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Coupling coordination analysis and spatiotemporal heterogeneity between sustainable development and ecosystem services in Shanxi Province, China

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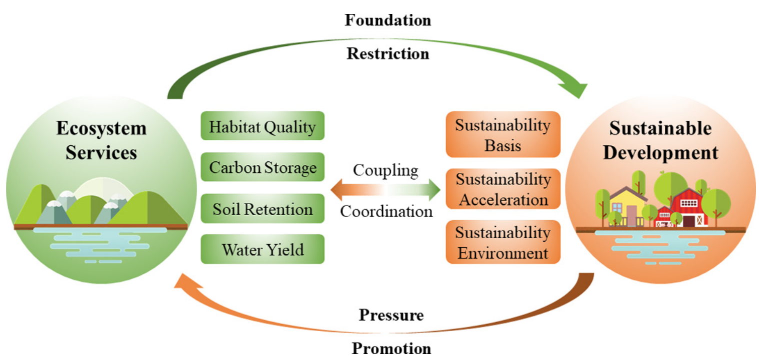
HIGHLIGHTS

- A localized SDGs assessment framework was established and applied to Shanxi Province at the county level.
- The sustainable development level and ecosystem services increased steadily with decreasing soil retention.
- The CCD between soil retention and sustainable development decreased as other services increased.
- The negative correlation between habitat quality and sustainable development was the strongest.
- The CCD and correlation between sustainable development and ES had obvious regional heterogeneity.

GRAPHICAL ABSTRACT



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ABSTRACT

Excessive human activities destroy the structure and function of ecosystem and threaten sustainable development. As a typical resource-based area, Shanxi Province is facing an increasingly serious contradiction between ecosystem and sustainable development, with the overexploitation of resources. In view of this, the coupling coordination degree model was used to measure the association between sustainable development and ecosystem services (SDESs), and geographically and temporally weighted regression model was used to explore the correlation between SDESs and measure the correlation between ecosystem services (ESs) and sustainable development at the county level from 2000 to 2015 in Shanxi Province. The results showed an increase in the sustainable development level and all ESs except soil retention. The coupling coordination degree (CCD) of soil retention and sustainable development decreased, while other services increased. Habitat quality had the strongest negative correlation with sustainable development. There were obvious spatiotemporal heterogeneities in the CCD and correlation of SDESs, which is helpful for promoting regional sustainable development and optimize ecosystem decision-making.

1. Introduction

The concept of sustainable development was introduced in 1987 in the United Nations report *Our Common Future*, and intergenerational and intragenerational equity are emphasized (Griggs et al., 2013). In 2015, to promote the coordinated development of sustained global economic prosperity, social justice and harmony and environmental security, the United Nations Summit on Sustainable Development adopted the *Transforming our World: The 2030 Agenda for Sustainable Development* with 17 Sustainable Development Goals (SDGs) and 169 subgoals and established the

Abbreviations: ESs, Ecosystem services; SDGs, Sustainable Development Goals; SD, Sustainable development; CS, Carbon storage; SR, Soil retention; HQ, Habitat quality; WY, Water yield; SDESs, Sustainable development and ecosystem services; CCD, Coupling coordination degree; GTWR, Geographically and temporally weighted regression; InVEST, Integrated Valuation of Ecosystem Services and Trade-offs; GFGP, the Grain for Green Program.

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evaluation mechanism framework of global sustainable development (Zhu et al., 2018). Goals involve no poverty, zero hunger, good health and well-being and many other aspects (United Nations, 2014).

Scientific monitoring and assessment of progress in sustainable development is key to ensuring that SDGs is achieved. Due to the differences in statistical systems and the absence of numerous data, the SDGs framework cannot be directly applied to assessments at the specific country and regional levels (Shao et al., 2021). The United Nations Development Programme highlighted the importance of achieving SDGs localization and urged countries to build SDGs indicators for localization in 2016. Allen et al. (2017) formulated a set of sustainable development indicator systems applicable at the national level for developing countries in combination with SDGs and the actual conditions of the Arab region. Scholars and institutions have also assessed sustainable development at the subnational administrative level. Based on the SDGs framework, the indicator system of city sustainable development of New York City was proposed in 2018 (Shao et al., 2021). Phillis et al. (2017) used 46 socioeconomic indicators to rank the level of sustainable development of 106 cities around the world. Liu et al. (2019) localized the subgoals of SDG 15 and quantitatively evaluated the implementation of SDG 15 in Deqing County, China.

The evaluation results of small administrative units are more targeted and have greater practical reference significance for the actions of local governments (Liu et al., 2019). However, there are few sustainable development assessments at the county level that encompass multiple goals. Therefore, carrying out SDG assessments in small administrative units, especially at the county level, helps put the concept of sustainable development into practice and promote the realization of the SDGs.

However, it cannot be ignored that excessive population growth, uncontrolled resource consumption, severe environmental pollution and rapid climate change have become major obstacles to the global realization of SDGs (Shi et al., 2019). A good ecosystem provides resources and materials for economic and social development, provides material support for sustainable development, and can create a relative balance of energy conversion and material circulation within human society (Wang et al., 2013; Yan et al., 2017; Zhang and Li, 2004).

Therefore, sustainable development requires us to protect ecosystem services that are critical to human livelihood and well-being while exploiting natural resources to ensure economic development and social functioning (Konstantinova et al., 2017). However, the reality is that due to the excessive influence of human activities, large areas of land, wetlands and marine ecosystem have been destroyed, and the ecosystem services they provide have also been jeopardized (Chen et al., 2021; Costanza et al., 2017; Xiao et al., 2020; Zhang and Li, 2004). The IPBES Global Assessment on Biodiversity and Ecosystem Services found an unprecedented decline in 14 of the 18 categories of nature's contributions to people and reported that the decline had a negative impact on sustainable development progress.

Many scholars use the coupling coordination model to explore the relationship between ecosystem and human development (Li et al., 2020; Xiao et al., 2020; Yang et al., 2020; Yang and Hu, 2019). Yang and Hu (2019) explored the coordination between ecology and the social economy along the Silk Road Economic Belt in China. Yang et al. (2020) measured the coupling degree and coordination degree between the environment and urbanization in Chongqing. These researches on ecosystem services and human development break from the long-standing underestimation of ecosystem services in the discussion of the SDGs. Although coupling coordination models are used to measure the association between the environment and social development, they do not prove the correlation between the two. Associations generally exist among variables, while correlations are a more specific type of association (Altman and Krzywinski, 2015). How trends in ecosystem services affect the realization of the SDGs and how ecosystem services in different regions affect the SDGs have not been fully explained (Reyers and Selig, 2020; Yuan and Lo, 2020). Understanding the correlation between ecosystem services and the SDGs can provide a basis for formulating and promoting larger policies, as well as identifying management needs at this stage. Therefore, it is necessary to test the correlation between ecosystem services and sustainable development using regression analysis to reveal the specific type of association between them.

As a typical resource-based area, Shanxi Province relies on coal and other resources to drive its rapid economic development, and serious resource consumption leads to the extremely fragile environment of the whole province. The accelerated degradation of the environment in turn restricts the development of the local economy and society, and the sustainable development of Shanxi Province faces severe challenges.

Based on the above background information, the following innovations are put forth. (1) In consideration of the development status and data availability in China, this study makes localization improvements to the SDG assessment framework. A sustainable development evaluation framework with Chinese characteristics is constructed and applied to the quantitative evaluation of the progress of sustainable development at the county level in Shanxi Province. (2) The coupling and coordination analysis of local key ecosystem services and sustainable development level was carried out at the county level to explore the relationship between the two. (3) A geographically and temporally weighted regression (GTWR) model was used to reveal the relationship between different types of ecosystem services and SDGs in time and space.

2. Study case

2.1. Study area

Shanxi Province (110°14′-114°33′E, 34°34′-40°44′N) is located in the north of China and the east of the Loess Plateau, with a total area of approximately 156,700 km^2 (Fig. 1). The geomorphic types of Shanxi Province are complex and diverse. It is a typical mountain plateau terrain, in which mountains and hills account for 80% of the area, and most areas are over 1000 m above sea level. The 2020 census report shows that the total population of Shanxi Province is 34.90 million, accounting for 2.48% of the national population. The GDP was CNY 1.77 trillion, accounting for 1.74% of the national GDP, and the per capita disposable income was CNY 25,214.

Shanxi was once one of the key provinces targeted for poverty alleviation and development. According to statistics, in 2014, 58 poverty-stricken counties in Shanxi Province with a poverty rate of 13.6% prior to the comprehensive elimination of poverty in 2020. Geographically, the poor counties in Shanxi Province are highly concentrated in eastern Taihang and western Luliang. The development of these poor counties is restricted by the natural environment and social and historical conditions, resulting in inconvenient transportation, lack of resources and frequent natural disasters. The natural environment has a great impact on local sustainable development. In 2020, poverty in Shanxi Province was basically eliminated, which means that extreme poverty conditions were reduced drastically in China to achieve the 2030 Sustainable Development Goal target. It is urgent to further consolidate the achievements of poverty eradication, comprehensively improve economic, social and ecological development and improve the level of sustainable development.

At the same time, Shanxi Province is an important source of coal and mineral resources in China. As a typical resource-based development area, its economic and social development is inseparable from the environment (Guo and Ma, 2017). However, due to excessive resource exploitation, Shanxi Province has become an extremely ecologically fragile area (Liu et al., 2018). The deterioration of the environment seriously threatens local sustainable development. Population, resources, ecosystem and development are fraught with contradictions.

Understanding the coupling characteristics of sustainable development and ecosystem services in this region is conducive to the realization of sustainable social development, the protection and utilization of ecosystem services, and the harmonious and win-win nature of human and ecological development. This study can also provide an important reference for other regions.

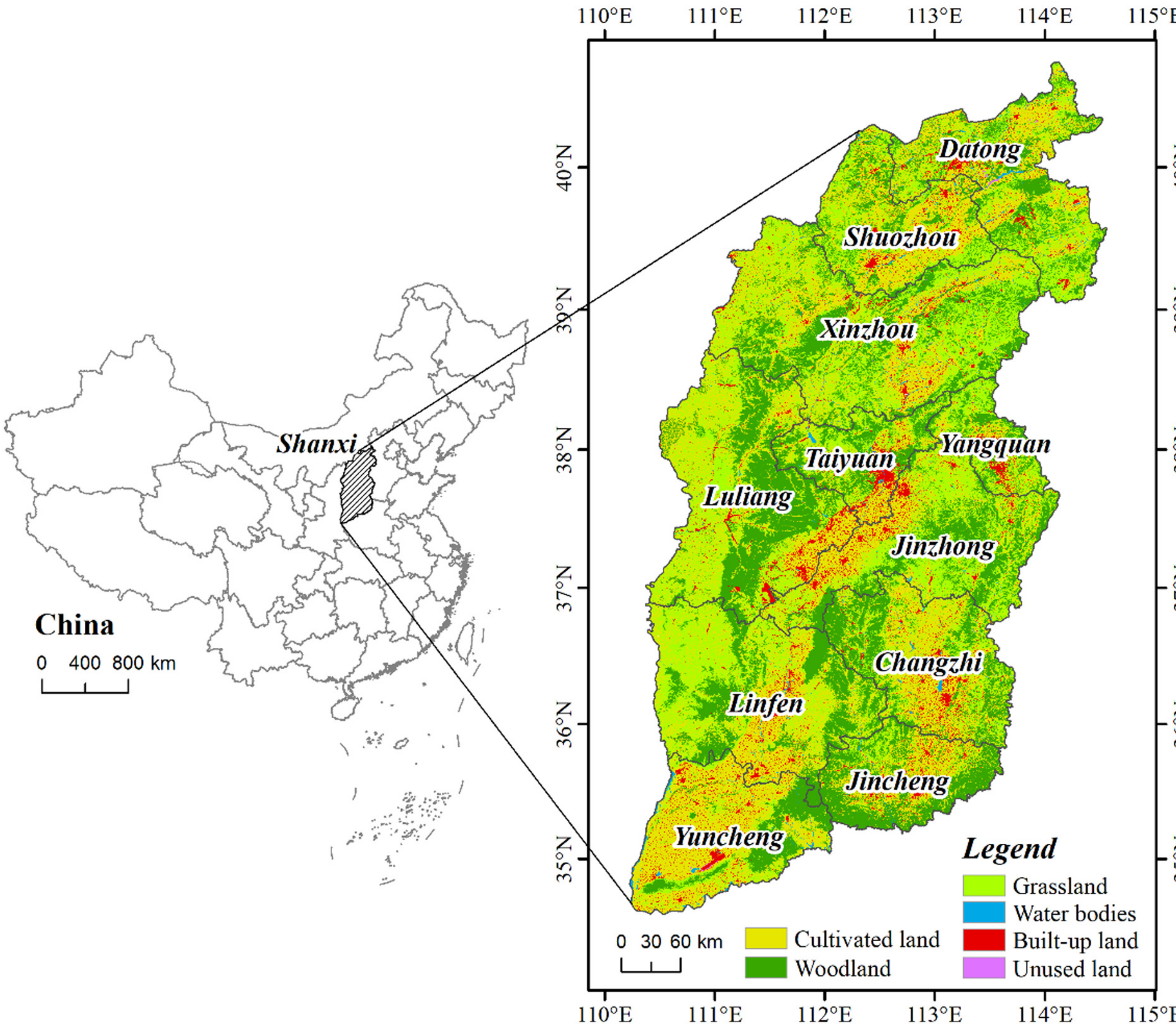

Fig. 1. Location and land use type of Shanxi Province.

2.2. Variables

Based on SDGs, previous research (Deng et al., 2020) and actual local conditions, twelve indicators were selected, and a sustainable development (SD) evaluation indicator system with Chinese characteristics was constructed (Table 1).

We broke down the implementation process of SD. First of all, in order to achieve SD, there must be certain social, natural and human capital. These physical conditions and their changes become the basis of SD, that is, sustainability basis. It represents the starting point of SD of a regional. Secondly, in the context of sustainability basis, a region starts to sprint towards the SD, and the quality of population determines the sprint speed, namely, sustainability acceleration, which represents the potential of SD of a region. Finally, sufficient thrust support is necessary for acceleration sprint in a region on basis, and the sustainability environment is the thrust support, which represents the external support force provided by various aspects to achieve SD.

Sustainability basis considers capital condition and capital change, and involves SDG 1, SDG 2, SDG 9, SDG 11 and SDG 12 (Table 1). As for capital

Table 1
Indicator system of sustainable development evaluation.

Dimensions	Factors	Indicators	Description	Unit	Weight	SDGs
Sustainability basis	Capital condition	Population resource	Number of employees	People	0.0391	SDG 11 Sustainable cities and communities
		Income level	Regional GDP	Yuan	0.1296	SDG 1 No poverty
		Natural capital	Output of grain	Tons	0.0365	SDG 2 Zero hunger
	Capital change	Income diversity	Proportion of nonagricultural industries	%	0.0013	SDG 9 Industry, innovation and infrastructure
		Major investment	Investment in fixed assets	Yuan	0.1439	SDG 11 Sustainable cities and communities
		Consumer spending	Total retail sales of consumer goods	Yuan	0.1743	SDG 12 Responsible consumption and production
Sustainability acceleration	Quality condition	Current education situation	Number of students in nine-year compulsory education	People	0.0385	SDG 4 Quality education
	Skill level	Employment situation	Employees	People	0.1584	SDG 8 Decent work and economic growth
Sustainability environment	Soft environment	Government support	Public finance expenditure	Yuan	0.1094	SDG 11 Sustainable cities and communities
		Livelihood opportunities	Number of enterprises		0.0502	SDG 9 Industry, innovation and infrastructure
	Hard environment	Geographical conditions	Land area of Administrative Region	km^2	0.0138	SDG 11 Sustainable cities and communities
		Public facility allocation	Number of beds in hospital		0.1049	SDG 3 Good health and well -being

condition and capital change, six indicators were selected to represent the status and change of human capital, economic capital and natural capital required to achieve sustainable development.

Sustainability acceleration involves quality condition and skill level, which respectively represent the realization of SDG 4 and SDG 8 (Table 1). As the main body of sustainable development, people determine the direction and speed of it, and good population quality contributes to the faster and better realization of sustainable development.

Sustainability environment is divided into soft environment and hard environment, which represents the process of SDG 3, SDG 9 and SDG 11 (Table 1). Four indicators were selected to reflect the support of economic environment, geographical environment and social environment to sustainable development.

2.3. Data sources

The data used for sustainable development evaluation were obtained from the Shanxi Statistical Yearbook of 2001, 2006, 2011 and 2016 (http://www.shanxi.gov.cn/sj/tjnj/).

The data were normalized to eliminate the effects of different dimensions and magnitudes on the calculation (Cui et al., 2019).

For positive indicators: $Y_{\theta ij} = \frac{X_{\theta ij} - \min(X_j)}{\max(X_j) - \min(X_j)}.$

For negative indicators: $Y_{\theta ij} = \frac{\min(X_j) - X_{\theta ij}}{\max(X_j) - \min(X_j)}$

where $X_{\theta ij}$ is the original value of indicator j of county θ in year i; $Y_{\theta ij}$ is the normalized value of $X_{\theta ij}$; and $\min(X_j)$ and $\max(X_j)$ are the minimum and maximum values of indicator j of all counties in all years.

In this study, habitat quality, carbon storage, soil retention and water yield were selected as representatives. Four key ecosystem services were modeled based on the meteorological raster dataset, digital elevation model (DEM), land use and land cover change (LUCC) raster data, soil types and physical properties dataset. Raster datasets, namely, minimum and maximum annual temperature, annual precipitation, annual reference evapotranspiration and rainfall erosivity raster, were obtained from the China Meteorological Data Service Center. Depth to root restricting layer, plant availability water fraction, organic matter, aboveground biomass, belowground biomass, soil carbon and soil erodibility raster dataset were obtained from Harmonized World Soil Database. The evapotranspiration coefficient was obtained from the Food and Agriculture Organization of the United Nations (FAO) online resource. DEMs, crop management factors and support management factors were sourced from the Geospatial Data Cloud.

3. Methods

The research methods and process adopted in this study are as follows: (1) The sustainable development level of 107 districts in Shanxi Province in 2000, 2005, 2010 and 2015 was calculated by the entropy weight method and linear weighting method. (2) Habitat quality, carbon storage, soil retention and water yield were calculated using the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model, Carnegie-Ames-Stanford Approach (CASA) and the Revised Universal Soil Loss Equation (RUSLE). (3) A CCDM was used to calculate the CCD between sustainable development and the ecosystem services (SDESs) system. (4) A geographically and temporally weighted regression model was used to calculate the interaction mechanism between SDESs in time and space.

3.1. Evaluation of sustainable development

The selection of sustainable development indicators is based on SDGs and takes into account previous studies (Deng et al., 2020). First, the entropy weight method is used to determine the weight of each indicator. The entropy weight method determines the weight through the principle of information entropy, which can objectively and accurately evaluate the research object (Yang and Sun, 2015). The larger the entropy value is, the more balanced the system structure is, the smaller the coefficient difference is, and the smaller the weight is (W. Li et al., 2021). Second, the linear weighting method was adopted to calculate the index values of sustainability and its subsystems. The specific formulas are as follows:

$$P_{\theta ij} = Y_{\theta ij} / \sum_{\theta} \sum_{i} Y_{\theta ij}$$

$$e_j = -k \sum_{\theta} \sum_{i} P_{\theta ij} \ln(P_{\theta ij}) \quad k > 0 \quad k = \frac{1}{\ln(rn)}$$

$$w_j = (1 - e_j) / \sum_j (1 - e_j)$$

$$S_{\theta i} = \sum_j (w_j Y_{\theta ij})$$

where $P_{\theta ij}$ refers to the proportion of indicator j for county θ in year i, e_j represents the entropy value of indicator j, w_j refers to the weight of indicator j, and $S_{\theta i}$ represents the value of the sustainable development level of county θ in year i.

3.2. Evaluation of ecosystem services

(1) Carbon storage. Net primary productivity (NPP) was used as a proxy for evaluating carbon storage. NPP is estimated by Carnegie-Ames-Stanford Approach (CASA), which is based on absorbed photosynthesis active radiation (APAR) (Potter et al., 1993):

$$NPP(x,t) = APAR(x,t) \times \varepsilon(x,t)$$

where NPP(x, t) is the net primary productivity at grid x in month t ($kgC \cdot hm^{-2}$), APAR(x, t) is the absorbed photosynthesis active radiation at pixel x in month t ($MJ \cdot hm^{-2}$), and $\varepsilon(x,t)$ is the actual light use efficiency of pixel x in month t ($gC \cdot MJ^{-1}$).

The production of 1 kg of dry matter by photosynthesis can fix 1.63 kg of CO_2 and release 1.2 kg of O_2 (Li and Zhou, 2016). The conversion relationship between the two is:

$$CS = 1.63NPP$$

where CS is the carbon storage ($kgC \cdot hm^{-2}$) and NPP is the net primary productivity ($kgC \cdot hm^{-2}$).

(2) Water yield. Tallis (2011) defined annual water yield as the amount of water runs off the landscape. Water yield is influenced not only by the topography, geology and climate patterns of an area, but also by the land cover type, soil condition and vegetation condition that related to local ecosystem. In InVEST model, the Water Yield module is based on annual average precipitation and the Budyko (1974) curve (Sharp et al., 2018). The equation is as follows:

$$Y_x = \left(1 - \frac{AET_x}{P_x}\right) \times P_x$$

where Y_x is the water yield at pixel x (mm), AET_x is the actual annual evapotranspiration at pixel x (mm), and P_x is the annual average precipitation at pixel x (mm).

(3) Soil retention. The Revised Universal Soil Loss Equation (RUSLE) was used to calculate the soil retention by quantifying soil erosion on hillslopes by water, which is expressed as (Panagos et al., 2015):

$$E_a = R \times K \times LS \times C \times P$$

$$E_p = R \times K \times LS$$

$$SR = E_p - E_a$$

where SR is the annual soil retention ($t \cdot ha^{-1} \cdot yr^{-1}$), E_a and E_p are the potential and actual annual average soil loss ($t \cdot ha^{-1} \cdot yr^{-1}$), R is the rainfall erosivity factor ($MJ \cdot mm \cdot ha^{-1} \cdot h^{-1} \cdot yr^{-1}$) and K is the soil erodibility factor ($t \cdot ha \cdot h \cdot ha^{-1} \cdot MJ^{-1} \cdot mm^{-1}$). LS, C and P are dimensionless, representing slope length and slope steepness factor, cover-management factor and support practices factor, respectively.

(4) Habitat quality. Habitat Quality module in InVEST was used to estimate the impact of habitat threat, habitat sensitivity to threat, and distance between habitat and threat location (Gomes et al., 2020). Though habitat quality cannot directly represent biodiversity, it was used as a proxy for biodiversity (Li et al., 2021; Ouyang et al., 2016; Sun et al., 2018) and indicated whether flora and fauna species were dominant in such habitats. Threats in the form of paved roads, cultivated fields and urban settlements were considered (Duarte et al., 2016). A habitat quality map was generated with a relative range between 0 and 1 (Gomes et al., 2020). High values represent low threat impact zones and vice versa. The community of flora and fauna species with low threat impact is assumed to be more biologically diverse. This model is mathematically expressed as (Li et al., 2021; Sun et al., 2019):

$$Q_{hx} = H_x \times \left[1 - \left(\frac{D_{hx}^z}{D_{hx}^z + K^z}\right)\right]$$

where Q_{hx} indicates the habitat quality of raster h in land use type x, and H_x is the habitat suitability of land use type x. The z is scalling parameters, and K is the half-saturation constant. D_{hx} is the total threat level of raster h in land use type x.

3.3. Coupling coordination degree model

In this study, the CCDM was applied to investigate the interactive coupling relationship between SDESs. Coupling analysis explains the interdependencies, associations and relationships between the two systems (Liu et al., 2021). Normally, the coupling analysis of ecological systems and human-induced activities is usually explained using the physics concept of the coupling degree model and CCDM to ascertain trends of coupling coordination (Fang et al., 2016; Sun et al., 2019). However, the CCDM model is able to evaluate the overall conflict or coordination among systems as opposed to the coupling degree model (Liu et al., 2021; Liu et al., 2011). This study employed the CCDM model to evaluate the relationship between SDESs. The model is mathematically expressed as follows:

$$\mathrm{C} = \left[\frac{(ES \times LS)}{(ES + LS)^2/4}\right]^{\frac{1}{2}}, C \in [0, 1]$$

$$\mathrm{T} = \alpha \mathrm{ES} + \beta \mathrm{LS}$$

$$\mathrm{CCD} = \sqrt{C \times T}, C \in [0, 1]$$

where C refers to the coupling degree between SDESs, T stands the comprehensive evaluation index between SDESs, and CCD represents the coupling coordinating degree between SDESs. Because of the equal importance of the SDESs to the coordination, α and β are given the same weight, that is, $\alpha = \beta = 0.5$. Referring to previous research (W. Li et al., 2021), we divide the CCD into five levels: seriously unbalanced, moderately unbalanced, basically balanced, moderately balanced and highly balanced (Table 2).

Table 2
Coupling coordinating degree.

Level	Degree
[0.00–0.30]	Seriously unbalanced
(0.30–0.40]	Moderately unbalanced
(0.40–0.50]	Basically balanced
(0.50–0.60]	Moderately balanced
(0.60–1.00]	Highly balanced

3.4. Geographically and temporally weighted regression model

The GTWR model incorporate temporal information in the traditional geographically weighted regression model, which can capture both temporal and spatial heterogeneity (Huang et al., 2010). Therefore, GTWR model was used to explore the spatiotemporal relationship between SDESs. The specific formula is as follows.

$$Y_{ik} = \alpha_0(m_i, n_i, t_i) + \sum_{i=1}^{k}(m_i, n_i, t_i)X_{ik} + \varepsilon_i$$

where Y_{ik} refers to the sustainable development level of county i at time k, $\alpha_0(m_i, n_i, t_i)$ represents geographical location i, X_{ik} represents the ecosystem services level of county i at time k, and ε_i is the random factor of county i at time k. This formula is used to measure the correlation between the ecosystem services and the sustainable development level in county i at time k.

4. Results

4.1. The spatio-temporal changes of sustainable development and ecosystem services

4.1.1. Sustainable development

Due to the large difference, the sustainable development of urban areas and counties was analyzed separately. Fig. 2(a)–(d) shows the sustainable development trend of 11 urban areas in 2000, 2005, 2010 and 2015, and Fig. 2(e)–(h) shows that of 96 counties. The results show that the sustainability basis, sustainability acceleration and sustainability environment level in urban areas increased steadily, so the sustainable development level was the same trend. The sustainability acceleration level in counties decreased, and the rest showed a steady increasing trend.

Fig. 2(a)–(d) shows that the sustainability basis, sustainability acceleration, sustainability environment and sustainable development (4S) level in 11 urban areas showed a steady upward trend from 2000 to 2015. Fig. 2a shows that the average value of the sustainability basis level increased from 0.0333 in 2000 to 0.1265 in 2015. Fig. 2b shows that the average value of the sustainability acceleration level increased from 0.0251 to 0.0648. From 2010 to 2015, the growth rate of the sustainability acceleration level far exceeded that of 2000 to 2005 and 2005 to 2010. Fig. 2c shows that the average value of sustainability environment was 0.0327 in 2000 and increased to 0.0698 in 2015. In Fig. 2d, the sustainable development level showed a steady increasing trend due to the increase in the above three subsystems. The 4S level in Taiyuan urban area always kept the highest from 2000 to 2015, followed by Datong urban area. As for the sustainable development level, Taiyuan urban area increased from 0.0912 in 2000 to 0.2610 in 2015, with Luliang urban area kept the lowest.

In Fig. 2(e)–(h), the average value indicates that the sustainability basis, sustainability environment and sustainable development level of 96 counties in Shanxi Province generally increased greatly, and the gaps among different counties were getting bigger from 2000 to 2015. However, the sustainability acceleration was on the contrary. After a slight increase from 2000 to 2005, the sustainability acceleration level decreased from 2005 to 2015, resulting in the lowest value in 2015.

Fig. 3 shows the spatial pattern of 4S in Shanxi Province in 2000, 2005, 2010 and 2015. The spatial pattern of sustainability basis, sustainability environment and sustainable development was relatively consistent from 2000 to 2015. In 2000, the high values of the three were very scattered. By 2015, the high values of the three were concentrated in the eastern, central and southwestern regions, and the contiguous low values appeared in the western regions. From 2000 to 2015, the spatial pattern of sustainability acceleration varies slightly. The high value area runs through the central part of Shanxi Province from top to bottom, presenting an obvious strip distribution.

After fifteen years, the values of sustainability basis, sustainability environment and sustainable development had improved greatly in the middle, northeast and south from 2000 to 2015. However, the rise of sustainability acceleration was slight and dispersed, even declining in the west and south.

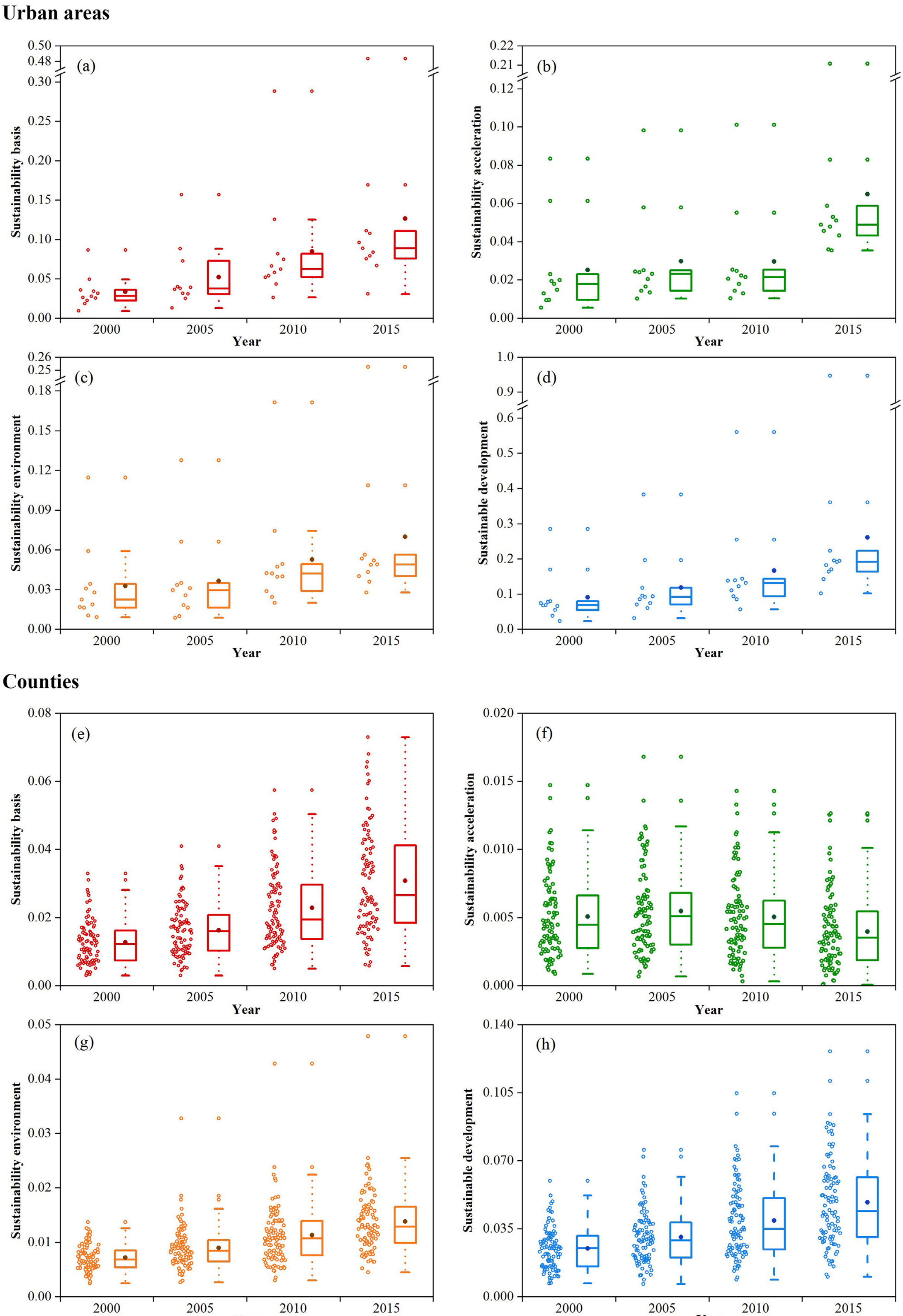

Fig. 2. Temporal trend of sustainable development level of 107 districts in Shanxi Province for selected years.

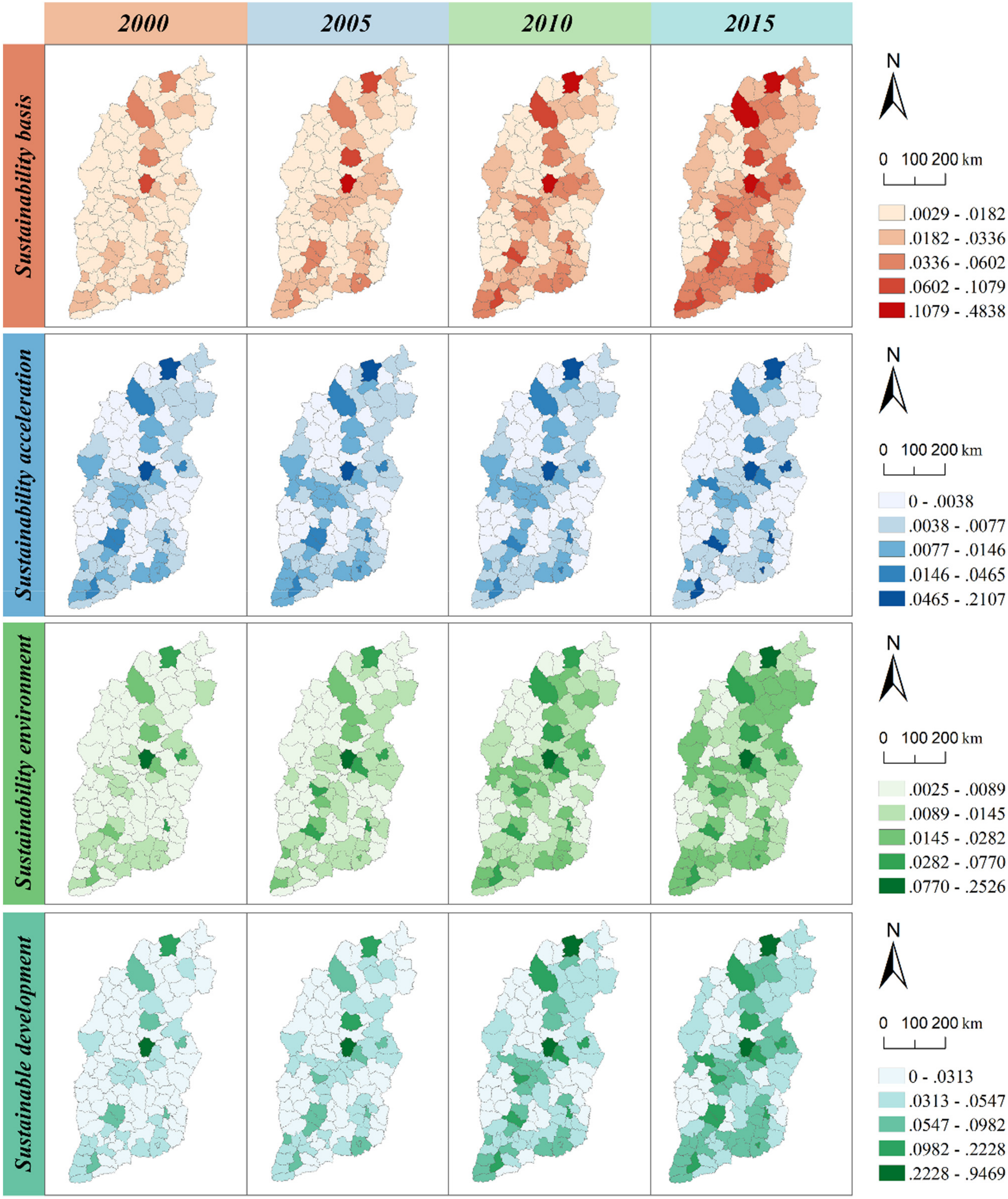

Fig. 3. Spatial pattern of sustainable development level of 107 districts in Shanxi Province for selected years.

On the whole, the sustainable development level in Shanxi Province showed a steady upward trend from 2000 to 2015, but there were obvious regional differences, showing the extremely unbalanced sustainable development status.

4.1.2. Ecosystem services

Fig. 4 shows the change trends of habitat quality, carbon storage, soil retention and water yield of 107 districts in 2000, 2005, 2010 and 2015. Specifically, habitat quality and soil retention showed a fluctuating and slowly declining trend, while carbon storage and water yield showed a fluctuating and slowly rising trend.

It can be seen from Fig. 4a that the habitat quality changed from 0.6464 in 2000 to 0.6439 in 2015, indicating that the habitat quality was relatively stable and maintained at a good level. Fig. 4b shows that carbon storage shows a fluctuating trend from 2000 to 2015 with a rapid rise from 2010 to 2015. In Fig. 4c, soil retention declined sharply from 2010 to 2015,

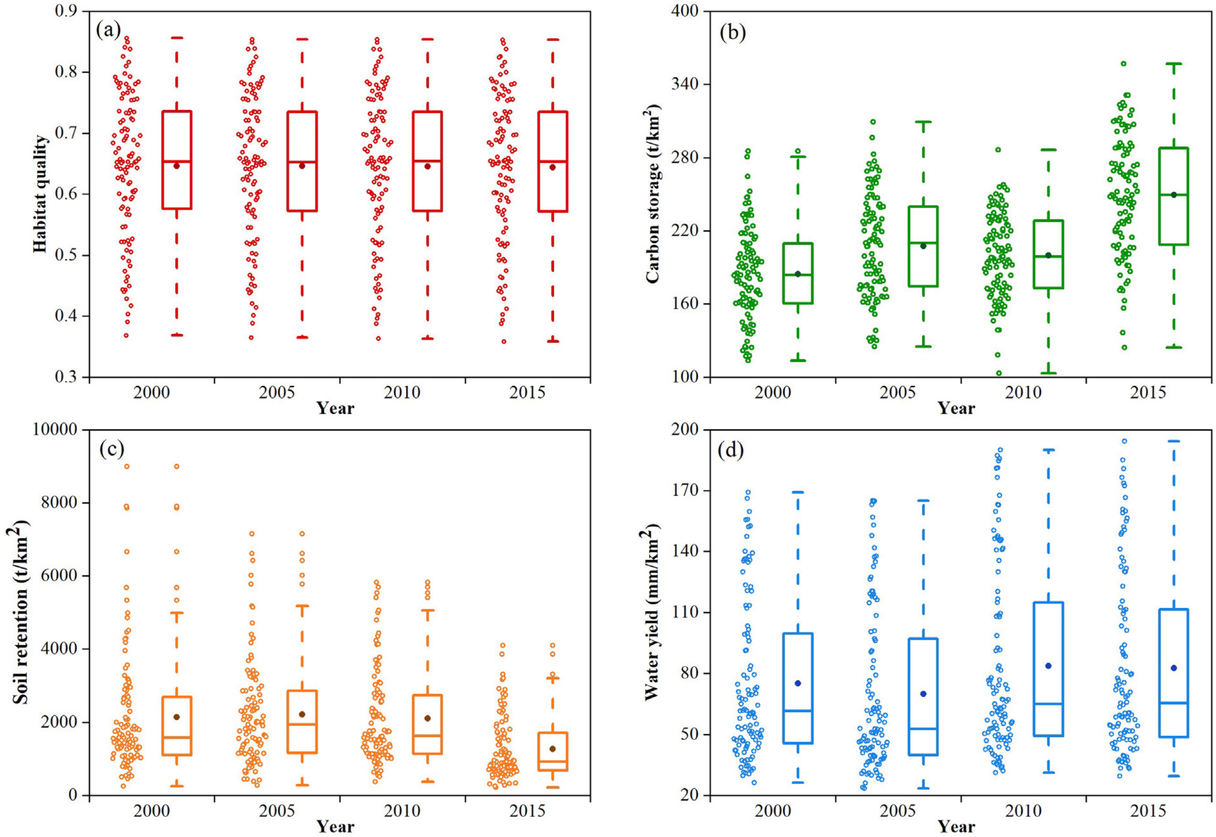

Fig. 4. Distribution and temporal trend of ecosystem services of 107 districts in Shanxi Province for selected years.

leading to the lowest average value in 2015. The gap among districts was narrowing, indicating that the soil retention services in Shanxi Province declined generally. In Fig. 4d, water yield experienced a decline from 2000 to 2005, but it shows an obvious upward trend from 2005 to 2010.

Fig. 5 shows the spatial patterns of habitat quality, carbon storage, soil conservation and water yield in Shanxi Province in 2000, 2005, 2010 and 2015. The unique geographical location of the province led to great differences in natural conditions, and there was significant heterogeneity in the ability of districts to provide ecosystem services.

From 2000 to 2015, persistent low-value habitat quality areas appeared in the southern and central parts of Shanxi Province, which was consistent with the distribution of cultivated land. During the past 15 years, the spatial pattern of habitat quality remained basically unchanged in most districts. However, it is worth noting that the habitat quality of Taiyuan urban area was getting worse, which reflects the threat of industrialization and urbanization in Taiyuan urban area to the local and surrounding habitat quality.

CS was mainly affected by vegetation coverage, so the high values of CS were distributed in mountainous areas with high forest coverage. The implementation of the Grain for Green Program (GFGP) promoted the growth of CS throughout Shanxi Province from 2000 to 2015, indicating continuous improvement of the environment resulting from afforestation projects.

Lower values of SR were distributed in the northern loess-rich hill and gully areas and the southern river valley plain areas. The districts with higher SR were concentrated in Mount Lüliang and Mount Taihang. The spatial pattern of soil retention changed greatly from 2000 to 2015, with the greatest decrease in the southern region.

WY formed a high-low-highest spatial distribution pattern from north to south, and its spatial heterogeneity is mainly due to regional precipitation differences. From 2000 to 2015, WY changed the most in the central region, decreasing first and then increasing, which was related to both precipitation of area and evapotranspiration of vegetation.

4.1.3. Coupling coordination degree

Based on the CCDM, we measure the CCD of sustainable development and habitat quality (SDHQ) system, sustainable development and carbon storage (SDCS) system, sustainable development and soil retention (SDSR) system and sustainable development and water yield (SDWY) system of 107 districts in Shanxi Province from 2000 to 2015, as shown in Fig. 6.

In SDHQ, SDCS and SDWY, the proportion of basically balanced, moderately balanced and highly balanced areas increased steadily from 2000 to 2015. The proportion of seriously balanced and moderately unbalanced areas decreased, indicating that the coupling coordination between SDHQ, SDCS and SDWY improved steadily. Shanxi Province has made remarkable achievements in improving the coordination between these three ecosystem services and sustainable development. The proportion of seriously balanced SDSRs decreased from 2000 to 2010 but rebounded in 2015, indicating that the coupling coordination status of SDSRs became more unbalanced from 2010 to 2015.

In general, according to the proportion of the three balanced states, namely, basically balanced, moderately balanced and highly balanced, sustainable development had the highest degree of coordination with habitat quality, followed by carbon storage and water yield and finally soil retention.

Fig. 7 shows the spatial distribution of the CCD between SDESs of 107 districts in 2000, 2005, 2010 and 2015. From 2000 to 2015, the CCD of SDESs improved significantly, with Taiyuan urban area kept the highest level.

The spatial pattern of CCD of SDHQ and SDCS was very similar. In 2000, SDHQ and SDCS were basically balanced in only a few districts in the central region, while the rest were moderately balanced. By 2015, only parts of the western and southeastern region were moderately balanced, while the rest was moderately balanced or above.

The spatial pattern of the CCD of SDSR varies slightly from 2000 to 2015, and only a few southern districts' coupling coordination status increased. There are a few high value areas in the east and northwest in 2015.

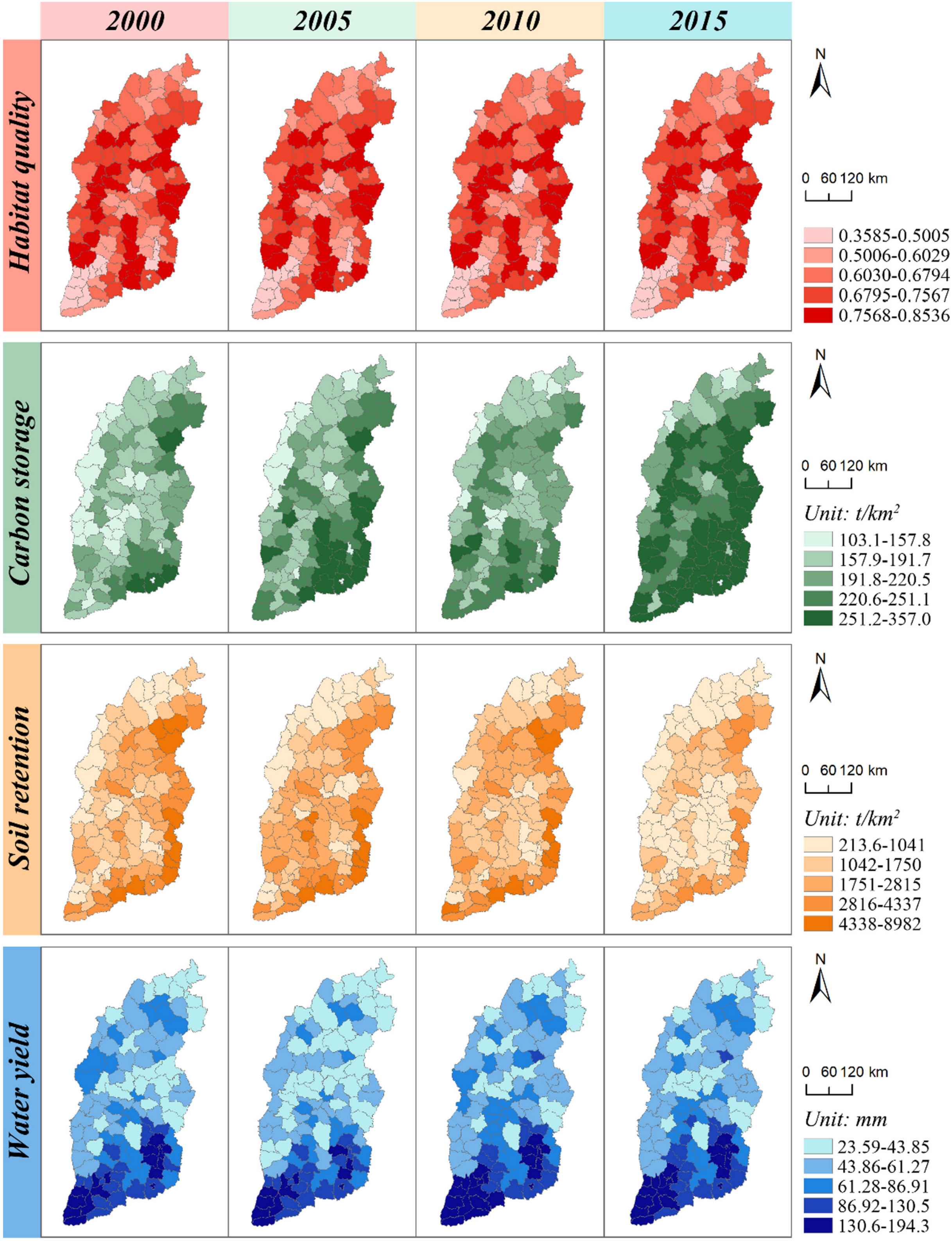

Fig. 5. The spatial pattern of four ecosystem services at the county level for selected years.

In 2000, most districts in the east and west demonstrated a lack of coordination between SDWY. In 2015, SDWY in most districts was in basically, moderately or highly balanced state. The coupling coordination state in the northeast and south was improved, with the west still seriously uncoordinated.

4.2. The temporal and spatial relationship between sustainable development and ecosystem services

To clarify the interaction mechanism between the SDESs, we applied the GTWR model to explore the correlation between the four ecosystem

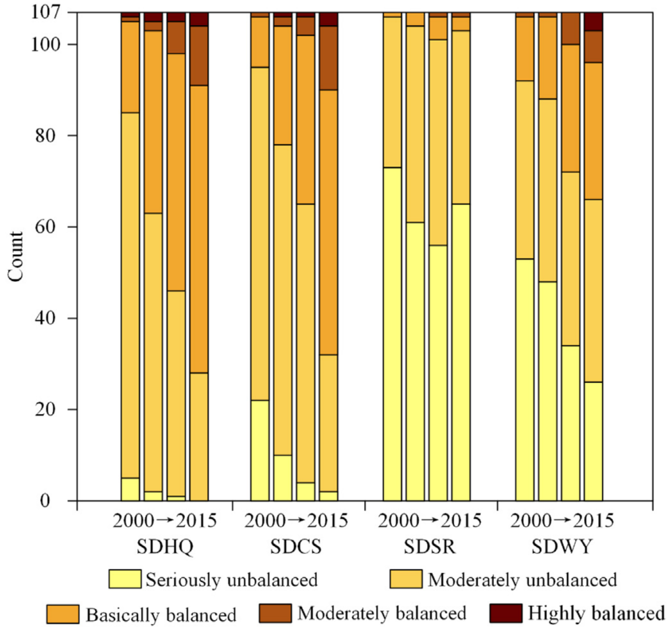

Fig. 6. Changes in coupling coordination degree between SDESs of 107 districts for selected years. Abbreviations: SDHQ: sustainable development and habitat quality; SDCS: sustainable development and carbon storage; SDSR: sustainable development and soil retention; SDWY: sustainable development and water yield.

services and sustainable development in 2000, 2005, 2010 and 2015. The calculation results and model parameters are shown in Table 3. The model has a high degree of interpretation and can effectively explain the relationship between the SDESs.

Fig. 8 shows the correlation of four key ecosystem services on sustainable development at the temporal scale. There were mainly negative correlations between SD and HQ and WY, while positive correlations between SD and CS and SR in most districts.

In 2000, HQ was negatively correlated with SD in 105 of 107 districts, which decreased to 104 in 2015. From 2000 to 2015, the restriction effect of poor HQ on SD strengthened even more where it was stronger in 2000. In a few districts where HQ had a promotion effect on SD, the positive correlation strengthened.

In 2000, the number of districts in which SR was positively correlated with SD was 80, and this number decreased and then increased over the past fifteen years. The intensity of positive correlation strengthened in different degrees, especially in the districts where SR had a stronger promotion effect on SD in 2000.

The correlation between SDCS was mainly positive. In 2000, CS promoted SD in 88 of 107 districts. By 2015, there were 81 districts where CS had a positive correlation with SD, and the correlation strengthened in most districts.

The correlation between SDWY was very similar to that of SDHQ, that is, inadequate WY had a restriction effect on SD in most districts. After fifteen years, although the number of districts where WY had a negative correlation with SD decreased, the negative correlation strengthened continuously, and those with stronger negative correlation in the past strengthened even more. The intensity of the main correlation type of four key ecosystem services on sustainable development showed a cumulative effect over time.

Based on the parameter results of the GTWR model, the correlation coefficients between SDESs in all counties in Shanxi Province in 2000, 2005, 2010 and 2015 were calculated, and these coefficients were divided into six types: high negative, moderate negative, low negative, high positive, medium positive and low positive.

As shown in Fig. 9, from 2000 to 2015, the region of medium and high negative types of SDHQ expanded with Taiyuan urban area as the center, and the intensity of negative correlation changed from weak to strong. Only a few districts in the southeast corner and center showed a weak positive type of SDHQ.

In 2000, CS has a negative correlation with SD only in Taiyuan city and the northeast region. Since 2005, CS was correlated negatively with SD continuously in the northeast and southeast, while positively in the central and northern regions. During the fifteen years, the range and the intensity of positive correlation extended significantly in the districts of Xinzhou city and Taiyuan city. In particular, the correlation of SDCS in some districts of Taiyuan city changed from low negative to high positive gradually. There were lots of efforts had been done in Taiyuan city and Xinzhou city to improve the environment and ensure the continuous supply of carbon storage as an ecosystem service, contributing to the promotion of sustainable development.

From 2000 to 2010, the range of negative correlations of SDSR kept expanding in the central and southeast corners of Shanxi Province, which reflected that the ecological fragility and serious soil erosion hindered sustainable development. However, from 2010 to 2015, the negative correlation between SR on SD was alleviated in the central region, and gradually turned into a positive correlation, while being more serious in the west and southeast.

The spatial heterogeneity of the correlation of SDWY is very similar to that of SDHQ. From 2000 to 2015, with Taiyuan as the center, the negative correlation of SDWY experienced an increase in intensity and scope. In 2000, SDWY had a positive correlation in the northeast and southeast corners of Shanxi Province, and then such areas moved to the southern and midwest regions. By 2015, only in the southeast and midwest regions, there was a positive correlation between SDWY.

5. Discussion

5.1. Changes in ecosystem services

The low values of HQ were distributed in the basin from the northeast to southwest and the basin in southeast. The changes in HQ mainly depend on anthropogenic and geomorphological factors (Hu et al., 2021). Therefore, both the large population and the rapid expansion of cultivated and construction land in the basin area lead to the low value of HQ under severe human disturbance (Liao et al., 2020).

The high values of CS were distributed in the mountainous areas with high vegetation coverage, that is, the west of Taihang Mountain and the east of Luliang Mountain. The change in CS mainly depends on anthropogenic and climatic factors (Hu et al., 2021). As a key area for the implementation of GFGP, CS in northwest Shanxi had significantly increased in a wide range (Zhao et al., 2021).

From 2000 to 2015, soil retention fluctuated sharply, and the high values area contracted significantly, with an obvious decrease in the southeast of Shanxi Province. The increase of CS was accompanied by the decrease of SR in the southern part of Shanxi Province, which was mutually confirmed by the results of Wang et al. (2022), namely, there was a tradeoff between CS and SR in this region. There are several reasons why SR did not perform well in 2015 with the implementation of GFGP. Hu et al. (2018) found that climate and geomorphological factors were the main factors affecting the change of SR from 2000 to 2020, with an explanatory degree of more than 70.7%. Our results showed that the regions with the lowest SR were distributed in the south with less annual precipitation.

WY presented a distribution pattern with high values around and low values in the middle, and the high values are scattered in the valley plain area. This is related to the difference in precipitation and potential evaporation caused by vegetation cover differences (Feng et al., 2016; Zhao et al., 2021). WY has fallen in some mountainous areas from 2000 to 2015, possibly due to the combination of tree planting and engineering implemented in the Loess Plateau that may had a negative impact on water yield (Sun et al., 2006).

On the whole, the environment of Shanxi Province has been improved due to the implementation of a series of policies, the most famous of which is the Natural Forest Protection Projects and the Grain for Green

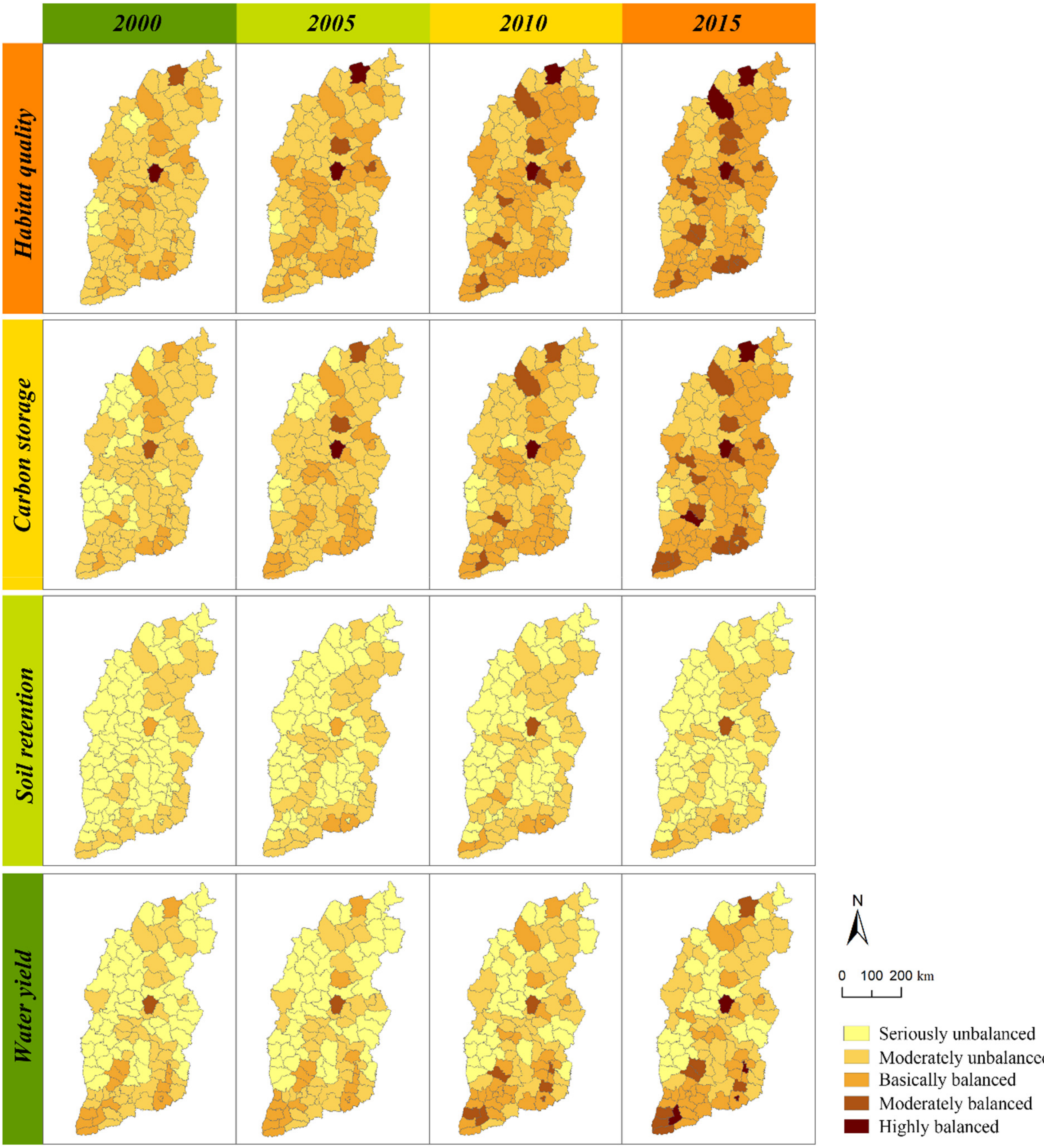

Fig. 7. The coupling coordination degree between SDESs at the county level for selected years.

Program. The vegetation coverage rate and net primary productivity of Shanxi province increased significantly (Fu et al., 2017), resulting in a significant increase in CS. However, the increase of evapotranspiration caused by vegetation expansion makes WY in some regions worse. The urbanization of Shanxi Province was carried out simultaneously with afforestation, which led to the expansion of the road network and construction land, resulting in a slight but significant decrease in HQ. The selection of exotic tree species (Fu et al., 2017) and high-density planting during the implementation of the GFGP affected the water content of soil (Jia et al., 2017). The newly planted vegetation would consume a lot of water in the soil, resulting in the formation of dry soil layer in the southern part of Shanxi Province with less annual precipitation (Wang et al., 2011), which exacerbates shallow and deep soil dryness. Shanxi Province is located in the east of the Loess Plateau, and loose topsoil is more vulnerable to erosion by wind and periodic heavy rains, leading to a decline in SR as a related ecosystem service (Fu et al., 2017; Jin et al., 2011).

Table 3
The GTWR model calculation results and parameters.

Dependent variable	R^2	Bandwidth	Sigma	AIC_C	Spatiotemporal distance ratio	Residual squares
Sustainable development	0.6896	0.1165	0.0365	−1445.39	0.2688	0.5698

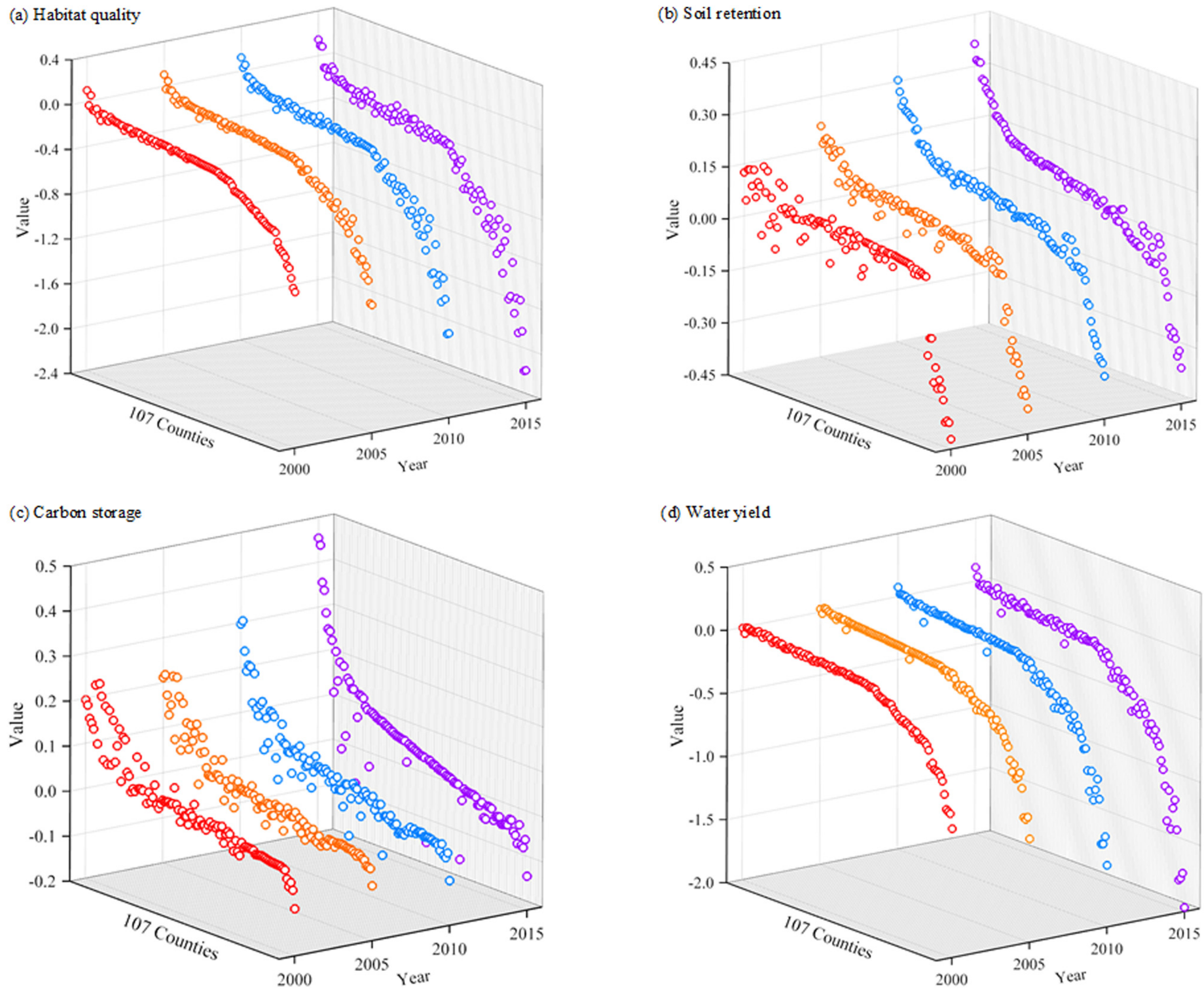

Fig. 8. The temporal relationship between SDESs at the county level for selected years.

5.2. Changes in sustainable development

The national strategic construction has greatly improved the sustainable development ability. In 2006, Shanxi Province was identified as the pilot province of policies and measures for the sustainable development of the coal industry. In 2010, a comprehensive supporting reform pilot zone for resource-based economy transition countries was established, and the industrial structure was adjusted and optimized to make the economic structure more diversified. The comprehensive capacity of sustainable development of Shanxi Province has been greatly improved from 2000 to 2015.

Among the 11 urban areas, the sustainable development level of 10 urban areas ranked in the top 10 in Shanxi Province, and the sustainability basis, sustainability acceleration and sustainability environment level of the above urban areas increased steadily. However, the sustainability acceleration of the lower-ranked counties is not enough, and there is an urgent need to improve the overall quality of local people's livelihood by increasing the level of education and skills. In other words, the sustainable development improvement rate varies among counties and urban areas. The top ten districts showed the fastest improvement from 2010 to 2015, indicating that areas with good sustainable development status can give full play to their advantages and better promote sustainable development in the future. Taiyuan, as the capital of Shanxi Province, showed the fastest improvement in sustainable development level, with an increase of 232.8% during the past 15 years, and it was the leader in Shanxi Province, while the counties' rate of increase ranged from 31.2% to 263.8%. This shows that with the continuous advancement of China's urbanization process, humans, capital, science and technology and other resources continue to gather in urban areas, which is conducive to promoting the sustainable development of local livelihoods.

Therefore, Taiyuan urban area was at the first development speed. As the leader of the sustainable development in Shanxi Province, the growth rate of Taiyuan urban area had also been the fastest from 2000 to 2015, and its sustainable development level was far higher than that of other regions. The middle east of Shanxi Province was at the second development speed. The sustainable development level had increased steadily with strong development potential. The western mountainous area was at the third development speed due to the limitation of geographical factors, inconvenient transportation and backwardness of economic.

5.3. Changes in CCD between SDESs

The coupling coordination degree between SDESs increased from 2000 to 2010, which is directly evidenced by the increase in the proportion of Basically, Moderately and Highly balanced in Fig. 6. However, the growth trend of CCD of SDSR was broken in the period from 2010 to 2015. From 2000 to 2015, the rise of coupling coordination degree between ecosystem services and sustainable development was due to the synergistic rise of ecosystem services and sustainable development in most districts, while the decline of CCD of SDSR from 2010 to 2015 was mainly due to the

Fig. 9. The spatial relationship of SDESs at the county level for selected years.

deterioration of soil retention with the improvement of sustainable development.

In the selected years, the relative high value area of CCD of SDESs showed a highly consistent spatial distribution with that of SD. From 2000 to 2015, with the improvement of SD of most districts in Shanxi Province, the CCD of SDESs also improved, and the spatial changes of CCD and SD also had a high degree of consistency. Areas with lower SD often have higher CCD levels if they are accompanied by higher ecosystem services. This suggests that SD process advancement or ecosystem services improvement can promote the coordination development of SDESs, and contribute to the win-win situation of development and ecology (Chen et al., 2021; W. Li et al., 2021).

The areas with ideal CCD levels are usually distributed in Taiyuan urban area, southern and northeastern Shanxi Province. CCD is relatively high in Taiyuan urban area because its social and economic development promotes the process of SD. On the premise of maintaining its own development advantages, it is necessary to prevent the damage to ecosystem caused by excessive urbanization or industrialization. The coordination between SDESs in the west of Shanxi Province needs to be further improved. Because the west is a mountainous area, the SD level is not ideal due to geographical location and other factors, and with the deterioration of soil conditions and increase of potential evaporation caused by blind afforestation (Fu et al., 2017), the relationship between SDSR or SDWY needs to be improved urgently.

Although Shanxi Province has made great progress in promoting coordination between SDESs, further measures need to be taken to ensure that the sustainable development process goes hand in hand with the improvement of ecosystem services.

5.4. Changes in spatio-temporal relationships between SDESs

The type and degree of correlation of SDESs mainly depend on the quality and development direction of the environment in different districts (Li et al., 2021). The positive correlation means that the existence of ESs promotes the improvement of SD, and then the capital investment brought by development can improve ESs. While the negative correlation means that the deterioration of ESs hinders SD, which is often caused by human activities, such urbanization, industrialization and expansion of cultivated land.

In terms of scope and intensity of relationship, CS and SR mainly were positively correlated with SD. With the environmental improvement brought by the implementation of eco-friendly policies, these two ecosystem services were playing more and more powerful positive roles in SD. The positive correlation of SDSR and SDCS is enhanced by implementing several ecological projects in Shanxi Province, as well as by promoting the development of the ecological economy and industrial structure adjustment. Vegetation coverage contributed to regional sustainable development (He et al., 2019), and the improvement of the environment ensures the continuous supply of ecosystem services. In 2007, Shanxi Province became a pilot province in ecological construction, carrying out several ecological restoration projects in air, water, soil and vegetation, increasing vegetation coverage, improving environmental quality and promoting sustainable development strategy. In the same year, Shanxi Province was listed in the second batch of national circular economy demonstration pilot provinces by the National Development and Reform Commission, which promoted clean production and realized transformational development, safe development and harmonious development, making a big step towards building a resource-saving and environmentally friendly society.

HQ and WY were mainly negatively correlated with SD. The increase in construction land and transportation networks interfered with the natural material circulation of the environment and destroyed the function of the ecosystem, thus restricting the sustainable development of the region (Mo et al., 2017). Since the reform and opening up, Shanxi Province has been faced with rapid urbanization. The aggregation of population and the change in land use type have threatened the local sustainable development. Therefore, Shanxi Province needs to pay more attention to improving the environment to break the deadlock between ecosystem services and sustainable development and strive to achieve sustainable development as soon as possible. Take Taiyuan as an example, as a heavy industry city, Taiyuan's large-scale urban expansion and severe industrial pollution have aggravated the destruction of the structure and function of the ecosystem, exceeding the carrying capacity of resources and the environment, threatening the habitat quality of itself and its surrounding areas, and the degradation of the ecosystem has a stronger negative correlation with sustainable development over time.

5.5. Limitations and future recommended works

Only HQ, CS, SR and WY were selected as key ecosystem services, which was based on the fact that Shanxi Province is the eastern part of the Loess Plateau. These ESs were emphasized when referring to the improvement of the Loess Plateau ecosystem (Feng et al., 2013; Jia et al., 2014; Song et al., 2021; Zhao et al., 2021). The Loess Plateau is ecologically fragile and has suffered serious soil erosion for a long time, and high-quality vegetation restoration can effectively control soil erosion (Sun et al., 2015; Zhao et al., 2013). Therefore, CS, WY and SR that have a significant correlation with local sustainable development need urgent attention (Feng et al., 2016). Excessive afforestation had a negative impact on the local species diversity (Cao et al., 2009), so HQ was chosen for observing the change. Future research should further analyze the selection of representative ecosystem services, and determine the appropriate ecosystem services selection criteria according to the tradeoff or synergistic relationship among ecosystem services and the relationship between specific ecosystem service and sustainable development. In subsequent studies, a wider range of ESs should be selected according to the natural and geographical conditions of the study area, so as to explore the relationship between other ESs and SD.

Uncertainty is inevitable when evaluating WY and HQ using the InVEST model. The WY module does not take into account the interaction between surface water and groundwater (Hu et al., 2021). The HQ module excessively relies on experts' knowledge, making the results susceptible to experts' judgment (Berta Aneseyee et al., 2020), and it does not involve prior information on species distribution or existence in the calculation (Terrado et al., 2016), so future studies need to combine landscape habitat quality parameters (Berta Aneseyee et al., 2020; He et al., 2017; Song et al., 2021).

Some SDGs that need urgent attention were chosen to construct the indicator system of sustainable development according to the development status of Shanxi Province. Other SDGs that are of priority importance to developing countries are not involved, such as affordable and clean energy and gender equality (Wu et al., 2022). Therefore, subsequent studies can expand the assessment scope of the SDGs, so as to obtain an indicator system that is more representative of the overall sustainable development situation.

5.6. Policy implications

At present, efforts are needed as follows for the long-term success of vegetation restoration in mountainous areas. First, the improvement of land use management policy. The existing ecosystem of perennial vegetation in Shanxi Province needs to be focused on controlling soil erosion (Fu et al., 2017). Second, the maintenance of soil moisture. Exotic tree species should be selected in accordance with the local environment (Feng et al., 2016), and the density and spatial distribution of vegetation should be well grasped to ensure the maintenance of the planting efficiency (Jia et al., 2017). The implementation of the above strategies can optimize the relationship among soil retention, water yield and land use, which is crucial to the sustainable development of Shanxi Province.

From 2000 to 2015, sustainability basis and environment of Shanxi Province rose steadily, but sustainability acceleration showed a decline in some areas. For sustainability basis, the government should implement some favorable policies to attract talents. In addition, the government should adjust the industrial structure and increase the proportion of non-agricultural industries. Sustainability acceleration is inseparable from the government's promotion of employment and the improvement of educational conditions. The improvement of the overall education level of residents is the most effective thrust in the process of sustainable development. As for sustainability environment, the government should increase investment in social public utilities and improve public service and management capacity (Li et al., 2021). Moreover, We should pay attention to the development of the county as increasing its wealth will drive sustainable development; giving full play to the economic radiation function of the urban area, transferring resources to the surrounding counties, and realizing the synchronous development of the urban area and local counties will achieve win-win results.

To improve the ecosystem services and promote sustainable development, we propose the following suggestions. First, we need to prioritize ecology and promote coordinated green development. We should correctly understand that a good ecosystem is an important driving force to achieving sustainable development and pay attention to the coordination of ecosystem and sustainable development. Second, the government should step up pollution control efforts, increase funding, reduce the environmental damage caused by industrialization, and strive to improve regional environmental quality. Third, land use should be properly planned and spatially arranged to avoid large-scale urban expansion affecting environmental quality. Furthermore, residents' awareness of environmental protection should be strengthened (Wang et al., 2020). These policy implications apply not only to Shanxi but also to China and other countries and regions.

6. Conclusion

An important turning point for the global realization of the SDGs has been reached. Assessment of SDGs in small-scale regions will help identify the stage of each region and make more targeted progress in achieving sustainable development. However, when the SDG evaluation framework proposed by the United Nations is directly evaluated at the county level in China, there are some challenges, such as data loss and inconsistency with the actual development status of the local area. At the same time, ecosystem services are an important factor affecting global sustainable development, and how they affect the realization of SDGs is not clear. In this context, a sustainable development evaluation framework with Chinese characteristics was constructed for small-scale regional studies. Combined with CCDM and GTWR models, the spatiotemporal heterogeneity and interaction between four key ecosystem services and the level of sustainable development were measured at the county level in Shanxi Province in 2000, 2005, 2010 and 2015.

The results show that: 1) From 2000 to 2015, the sustainable level of counties and counties in Shanxi Province demonstrated a stable upward trend, and the sustainable development level of urban areas was much higher than that of counties, which was due to the construction of urbanization and the promulgation of local sustainable development policies. Habitat quality and soil retention fluctuated, while carbon storage and water yield increased slowly. There is obvious heterogeneity in the ability of each region to provide ecosystem services. The above changes are mainly due to the increase in vegetation coverage due to the policy of returning farmland to forest and the expansion of construction land due to rapid urbanization. 2) From 2000 to 2015, the CCD of SDHQ, SDCS and SDWY in Shanxi Province showed an upward trend, but SDSR became more maladjusted in 2015. The degree of coordination between sustainable development and habitat quality was the highest, followed by carbon storage and water yield and finally soil conservation. 3) The correlation between habitat quality and water yield on sustainable development is mainly negative, while carbon storage and soil conservation contribute to local sustainable development positively. The correlation between ecosystem services and sustainable development, whether negative or positive, is most obvious in the central and northern regions with the Taiyuan urban area as the center. Local levels of sustainable development are hampered by ecosystem that are structurally and functionally destroyed.

CRediT authorship contribution statement

Zheng Yang: Data curation, Original draft. **Jinyan Zhan**: Review and editing. **Chao Wang**: Data curation, Software. **Michael Jordan Twumasi-Ankrah**: Methodology.

Declaration of competing interest

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.

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