Article

Coupling and Coordination Relationship between Urbanization Quality and Ecosystem Services in the Upper Yellow River: A Case Study of the Lanzhou–Xining Urban Agglomeration, China

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Abstract: The study of man-land relationship in urbanization process is the current frontier and focus of international research. How to balance urban development and ecosystem conservation in the Upper Yellow River is a key issue for sustainable development in China. In this study, we evaluated the Lanzhou-Xining urban agglomeration（LXUA）by constructing a multi-dimensional assessment system for urbanization quality and ecosystem services. The efficacy function model, entropy weight method, and Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model were used to quantitatively assess the subsystems' state of development. Then, the coupling model (CD) and the coordination degree（CCD）model were used to explore the coupling coordination relationship and spatial-temporal change characteristics of the composite system. The findings indicate that: 1）In 2020, the quality of urbanization in LXUA showed the pattern of "double core". The development of urban centers in each city is insufficient, and the proportion of counties with low-level is too high. 2）Integrated ecosystem services showed an increasing distribution pattern from the northeast to the southwest. Water provision services, soil conservation services and carbon fixation services all showed growth trends. 3）Each county's composite system was in the run-in stage or highly coupled stage. The subsystems were closely related to each other. 4）The CCD was decreased by 6% between two decades. The number of counties on the verge of disorder was the highest. About 80% of the counties are relatively lagging behind in ecosystem services.

Keywords: urbanization quality; ecosystem services; coupling coordination; spatial-temporal variations; Lanzhou-Xining Urban Agglomeration

1. Introduction

The first explosion of industry in the late 18th century required greater concentration and continuity of production. Factors of production such as capital, manpower and resources are highly combined in a limited space, driving the formation and development of cities. Currently, more than half of the world's people live in urban areas. Although urbanization is of great significance in promoting population transformation, industrial development, scientific and technological progress, and cultural exchange, it has also produced some negative effects, such as widening urban-rural gap, tightening of resources and energy, intensifying environmental pollution, and overwhelming the ecosystem [1-2]. In this context, the Third United Nations Conference on Housing and Sustainable Urban Development (Habitat III) and the "Future Earth"（FE） all emphasized that the regional urbanization process should be coordinated with the state of the ecosystem and matched with the carrying capacity of the resource and environment. The goals of building inclusive, safe, disaster-resilient and sustainable cities and human settlements, and protecting, restoring and promoting sustainable use of terrestrial ecosystems were included in the 2023 Agenda for Sustainable Development as part of the next 17 global sustainable development priorities. How to reduce the negative impacts of rapid urbanization on ecosystems and promote the synergistic development of urbanization and ecosystem services has become a hot topic of widespread concern worldwide. At present, China's urbanization development is in a critical transition period from the medium-term rapid growth stage to the later stage of quality improvement. The report of the 20th National Congress of the CPC and the Central Urbanization Working Conference pointed out that we should plan for development at the height of harmonious coexistence between human and nature, focus on improving the quality of urbanization development, improve the diversity, stability and sustainability of the ecosystem, and take a green, intensive and efficient high-quality urbanization road. Therefore, from the perspective of system coupling, it is of great theoretical and practical significance to scientifically and accurately evaluate the current situation of urbanization quality and ecosystem services， as well as the coupling and coordination relationship between them.

The coupling relationship between urbanization and ecosystem is one of the core issues of regional man-land relationship, which has been studied by domestic and international scholars. The research has shifted from the discussion of one-way causality to the coupling and coordination analysis of interaction, from the analysis of static mechanism to the dynamic characteristics of time series [3-5]. Many scholars have found 'positive correlation', 'negative correlation', or 'inverted U' relationship between urbanization and ecosystems [8-13]. In terms of research content, urbanization was mostly evaluated in terms of population movement [14-15], industrial agglomeration [16-17], construction land expansion [18-19] and infrastructure construction [20-21]. The value of ecosystem services was mostly determined through continuous improvement of value equivalent factors based on the value scale developed by Costanza [22-23]. From the perspective of methods, regression analysis [24-25], input-output models [26-27], system dynamics models [28-29], and other mathematical statistical models or spatial analysis models were mostly used. In terms of location choice, empirical studies mostly focused on the provincial or municipal level and were dominated by the more economically developed regions, such as the Yangtze River Delta, Pearl River Delta, Beijing-Tianjin-Hebei and Chengdu-Chongqing regions. In general, the limitations of unidirectional research on urbanization and ecosystems have not been broken, lacking the analysis of factor relationships and subject behaviors under the guidance of synergistic ideas. In addition, traditional studies tend to use statistical data to evaluate the ecological and environmental conditions of the region when analyzing the coupled multi-system relationship, such as data on three waste emissions, resource utilization, and pollution control, resulting in the natural attributes of the ecosystem being concealed and the evaluation results hardly reflecting the true ecological and environmental conditions of the region.

Ecosystem services refer to the conditions and processes that ecosystems and their species can provide to humans to satisfy and sustain their needs [30]. It is a frontier area of research in ecology and geography, and a link and bridge that connects natural and human processes [31]. For the purpose of identifying regional ecosystem service issues, preserving regional ecological balance, and advancing regional sustainable development, it is crucial to comprehend the intrinsic interaction mechanism between the external spatial and temporal evolution of ecosystem services and the economic society [32–34]. In order to clarify the spatial and temporal differentiation characteristics, this study introduced an exponential efficacy function model to quantitatively measure the development of economic and social systems based on pertinent studies. It also used multi-source data and the InVEST model to analyze the regional ecosystem services based on raster cells and explore the current development status and coupled coordination of the complex ecosystem of the LXUA. The aim is to clarify the synergistic evolution mechanism of the human-earth relationship in the ecologically sensitive area of the Upper Yellow River, and provide reference for ecological protection and high-quality development.

2. Materials and Methods

2.1. Study Area

The LXUA, with coordinates of 34°26'N-37°38'N, 98°55'E-105°55'E, is the westernmost town dense region in the Yellow River basin. It is situated below Longyangxia, in the basin of the Yellow River and Huangshui River valley. (Figure 1). The LXUA, which spans 97,500 km2, consists of 39 counties in 9 cities, including Lanzhou, Xining, and Haidong. Mountains and river valleys dominate the region's terrain, which is complicated and varied. With an average height of 2000 meters or more, the elevation varies from 1258 to 5255 meters. In 2020, the GDP of LXUA reached 61.4 billion RMB, accounting for 51% of the GDP in the two provinces. The population reached 12.19 million, accounting for 66.5% of the permanent population in the two provinces. The city group is rich in hydraulic resources, climate geographic distribution differences, thick soil, complex and diverse vegetation types, among which the eastern agricultural area of Qinghai is located in the Huangshui and Yellow River basin triangle, has fertile soil, a mild climate, and a wealth of natural resources that are advantageous for developing agriculture and animal husbandry. Lanzhou, Xining, Huangzhong, Datong, Xunhua, etc. are important towns on the ancient Silk Road transportation route. Lanzhou is known as the "heart of the land", Xining is the "Pearl City" on the Qinghai-Tibet Plateau, the two cities are the "growth poles" to promote population clustering and economic development of the urban agglomeration.

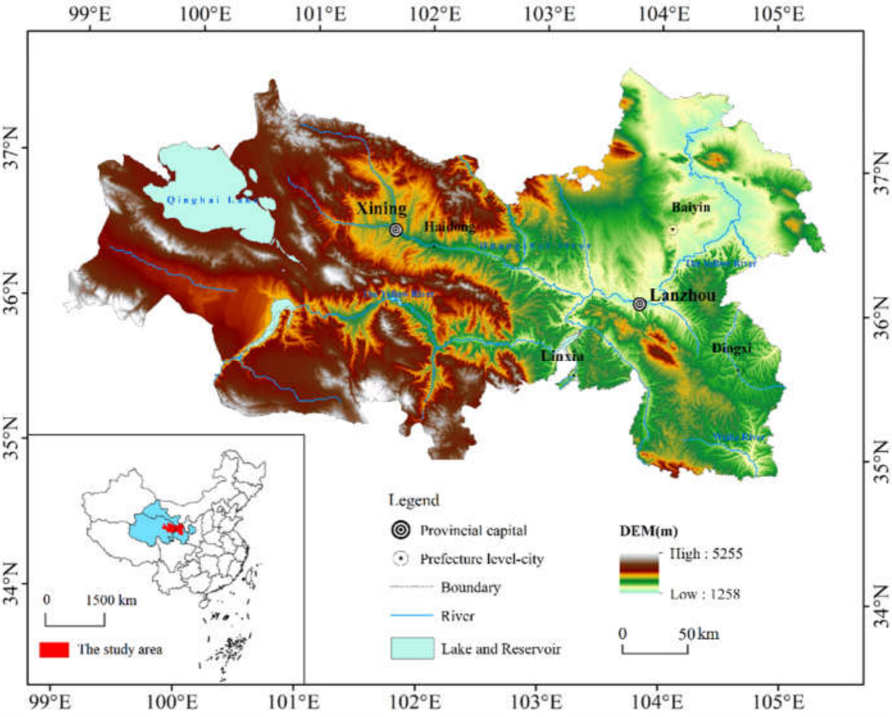

Figure 1. Diagram of the study area.

2.2. Analysis framework

Urbanization and ecosystems together make up a complex system that is a synthesis of ecological processes brought about by the interaction of human social, economic, and cultural actions with the environment [35]. The two subsystems are connected and engage in interactions with one another in terms of amount, structure, order, quantity in space, and time. The quality of urbanization refers to a comprehensive concept with rich connotation that reflects the quality of urbanization in the process of urbanization [36]. In this paper, evaluation indicators were primarily created in seven dimensions: economic development, people's lives, environmental protection, infrastructure, public services, urban vitality, and relationships between urban and rural areas [37–39]. (Table 1). The regional ecosystem condition is an important basic condition for the smooth promotion of urbanization. The LXUA, which is an essential strategic support for maintaining China's ecological security, is situated in the crucial zone of transition from the first to the second terrain in China. It contains significant ecological security barriers like Sanjiangyuan, Qilian Mountains, and Gannan Plateau. The changes in its ability to contain water, maintain soil and water, and sequester carbon and release oxygen will have an important impact on the ecological security of the Upper Yellow River and the country as a whole. Therefore, the study was based on the InVEST model, and four aspects of water containment, soil conservation, carbon sequestration and oxygen release, and integrated ecosystem services were selected for assessment. The analysis framework is shown in Figure 2.

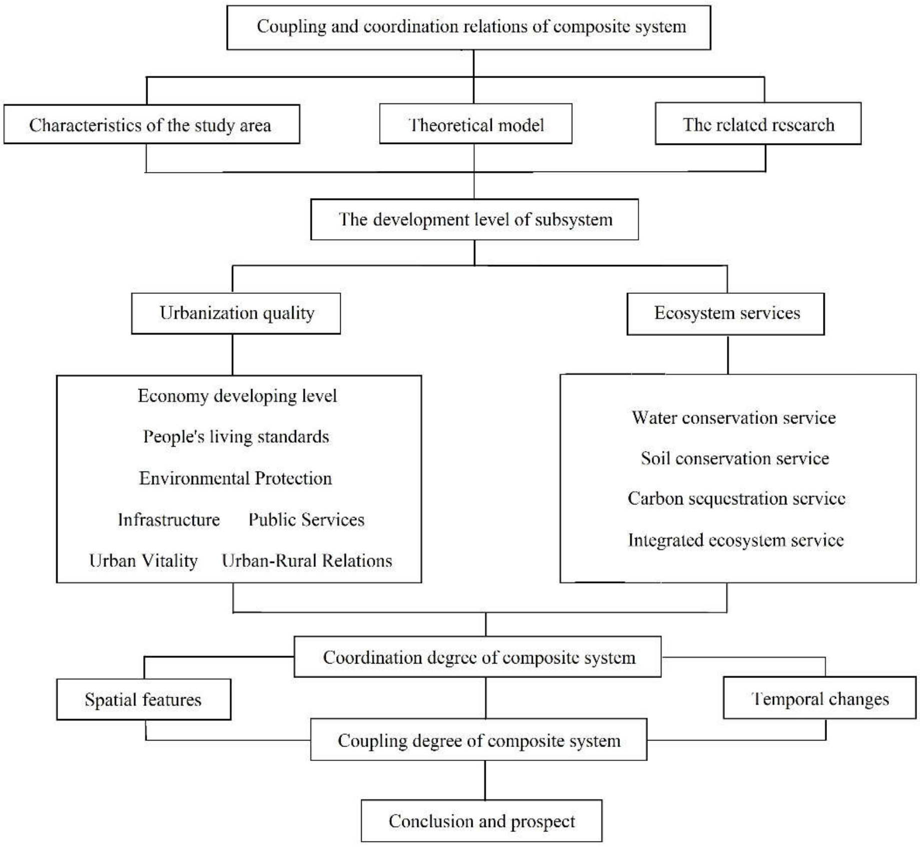

Figure 2. Analysis framework.

Table 1. Indicators of urbanization quality.

Functional Layer	Indicator Layer	Attribute	Weight
Economic development level	Per capita GDP (RMB)	+	0.0417
	Total retail sales of consumer goods (RMB 10,000)	+	0.0372
	Fixed assets investment (RMB 10,000)	+	0.0462
	The proportion of tertiary industry (%)	+	0.0389
People's living standards	Employment rate of urban population (%)	+	0.0374
	Urban per capita disposable income (RMB)	+	0.0346
	The average wage of workers (RMB)	+	0.0227
	Urban per capita water consumption (ton)	-	0.0431
Environmental protection	Greening coverage of built-up area (%)	+	0.0424
	Comprehensive utilization rate of industrial solid waste (%)	+	0.0351
	Urban domestic sewage treatment rate (%)	+	0.0318
	Harmless disposal rate of domestic waste (%)	+	0.0347
Infrastructure	Residential area per capita (m^2)	+	0.0406
	Road area per capita (m^2)	+	0.0428
	Broadband penetration (%)	+	0.0251
	Gas penetration (%)	+	0.0242
	Park area per capita (m^3)	+	0.0352
Public service	Number of teachers per 10,000 people	+	0.0295
	Number of hospital beds per 10,000 people	+	0.0371
	Pension insurance coverage (%)	+	0.0355
	Number of books in a library	+	0.0439
Urban vitality	Population per square kilometer	+	0.0507
	Number of public buses per 10,000 people	+	0.0381
	The GDP output of per unit land area (RMB 10,000/km^2)	+	0.0293
	Number of enterprises with considerable scale	+	0.0467
Urban-rural relations	Average income ratio between urban and rural residents	-	0.0359
	Average consumption expenditure ratio between urban and rural residents	-	0.0396

2.2. Data Sources

This study created an ecosystem classification map of the LXUA using the 100 m×100 m land use remote sensing monitoring data in 2000 and 2020 provided by the Resource and Environment Science and Data Center (https://www.resdc.cn). (Figure 2).

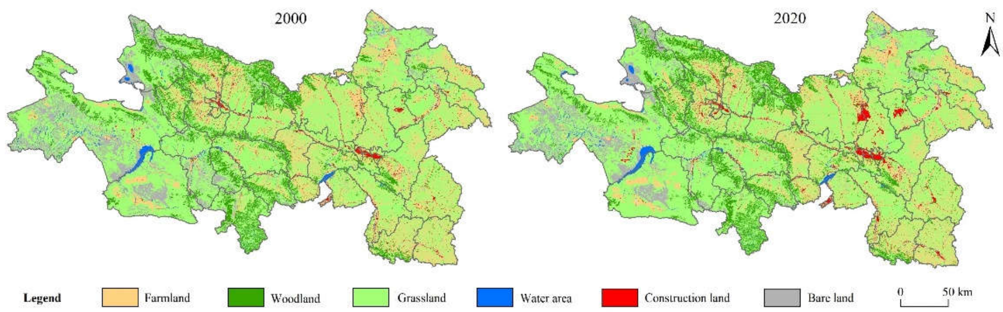

Figure 3. Land-use types of LXUA in 2000 and 2020.

The socio-economic data used in this study was mainly obtained "*China Statistical Yearbook*", "*Gansu Development Yearbook*", "*Qinghai Statistical Yearbook*", "*Gansu Urban Yearbook*", statistical yearbooks and statistical bulletins of various cities. Basic geographic data, including roads, rivers, administrative boundaries of counties, were sourced from the National Basic Information Center.

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Meteorological data, including temperature, precipitation, water pressure, etc., were obtained from the China Metrological Data Service Centre (http://data.cma.cn), and the local 5-year average meteorological data were taken for the calculation considering the interannual fluctuation of the data. the soil data is sourced from National Earth System Science Data Center (http://www.geodata.cn).

2.4. Methods

2.4.1. Exponential efficacy function model

In previous studies, when using the comprehensive index method to analyze the coupling relationship of multiple systems, the linear power function model was usually used to standardize the data. The linear efficacy function defines the change of indicators as "uniform change", that is, the evaluation value of indicators rises or falls in equal proportion to the actual value. However, in the normal course of economic and social development, if an indicator increases continuously and reaches a certain number and scale, the actual utility provided by it will typically decrease over time, much like the well-known "diminishing marginal utility" law in economics. It will then be more challenging to maintain the indicator's growth or progress. In the actual evaluation and application, the exponential efficacy function is chosen to better fit the development process and trend of the data. The formula is as follows:

$$d = Ae^{(x-x^s)/(x^h-x^s)B} \tag{1}$$

Where, d is the efficacy score, x_s is not allowed, x_h is satisfactory, which is mainly determined by the international and domestic standard values and the national average. The estimated parameters A and B were determined by the critical point rating. When the index and the disallowed value were the same, that is, $x=x_s$, according to the linear power function method, d=60, 60=A, B=-ln0.6[40~41].

$$d = 60e^{-(x-x^s)/(x^h-x^s)\ln 0.6} \tag{2}$$

2.4.2. The entropy method

The entropy method is an objective weighting method that determines the weight ac-cording to the dispersion degree of the indicator, which can deeply reflect the utility value of the indicator information and avoid the interference of human factors in the evaluation process. The greater the dispersion of the indicator value, the smaller its entropy value, the greater the amount of information provided by the indicator, and the greater the weight. The specific calculation process is as follows:

$$Y_{ij} = x_{ij} / \sum_{i=1}^{m} x_{ij} \tag{3}$$

$$k = \frac{1}{\ln m} \tag{4}$$

$$e_j = -k\sum_{i=1}^{m}(Y_{ij}\ln Y_{ij}) \tag{5}$$

$$D_j = 1 - e_j \tag{6}$$

$$W_j = D_j / \sum_{j=1}^{n} D_j \tag{7}$$

$$U_a = \sum(D_j \times W_j) \quad (a = 1,2,3) \tag{8}$$

In the formula, m and n represent the number of samples and indicators respectively, Y_{ij} is the i sample of the j indicators accounted for the proportion of the indicator of the total sample value. e_j, D_j and W_j are the entropy value, variability coefficient and weight value of the j indicator, and U_a is the subsystem orderliness. The specific weights of each index are shown in Table 1.

2.4.3. InVEST model

The InVEST model is based on the distributed algorithm of "3S" technology. Spatial representation, dynamic assessment and quantitative evaluation of ecosystem service functions can be carried out quickly and accurately.

a. Water provision

Water provision is equal to the difference between precipitation and evapotranspiration, which is obtained from the water yield module of InVEST model. The model is based on the Budyko water and heat coupling equilibrium assumption, taking into account such factors as terrain, climate, soil layer thickness and permeability [42]. The calculation formula is:

$$Z_{ij} = (1 - AETi_j / P_j) \times P_j \tag{9}$$

Where, Y_{ij} denotes the annual water yield of land use type j in grid i (mm). AET_{ij} represents the annual actual evapotranspiration of land use type j in grid i (mm). P_i represents the average annual precipitation of grid i (mm).

b. Soil conservation

The modified general soil loss equation can be used to determine soil retention, which is equal to the difference between the amount of possible soil erosion and the amount of potential soil loss. The following calculation formula.

$$SD = R \times K \times LS \times (1 - C \times P) \tag{10}$$

Where, SD denotes the amount of soil conservation（$t \cdot hm^{-2} \cdot a^{-1}$）. R is rainfall erosivity（$MJ \cdot mm \cdot hm^{-2} \cdot h^{-1} \cdot a^{-1}$）. K is soil erodibility（$t \cdot hm^{2} \cdot h \cdot hm^{-2} \cdot MJ^{-1} \cdot mm^{-1}$）. LS is the gradient and slope length factor calculated by DEM. C is vegetation coverage and management factor. P is the engineering measure factor.

c. Carbon fixation

Carbon storage represents the carbon fixation capacity of terrestrial ecosystems. The calculation formula is:

$$C = C_{\text{above}} + C_{\text{below}} + C_{\text{soil}} + C_{\text{dead}} \tag{11}$$

Where, C is the underground carbon storage（$t \cdot hm^{-2} \cdot a^{-1}$）. C_{above} is the aboveground carbon storage（$t \cdot hm^{-2} \cdot a^{-1}$）. C_{below} is the underground carbon storage（$t \cdot hm^{-2} \cdot a^{-1}$）. C_{soil} is the density of soil organic matter（$t \cdot hm^{-2} \cdot a^{-1}$）. C_{dead} is carbon storage of litter（$t \cdot hm^{-2} \cdot a^{-1}$）.

d. Integrated ecosystem services

We constructed the comprehensive index of regional ecosystem services by using the method of dispersion coefficient, and the geometric average method was used for grid cells [43]. The calculation formula is:

$$ES_i = \frac{\sigma_{ik}}{x_{ik}} = \frac{1}{x_{ik}} \sqrt{\frac{1}{N} \sum_{k=1}^{N} (x_{ik} - \overline{x_{ik}})^2} \tag{12}$$

Where, ES_i is the ecosystem services of the *i-th* grid cell. x_{ik} is the normalized value of ecosystem services of the *k-th* category on the *i-th* grid unit in the region. $\overline{x_{ik}}$ is the average of normalized values of the *k-th* ecosystem services on the *i-th* grid cell. N is the main ecosystem service category.

2.4.4. Coupling coordination degree model

Coupling is originally a physical concept. It refers to that two or more systems or modes of motion restrict, select, coordinate and amplify each other through the exchange of matter, energy and information [44]. The coupling degree can describe the order degree of the whole system and the strength of interaction between subsystems. The calculation formula is:

$$C=\left[\frac{\prod_{i=1}^{n}U_i}{\left(\frac{1}{n}\sum_{i=1}^{n}U_i\right)}\right]^{\frac{1}{n}} \tag{13}$$

Where, n is the number of subsystems; U_i is the value of each subsystem, C is the coupling degree, and the value of C is between 0 and 1. When the value of C tends to 0, the coupling degree is extremely low, which indicates that the systems are in an irrelevant state and the system develops in a disorderly manner. When the value of C tends to 1, it indicates that the subsystems reach a good coupling between them and tend to a new order. The measurement functions of urbanization quality and ecosystem services at stage t are $f(t, x)$ and $g(t, y)$, where x and y are the evaluation indexes of the two systems, respectively. The expression of coupling degree and coordination degree is:

$$C=\left\{\left[f(t,x)\times g(t,x)\right]/\left[\frac{f(t,x)+g(t,x)}{2}\right]^2\right\}^{\frac{1}{2}} \tag{14}$$

$$D=\sqrt{C\times T}=\sqrt{C\times\left[af(t,x)\times bg(t,x)\right]} \tag{15}$$

Where, D is the coordination degree; C is the coupling degree; a and b are the weights. In this study, it is considered that both urbanization quality and ecosystem services are crucial to the evolutionary development of the composite system, and it was more beneficial to compare the actual conditions of different county subsystems horizontally by assigning the same pending coefficients to each system on the basis of the control variables [45], so a and b were each assigned weight of 0.5.

3. Results

3.1. Status of subsystem development

3.1.1. Urbanization quality subsystem

The enhancement of LXUA's urbanization quality is crucial for advancing the coordinated development of Northwest China and serving as a crucial assurance for the construction of a multiethnic demonstration area of shared prosperity. According to the seventh national census, the resident population of LXUA was 12.47 million, accounting for 40% of the total population of Gansu and Qinghai, among which the urbanization rate of resident population in Lanzhou and Xining was 83.1% and 78.63% respectively. In terms of distribution pattern, the urbanization quality of LXUA in 2000 was in the barbell-shaped "double core" pattern, with areas higher than 0.4 mainly concentrated in Lanzhou and Xining urban areas, the eastern and western cores of the urban agglomeration. At the same time, the urbanization quality of Baiyin and Linxia, the municipal and prefectural government locations, was also higher than 0.4. Compared with 2000, the number of medium and high value areas of urbanization quality in LXUA increased in 2020, including Haiyan of Haibei urban area and Ping'an of Haidong urban area, which had increased to more than 0.4; the main urban areas of Lanzhou and Xining, and Baiyin increased to more than 0.6. It is worth noting that there were no counties with urbanization quality higher than 0.6 in 2020 in Dingxi, Hainan and Huangnan urban areas within the city cluster.

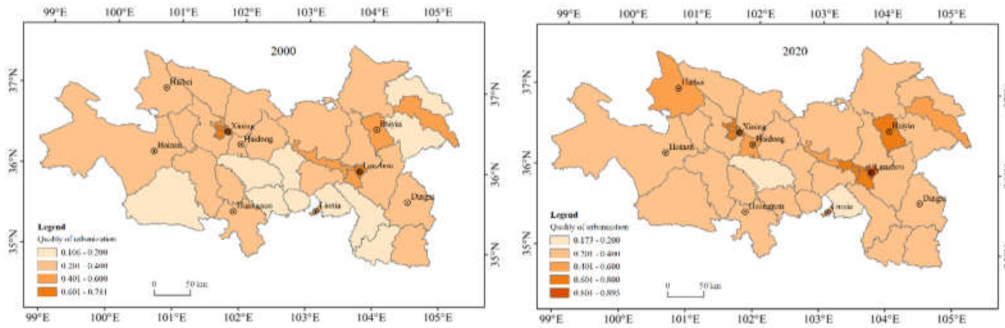

Figure 4. Urbanization quality of LXUA in 2000 and 2020.

On the whole, the urbanization quality of the LXUA has fewer areas with medium and high values, and the development of sub-central cities in the urban agglomeration is relatively insufficient. At the same time, the average urbanization quality of all counties in Lanzhou in 2020 was only 0.538, while the Xining was 0.541. As the leading and core of the urban agglomeration, its development potential has not been fully released, and the leading and driving effects of both on regional urbanization development need to be further strengthened. The urbanization quality of 25 counties in the urban agglomeration in 2020 was between 0.2 and 0.4, accounting for 64% of the total number of counties; among them, 10 counties were less than 0.3. The counties in the LXUA have a single level of economic development, insufficient development of secondary centers, and obvious characteristics of extensive distribution of low-level counties. At present, Lanzhou and Xining are still in the stage of polarized development, the ' siphon effect ' is obvious, a large number of production factors are gathered in the core area, the development vitality of the secondary core areas around the provincial capital is insufficient, and the economic radiation and driving capacity of the central cities needs to be strengthened.

In terms of temporal changes, the average urbanization quality of the counties in the LXUA was 0.329 in 2000, rising to 0.406 in 2020, with an overall increase of 23.25% and an average annual increase of 1.16%. There were big differences in the improvement of each county, among which Gaolan, Yuzhong, Jingyuan, Weiyuan, Dongxiang, Jishishan and Ledu's urbanization quality increased by more than 40%; Yongdeng, Anding, Longxi, Lintao, Yongjing, Huangyuan and Huangzhong increased by more than 30%, mostly in the eastern Gansu section of the urban cluster. The junction of Yongdeng and Gaolan, Lanzhou New was established in 2010. With the gathering of population and industry, infrastructure construction and production and living services enhancement, its urbanization quality has achieved obvious improvement. Lintao, Yuzhong and Yongjing, close to Lanzhou, are radiated and driven by the core of the provincial capital, and the urbanization quality is also improved at a faster rate. The number of counties with an increase in urbanization quality of 20% to 30% was the largest, accounting for one-third of the total number of counties, mainly distributed in the urban agglomeration Qinghai area. The counties with less than 20% increase were concentrated in the main urban areas of Lanzhou and Xining, as well as Baiyin, Pingchuan and Linxia. The urbanization quality of such counties in 2000 was higher than other surrounding counties. In the case of the same absolute value of growth, the larger the previous base, the lower the increase will be; at the same time, the development of regional urbanization also conforms to the law of marginal diminution, and the higher its development degree, the more difficult it will be to improve it.

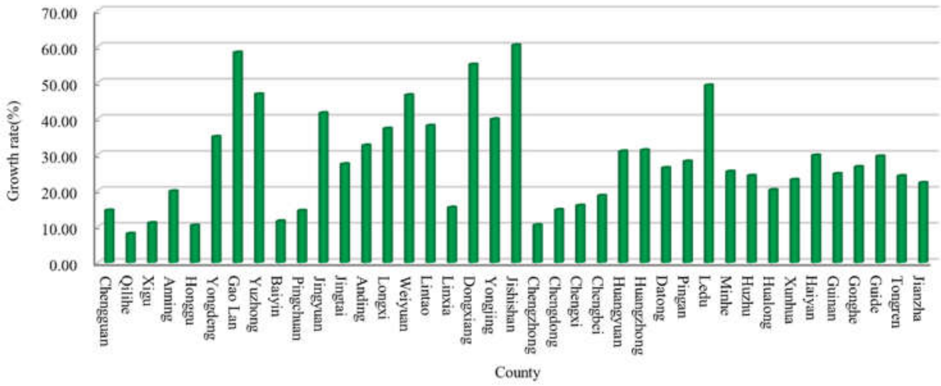

Figure 5. Growth rate of urbanization quality in LXUA from 2000 to 2020.

3.1.2. Ecosystem service subsystem

Water provision services refer to the ability of ecosystem to intercept or store water resources from rainfall. From 2000 to 2020, the water provision services of LXUA improved significantly. The area of the high-value area in the southwestern Sanjiangyuan region had increased most significantly. The Laji Mountains and the Lianhua Mountains in the southeast evolved from the median area to the higher value area. At the same time, the proportion of low value areas for water provision services had increased in Yongdeng, Gaolan and Yuzhong counties in the northeast of the urban agglomeration (Figure 6); In 2020, water provision services increased from the northeast to the southwest, and high altitude mountains became the main area for improving water provision service.

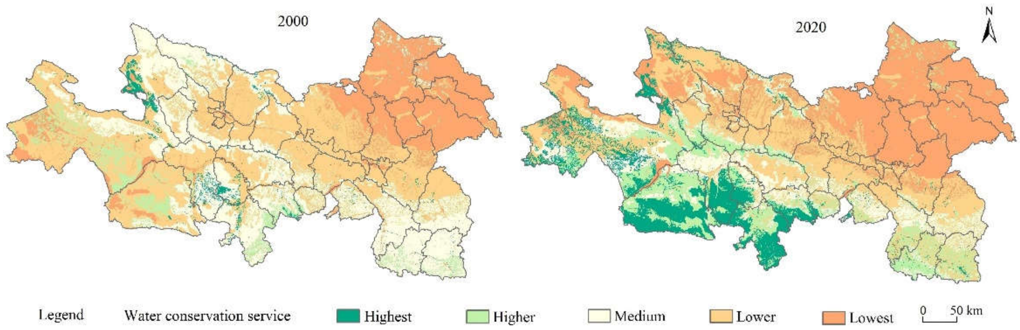

Figure 6. Water provision service of LXUA in 2000 and 2020.

Soil conservation services refer to the ability of the ecosystem to hold the soil in a given time, which is an important guarantee for regulating water and soil loss, preventing soil degradation and reducing the risk of geological disasters. From 2000 to 2020, the overall change of soil conservation services was not significant, and the areas to be promoted were mainly concentrated in the west of urban agglomeration. The median area along the central Laji Mountains and the southern Xiqing Mountains increased, while the area of the low value area decreased. In 2020, soil conservation services mainly served in low and middle value areas, with a single hierarchical structure and a lack of high value areas, showing a differentiation pattern of slightly higher in the middle and lower in the east and west.

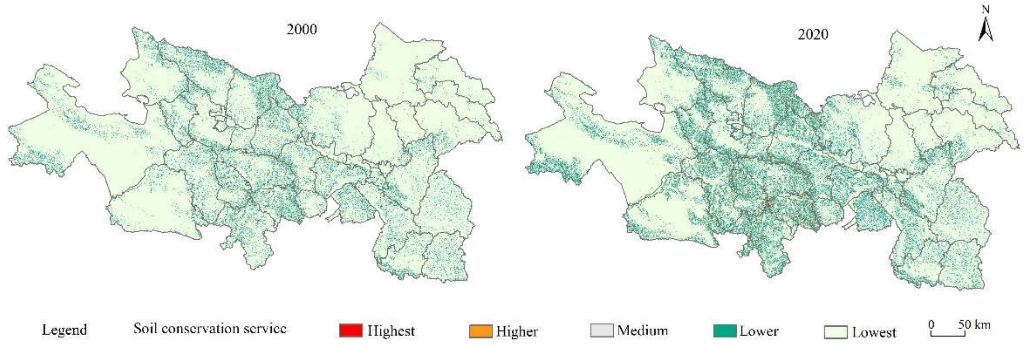

Figure 7. Soil conservation service of LXUA in 2000 and 2020.

Carbon fixation services refer to the capacity of terrestrial ecosystem to store carbon. There are two common ways of carbon fixation in nature, one is photosynthesis of green plants, and the other is chemosynthesis of microorganisms such as nitrifying bacteria. The former as the main mode of carbon fixation is closely related to regional vegetation coverage and land use type. The high-value areas of carbon fixation service in LXUA were mainly located in Daban Mountains in the north, Laji Mountains in the middle, the southern Xiqingshan residual vein and around Xinglong Mountains in the east. The low value areas were mainly concentrated in the desert, water area and urban built-up areas of municipalities in the southwest. In terms of spatial distribution, the carbon fixation services in 2000 were mainly in the median area, with a relatively single hierarchical structure. In 2020, with the accelerated transformation of land use types, the spatial distribution of carbon fixation services became more complex. The high and the low value were staggered, and the trend of "fragmentation" and "fragmentation" was obviously intensified.

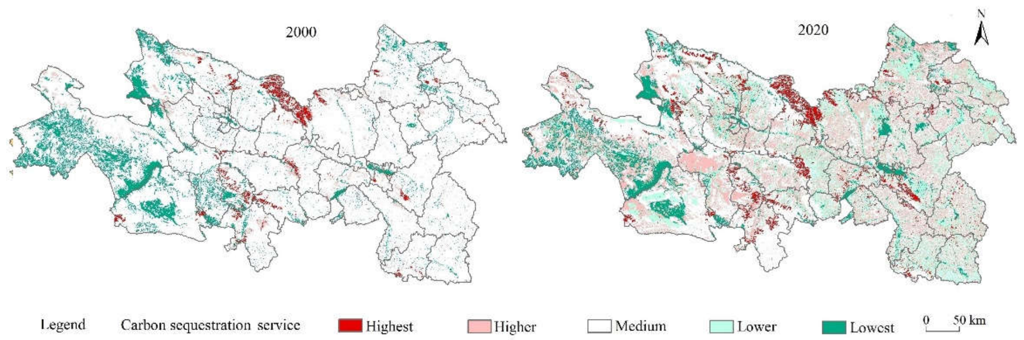

Figure 8. Carbon fixation service of LXUA in 2000 and 2020.

Overall, the integrated ecosystem services of the LXUA showed an overall stepped distribution pattern from northeast to southwest (Figure 9). The highest value areas were mainly located in Hainan and Huangnan in the southwest. The terrain was dominated by high mountain landforms, with towering terrain and continuous mountain systems. The highest value areas in the eastern urban agglomeration were small, scattered in Maxian Mountains at the boundary between Yuzhong and Lintao, and Lianhua Mountains in the south of Weiyuan urban area. Through comparative analysis, the high mountain area with an altitude of more than 2500m in the urban agglomeration coincided with the high value area of ecosystem services, showing a strong correlation. The land use types in mountainous areas were mainly forestland and grassland. Its vegetation coverage was high, root system was developed, and ability to conserve water and soil was strong. Compared with 2000, the area of high-value ecosystem service in the southwest of urban agglomeration increased significantly in 2020. As an important part of the ecological barrier area of the Qinghai Tibet Plateau, Hainan and Huangnan are also the birthplace of the Yellow River and an important supply area of fresh water resources in China. Driven by the National Sanjiangyuan Ecological Protection and Construction

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Phases I and II, the forest coverage and wetland area in the region had increased significantly in the past two decades. The service level of regional integrated ecosystem had been significantly improved.

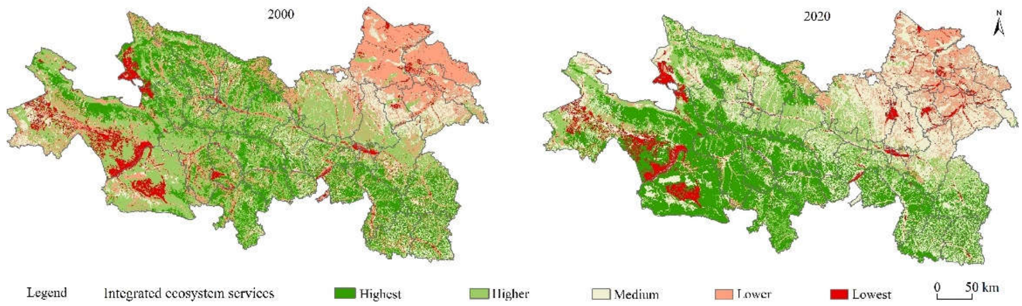

Figure 9. Integrated ecosystem services of LXUA in 2000 and 2020.

In 2020, the higher value areas of ecosystem services distributed along the Huangshui River, showing a belt pattern from northwest to southeast. Topographically, it mainly included Huangshui Valley, Lanzhou Basin, Zhuanglang Valley and Yuanchuan Valley. The land usage in this area is primarily made up of arable land and forest land, with the arable land being primarily dispersed along the rivers. These areas of the region is relatively low in elevation and has plentiful inflow water supplies. Crops, herbs and shrubs in cultivated land and forest land can increase soil organic matter content. The climate is regulated through carbon fixation and oxygen production, so as to reduce surface water and soil loss and effectively conserve water. The higher value areas are strongly affected by human activities. So, the ecological environment of the valley basin should be effectively protected to reduce ecological damage and environmental pollution.

The medium and lower value areas of ecosystem services was located in the northeast of LXUA, including Baiyin and Yongdeng, Gaolan and Yuzhong of Lanzhou urban area. Land use in this area was mainly farmland and grassland. This region is located at the northwest edge of the Longxi Loess Plateau and the transitional zone from the eastern extension of the Qilian Mountains to the Tengger Desert. In this region, the climate is relatively dry, the ground vegetation is sparse, and the ecosystem services are under great pressure. The lowest value areas of ecosystem services were highly overlapped with water area, unused and construction land. The western part of the urban agglomeration was scattered in the Mugetan Desert of Guinan, the Tala Beach of Gonghe, the sand island in the northeast of Qinghai Lake and the Longyang Lake at the boundary between Gonghe and Guinan. The lowest value areas in the east were mainly located in the urban built-up areas of each city, including the main urban area of Lanzhou, Lanzhou New Area and Baiyin.

3.2. Coupling and coordination relationship of composite system

3.2.1. Coupling degree (CD) of composite system

According to the principle of entropy increase, the system always moves from order to disorder, and the process of entropy increase is irreversible. In the composite ecosystem, composed of urbanization and ecosystems, economic, social, and ecological subsystems continue to generate biomass cycles, energy flows, and information exchanges, promoting the evolution of the complex ecosystem towards disorder. According to the synergy theory, the synergy between elements leads to overall system identity, structural stability, evolutionary ordering, and functional optimization, which are the main forces that slow down the entropy increase process. The CD is a comprehensive measure of system synergy. According to the calculation results and relevant research [44], the CD is between 0.6 and 0.8, indicating that the system is in the running-in stage; The CD is between 0.8 and 1.0, and the system is in a high coupling stage

The CD between urbanization quality and ecosystem services in LXUA was 0.794 in 2000 and 0.844 in 2020, with an overall growth of 6.3% over the past two decades. In terms of changes in each county, 31 counties in the urban agglomeration had shown varying degrees of growth in coupling, with 11 counties rising from the grinding stage to the highly coupled stage (Figure 10). The growth of the CD reflects the improvement of the internal order degree of the composite system, the overall evolution trend of the subsystems is consistent, and the interaction is close. The CD of the eight counties had decreased, with a decrease of less than 5%, mainly located in the centers of various cities. After 2000, the quality of urbanization in such counties has steadily improved, but the population is relatively dense, the proportion of construction land is relatively high, the area of natural vegetation is small, and ecosystem services are in a downward trend. The development direction of subsystems is contrary, making the CD of composite systems show a downward trend.

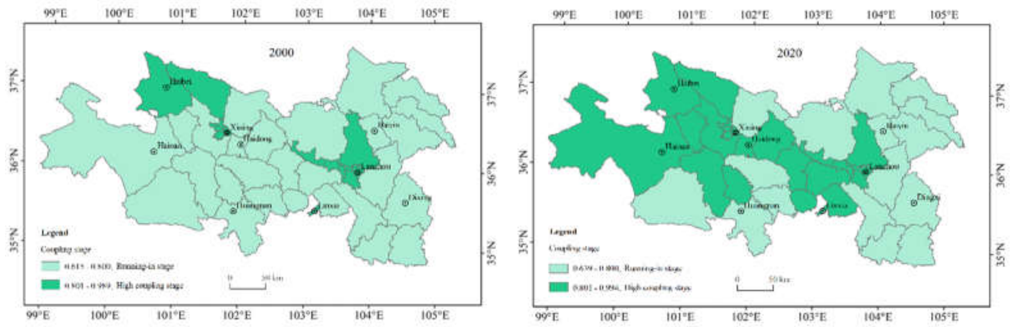

Figure 10. The coupling degree of composite ecosystem in LXUA in 2000 and 2020.

From the perspective of distribution pattern, in 2020, the CD of Qinghai area in the west of LXUA was higher than east. In 2020, there were 15 counties with CD above 0.8, which were in a high coupling stage, mainly concentrated in Xining Haidong， and Linxia urban area. The CD of 24 counties was between 0.6 and 0.8, which was in the running-in stage. The counties in the running-in stage can be divided into two categories in total; The first is Dingxi and Baiyin, which are affected by natural factors such as climate and terrain, and their ecosystem services are at a low level. Compared to the rapid development of urbanization, the ecosystem service capabilities centered on water conservation, soil conservation, carbon fixation and oxygen release have not been effectively improved, and even some regions have shown a downward trend. The low level of ecosystem services is the main reason for affecting the CD of the system.The other is the counties in the southwest of the urban agglomeration, such as Guinan and Tongren. These areas are located in the Nature Preservation Zone of Sanjiangyuan, with abundant water resources, a wide variety of biological species, and a good ecological environment. In recent years, with the increase of national protection efforts and the promotion of relevant policies, the regional ecosystem service capacity has been significantly improved. However, due to the high altitude and relatively sparse population in this region, the development of urbanization is limited to some extent. The urbanization quality subsystem is significantly lagging behind the ecosystem service subsystem, and there is significant room for improvement in coupling.

3.2.2. Coupling coordination degree (CCD) of composite system

The degree of coupling can better represent the overall order of the composite system and the strength of the interaction between the internal subsystems, but it is impossible to judge whether the coupling is benign, that is, when the quality of urbanization and the level of ecosystem services are low, a higher degree of coupling can still be obtained. The concept of ecological civilization emphasizes the interdependence and coexistence of production, life, and ecological development. If a subsystem in a composite system is in poor condition, it will affect the overall development of the system. Only when the two are at a high level and have a high degree of coupling can system coupling truly be achieved. The introduction of coordination as a comprehensive measure of coupling and development level can reflect the degree of order of the internal structure of the system and the accumulation of external scale. According to relevant research results, the coordination degree was divided into 10 intervals (Table 2), and the lowest scoring subsystem was defined as a lagging subsystem.

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Table 2. Evaluation criteria for coordination levels.

Number	1	2	3	4	5
Coordination degree	0-0.09	0.10-0.19	0.20-0.29	0.30-0.39	0.40-0.49
Coordination level	Extreme disorder	Serious disorder	Moderate disorder	Mild disorder	On the verge of disorder
Number	**6**	**7**	**8**	**9**	**10**
Coordination degree	0.50-0.59	0.60-0.69	0.70-0.79	0.80-0.89	0.90-1.00
Coordination level	Barely coordination	Primary coordination	Intermediate coordination	Well coordination	High quality coordination

In 2000, the average coordination degree between urbanization quality and ecosystem service in 39 counties of the LXUA was 0.467. In 2020, it was 0.495, an overall increase of 6%. Among them, the ecosystem service index in 31 counties was lower than the urbanization quality index. The coordination degree of various counties ranged from 0.372 to 0.753, with a total of 11 counties higher than 0.5, including the intermediate coordination area Chengguan in Lanzhou urban area, the primary coordination area Qilihe and Anning, the central and western urban area of Xining, and six barely coordinated areas (Figure 11). Such counties belong to the central urban areas of various cities, and are also the core and secondary core of the development of urban agglomerations. They have a relatively good industrial foundation and a densely distributed urban population. Under the strong impetus of regional urbanization, the overall coordination degree of the composite system is at a high level. At the same time, 7 lagging subsystems in 11 counties, including Chengguan, Anding, and Chengzhong, are ecosystem service subsystems, and there is significant room for improvement in regional ecosystem services.

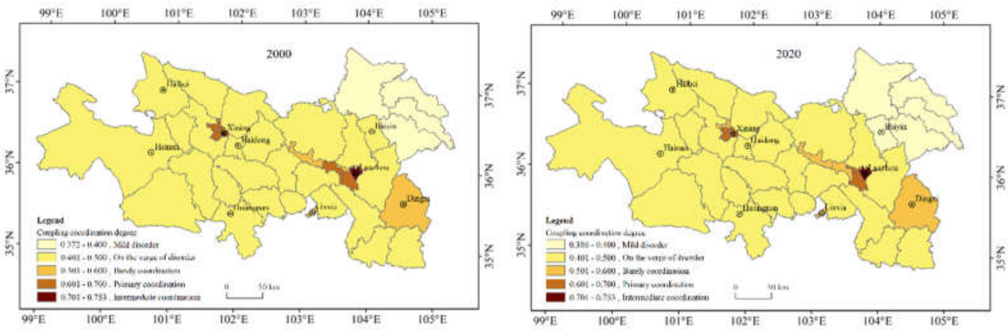

Figure 11. Coupling coordination degree of composite ecosystem in LXUA in 2000 and 2020.

In addition to Baiyin and the intermediate, primary and barely coordinated areas, the remaining 24 counties were on the verge of imbalance. As the main type of urban agglomeration coordination level, its internal structure and external scale represent the overall state and development level of urban agglomeration. Except for Lintao, Weiyuan, and Datong, the urbanization quality index in the near imbalance areas was significantly lower than the ecosystem service index. Based on the analysis of the status of subsystems and the degree of coupling, it was found that the key factor affecting the degree of coordination lies in the low comprehensive development score of the composite system, and more specifically, the low quality of urbanization. According to relevant indicators, the per capita GDP of the 24 counties on the brink of imbalance in 2020 was only about 60% of the national average. The proportion of high-tech industries is low, and the problem of industrial isomorphism and homogeneous competition in each county is more prominent. At the same time, the overall scale of each county is relatively small, mostly small and medium-sized towns with less than 500000 people, with many infrastructure weaknesses and low public service levels. Building a platform of distinctive and advantageous industries in counties, increasing their overall carrying capacity, and directing the orderly transfer of agricultural population are all essential to the high-quality development of counties in the current urban agglomeration.

The four counties belong to the mild disorder area, mainly distributed in Baiyin urban area in the northeast of the urban agglomeration, including Baiyin, Pingchuan, Jingyuan and Jingtai, and the lagging subsystems are all ecosystem service subsystems. The CD of the four counties with mild disorder was at a relatively low level among the 39 counties, and the overall level of ecosystem services was low. Baiyin is located in the northwest of LXUA, adjacent to Tengger Desert in the north. The climate is relatively dry, with annual rainfall of 180~450mm, annual evaporation of 1500~1600mm, and the forest coverage rate of the city is only 5.30%. Located in the transitional zone from the Loess Plateau to the inland denuded plateau, the ground is broken. The surface is mostly covered with loess, mainly composed of silty sand, with vertical joints developed, high porosity, and weak corrosion resistance. The fine soil covering layer on the surface is relatively thin and has a loose structure, which is prone to wind erosion and poplar blowing. At the same time, the backbone enterprises in Baiyin are still enterprises mainly engaged in raw materials and heavy chemicals built during the "First Five-Year Plan" and "Third Line" periods, with high energy consumption industries such as nonferrous metals, chemical industry, thermal power, and building materials accounting for about 90%. The task of energy conservation and carbon reduction is relatively arduous. Strengthening environmental governance and protection, and promoting the transformation and upgrading of industrial structure are currently the top priorities for the sustainable development of mild disorder areas.

4. Discussion

In the new era, geography places more emphasis on the comprehensive study of land surface systems. The coupling and coordination relationship between urbanization and ecosystems is a frontier and hotspot in geographical research. This article constructed multidimensional indicators based on the quality of urbanization and ecosystem services, which is an effective interpretation of the connotation of high-quality development. Based on the results of this study, when analyzing the coupling relationship between urbanization and ecosystem in northwest China, the following points should be noted: First, The assessment index system should decrease the total indicators and adopt more per capita indicators in order to better emphasize the quality and efficiency of development because the northwest region's overall economic and social volume and scale are relatively small. At the same time, the development and evolution of indicators in the diachronic state and the distribution characteristics in the synchronic state need to have a fixed reference basis. The second is that each county in the northwest has a vast area and significant spatial differences in ecosystem conditions. Therefore, multi-source data should be used for analysis based on grid units to highlight the natural characteristics of the ecosystem.

At the same time, this paper based on the research results puts forward the following suggestions: The LXUA's development concept should be changed from linear thinking to system thinking, the production mode should be changed from chain industry to ecological industry, and the way of life should be changed from material civilization to ecological civilization as part of the promotion of the ecological protection and high-quality development strategy of the Yellow River Basin. [38]. All counties shall implement policies according to local conditions and classification based on the development level and coupling coordination status of the composite ecosystem. The construction of public green space such as park green space, protective green space, square land, ancillary green space and regional green space should be strengthened in the intermediate, primary and barely coordinated areas. In addition, the regions also need to strengthen urban pollution control, promote waste recycling and low-carbon treatment, and improve urban resilience and ecological security guarantee capacity. On the verge of disorder counties should rely on ecological security barriers such as the Sanjiangyuan region and the Gannan Plateau, accelerate the construction of the ecological protection belt in the Upper Yellow River, and actively protect the Huangshui River, Datong River, Daban Mountains, Laji Mountains and other ecological corridors. All counties should actively promote county level urbanization. The operation system of municipal infrastructure, the quality of the county's human settlements and the county's ability to radiate and drive the countryside should be impoved. In areas with mild disorder, desertification prevention and soil

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erosion control should be strengthened, industrial structure adjustment and energy structure adjustment should be promoted, pollutant discharge control and environmental risk prevention and control should be strengthened, and the restoration of industrial and mining wastelands and the comprehensive treatment of tailings ponds left over from history should be promoted. Actively build a circular industrial system to realize the green transformation of the economy and society.

The regional system of man-land relationship is a diverse and complex whole. Based on relevant research, this paper constructed regional urbanization quality evaluation indicators from seven aspects: economic development - people's livelihood - environmental protection - facility supply - public services - urban vitality - urban and rural coordination, and evaluates the status of the ecosystem from four dimensions: water provision - soil conservation - carbon fixation-comprehensive services. The evaluation framework of this article has certain reference and guiding significance for understanding the man-land relationship in the northwest region. However, with the shift towards people-oriented, resource saving, and environmentally friendly development, the connotation of evaluation indicators may still be not systematic and comprehensive, and subsequent research will continue to be supplemented and improved. At the same time, urban agglomeration is different from a simple collection of administrative units. The development of various counties is not independent of each other. Each county needs to strengthen communication on the basis of its own development, and cooperate closely on the basis of giving play to its comparative advantages. Therefore, exploring ways and measures to promote the coordinated development and integrated construction of urban agglomeration will also be the focus of research in the future.

5. Conclusions

This paper takes the LXUA in the Upper Yellow River as a case study area. We constructed a comprehensive evaluation index system for urbanization quality and ecosystem services. Through the exponential efficacy function model, the InVEST model and the coupling coordination model, we analyzed the respective development status of urbanization quality and ecosystem services in LXUA, and explored the coupling coordination relationship between them. This study is important to clarify the co-evolution mechanism of the man-land areal system in the Upper Yellow River. The results of the study can provide decision support and theoretical basis for ecological protection and high-quality development of the Yellow River Basin. The main conclusions are as follows:

(1) In 2020, the urbanization quality of LXUA presented a barbell shaped "dual core" distribution pattern, with insufficient development of secondary cores and prominent problems of widespread low-level counties. From 2000 to 2020, the overall urbanization quality of the LXUA increased by 23.25%, with each county showing a growth trend, but there were significant differences in the growth rate.

(2) The level of water provision, soil and water conservation, and carbon fixation services in urban agglomerations has shown an increasing trend since 2000, with different spatial distribution trends. Ecosystem services presented a stepwise distribution pattern that increases from northeast to southwest. High value areas were mainly distributed in the Sanjiangyuan area in the southwest of the urban agglomeration, while low value areas were mainly concentrated in Baiyin in the northeast of the urban agglomeration.

(3) In 2020, the CD between urbanization quality and ecosystem services in LXUA was 0.844, with an overall growth of 6.3%. Among them, 15 counties were in the run-in stage, and 24 counties were in the highly coupled stage. The CD of most counties was increasing, and the reduced areas were mainly concentrated in the centers of various cities.

(4) In 2020, the coordination degree between urbanization quality and ecosystem services in LXUA was 0.495, with an overall growth of 6%. Among them, the number of counties on the verge of disorder was the largest and the area was the widest. The intermediate, primary, and barely coordinated areas were mainly distributed in the central urban areas of various cities, while the mild disorder areas were distributed in Baiyin, northeast of the urban agglomeration; The lagging subsystems in 31 counties served as ecosystem service subsystems.

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Abbreviations

LUXA Lanzhou-Xining urban agglomeration

CD Coupling degree

CCD Coupling coordination degree

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