Potential water yield reduction due to forestation across China. J Hydrol 328(3–4):548–558. https://doi.org/10.1016/j.jhydrol.2005.12.013

Tanner EP, Fuhlendorf SD (2018) Impact of an agri-environmental scheme on landscape patterns. Ecol Ind 85:956–965. https://doi.org/10.1016/j.ecolind.2017.11.043

Turner BL, Lambin EF, Reenberg A (2007) The emergence of land change science for global environmental change and sustainability. Proc Natl Acad Sci 104(52):20666–20671. https://doi.org/10.1073/pnas.0704119104

Turner MG, Donato DC, Romme WH (2013) Consequences of spatial heterogeneity for ecosystem services in changing forest landscapes: priorities for future research. Landsc Ecol 28(6):1081–1097. https://doi.org/10.1007/s10980-012-9741-4

Wang BY, Liu ZC, Mei YT, Li WJ (2019) Assessment of Ecosystem Service Quality and Its Correlation with Landscape Patterns in Haidian District, Beijing. Int J Environ Res Public Health 16(7):1248. https://doi.org/10.3390/ijerph16071248

Wang G, Yue DP, Niu T, Yu Q (2022a) Regulated Ecosystem Services Trade-Offs: Synergy Research and Driver Identification in the Vegetation Restoration Area of the Middle Stream of the Yellow River. Remote Sens 14(3):718. https://doi.org/10.3390/rs14030718

Wang QK, Wu W, Yang XQ, Sang GQ (2022b) Spatial-temporal changes and driving factors of habitat quality in Shaanxi Province during the past 20 years. Arid Zone Res 39(5):1684–1694. https://doi.org/10.13866/j.azr.2022.05.32

Wang Y, Zhao PX, Li ZG, Xia B, Gao JZ, Ma PY (2022c) Ecosystem Service Dynamics and Hotspot Identification under the Background of Grain to Green Program in Northern Shaanxi. J North China Univ Water Resour Electr Power (Natural Science Edition) 43(5):92–100. https://doi.org/10.19760/j.ncwu.zk.2022068

Wang SQ, Liu YX, Li Y, Fu BJ (2023) Research progress on the ecosystem services on the Loess Plateau during the recent 20 years. Acta Ecol Sin 43(1):26–37. https://doi.org/10.5846/stxb202204291190

Wu F, Liang YJ, Peng SZ, Huang JJ, Liu LJ (2022) Challenges in trade-off governance of ecosystem services: Evidence from the loess plateau in China. Ecol Ind 145:109686. https://doi.org/10.1016/j.ecolind.2022.109686

Xia HJ, Kong WJ, Zhou G, Sun OJ (2021) Impacts of landscape patterns on water-related ecosystem services under natural restoration in Liaohe River Reserve, China. Sci Total Environ 792:148290. https://doi.org/10.1016/j.scitotenv.2021.148290

Xue S, Liu GB, Zhang C, Fan LX (2011) Effects of terracing slope cropland on soil quality in Hilly Region of Loess Plateau. Trans Chin Soc Agric Eng 27(4):310–316. https://doi.org/10.3969/j.issn.1002-6819.2011.04.054

Xue CL, Chen XH, Xue LR, Zhang HQ, Chen JP, Li DL (2022a) Modeling the spatially heterogeneous relationships between tradeoffs and synergies among ecosystem services and potential drivers considering geographic scale in Bairin Left Banner, China. Sci Total Environ 855:158834. https://doi.org/10.1016/j.scitotenv.2022.158834

Xue CL, Zhang HQ, Wu SM, Chen JP, Chen XH (2022b) Spatial-temporal evolution of ecosystem services and its potential drivers: a geospatial perspective from Bairin Left Banner, China. Ecol Indic 137:108760. https://doi.org/10.1016/j.ecolind.2022.108760

Yu XX, Zhou B, Lv XZ, Yang ZG (2012) Evaluation of Water Conservation Function in Mountain Forest Areas of Beijing Based on InVEST Model. Sci Silvae Sin 48(10):1–5. https://doi.org/10.11707/j.1001-7488.20121001

Zhang J, Qu M, Wang C, Zhao J, Cao Y (2020a) Quantifying landscape pattern and ecosystem service value changes: A case study at the county level in the Chinese Loess Plateau. Glob Ecol Conserv 23:e01110. https://doi.org/10.1016/j.gecco.2020.e01110

Zhang ZY, Liu YF, Wang YH, Liu YL, Zhang Y, Zhang Y (2020b) What factors affect the synergy and tradeoff between ecosystem services, and how, from a geospatial perspective? J Clean Prod 257:120454. https://doi.org/10.1016/j.jclepro.2020.120454

Zhao J, Li C (2022) Investigating Ecosystem Service Trade-Offs/Synergies and Their Influencing Factors in the Yangtze River Delta Region, China. Land 11(1):106. https://doi.org/10.3390/LAND11010106

Zhou ZX, Li J, Ren ZY (2012) The Relief Degree of Land Surface and Population Distribution in Guanzhong-Tianshui Economic Region Using GlS. Sci Geogr Sin 32(8):951–957. https://doi.org/10.13249/j.cnki.sgs.2012.08.007