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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

Wusheng Zhao [1], Peiji Shi [1,*], Ya Wan [1] and Yan Yao [2]

[1] College of Geography and Environment Science, Northwest Normal University, Lanzhou 730070, China; 2017212169@nwnu.edu.cn (W.Z.)
[2] College of Economics, Northwest Normal University, Lanzhou 730070, China
* Correspondence: shipj@nwnu.edu.cn; Tel.: +86-138-9366-5158

Abstract: The study of the man–land relationship in the 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 the LXUA showed the pattern of "double core". The development of urban centers in each city is insufficient, and the proportion of counties with a 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 were relatively lagging behind in ecosystem services.

Keywords: urbanization quality; ecosystem services; coupling coordination; spatial-temporal variations; Lanzhou–Xining urban agglomeration

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1. Introduction

The first explosion of industry in the late 18th century required a 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 the urban–rural gap, tightening resources and energy, intensifying environmental pollution, and overwhelming the ecosystem [1]. 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 the 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.

International research is abundant regarding the relationship between urbanization and ecosystems. The Organization for Economic Cooperation and Development (OECD) and the United Nations Environment Programme (UNEP) pioneered the "Pressure-State-Response" model in the 1980s. This model fostered a two-way perspective for studying the interplay between urbanization and ecosystems. Through the application of econometric methodologies, Grossman and Krueger discovered the renowned environmental Kuznets curve based on panel data from 42 developed countries in 1995. This curve uncovers an inverted "U"-shaped evolution law, correlating urban economic development with the quality of urban ecological environments, thus providing a basis for further research. Contemporary international research can be classified broadly into two categories from a research perspective. One category focuses on the quantitative relationship between urbanization and ecosystems on a global scale. For example, Li studied the coupling mechanism between urbanization systems and ecosystems [2]. Howard delved into the interaction mechanism between urbanization and environmental evolution [3]. On the other hand, Deosthali used simulation to assess the impact of urbanization on the local climates of cities [4]. Vester uncovered the mechanism linking urban economic growth and its environmental evolution [5]. Girmm explored the correlation between changes in urban landscape ecology and global change [6]. Berry identified the primary factors impacting urban ecology due to urbanization. As for research methods, current studies primarily employ disciplines such as economics, ecology, biology, and physics. Howard implemented a system dynamics model, Berry utilized ecological factor analysis, Deosthali leveraged bioclimatic indices, and Vester applied sensitivity models. Overall, the regional scale of foreign research is larger, focusing on exploring the general rules of urbanization and ecosystems in long-time serial variation.

The domestic research began in the 1980s. In 1979, Wu Chuanjun innovatively proposed the theory of regional system of the man–land relationship, underlining the importance of geographical studies focusing on the interaction and negative feedback between humanity and nature within the man–land system [7]. As articulated by Lu Daodao, studying regional human–earth systems requires an understanding of their dynamic changes across different stages of societal development, necessitating an integrated qualitative and quantitative approach and advocating for a harmonious relationship between humans and nature at varying scales [8,9]. Domestic research in this field has also yielded a wealth of findings. Concerning research content, scholars have deployed mathematical models to elucidate various relationships between urbanization and ecosystems, such as "positive", "negative", or "inverted-U" relationships [10–13]. Evaluations of urbanization are predominantly conducted from the perspectives of population movement [14,15], industrial agglomeration [16,17], expansion of construction land [18,19], and infrastructure development [20,21]. Assessments of ecosystem services typically rely on the value scale formulated by Costanza and others [22], with the value of ecosystem services determined by continuously refining the value equivalent factor [23]. As for research methodologies, most existing studies have employed mathematical and statistical models such as regression analysis [24,25], input-output models [26,27], system dynamics models [28,29], or spatial analysis models. Regarding study area selection, empirical studies have mainly concentrated on provincial or municipal levels, predominantly targeting economically advanced regions, such as the Yangtze River Delta, Pearl River Delta, Beijing-Tianjin-Hebei region, and Chengdu-Chongqing region. Overall, contemporary domestic research on the relationship between urbanization and ecosystems exhibits three key characteristics. Firstly, the assessment dimensions of urbanization tend to be somewhat singular, primarily encompassing population aggregation, economic growth, and construction land expansion, with inadequate attention given to the comprehensive benefits of urbanization. Secondly, an over-reliance on statistical data often overlooks the natural attributes of ecosystems, which may result in the assessment findings not accurately reflecting the actual regional ecosystem conditions. Thirdly, the limitations of one-way research remain unaddressed, lacking the analysis of factor relationships and subject behaviors guided by synergistic ideas. The research primarily centers around the ecological effects prompted by urbanization, with insufficient focus on the feedback mechanism and mode of action of the ecosystem.

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 hu-man processes [31]. For the purpose of identifying regional ecosystem service issues, preserving regional ecological balance, and advancing regional sustainable development, it is crucial to explore the intrinsic interaction mechanism between the external spatial and temporal evolution of ecosystem services and the economic society [32–34]. We introduced an exponential efficacy function model to quantitatively measure the development of economic and social systems based on pertinent studies. Meanwhile, we used multivariate data and the InVEST model to analyze the regional ecosystem services and explore the current development status and coupled coordination of the complex ecosystem of the LXUA. The purpose of this research is to clarify the synergistic evolution mechanism of the man–land relationship in the ecologically sensitive area of the Upper Yellow River and provide a 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 km^2, 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 m or more, the elevation varies from 1258 to 5255 m. 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; and complex and diverse vegetation types, among which the eastern agricultural area of Qinghai is located in the Huangshui and Yellow River basin triangle. It 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, and the two cities are the "growth poles" to promote the population clustering and economic development of the urban agglomeration.

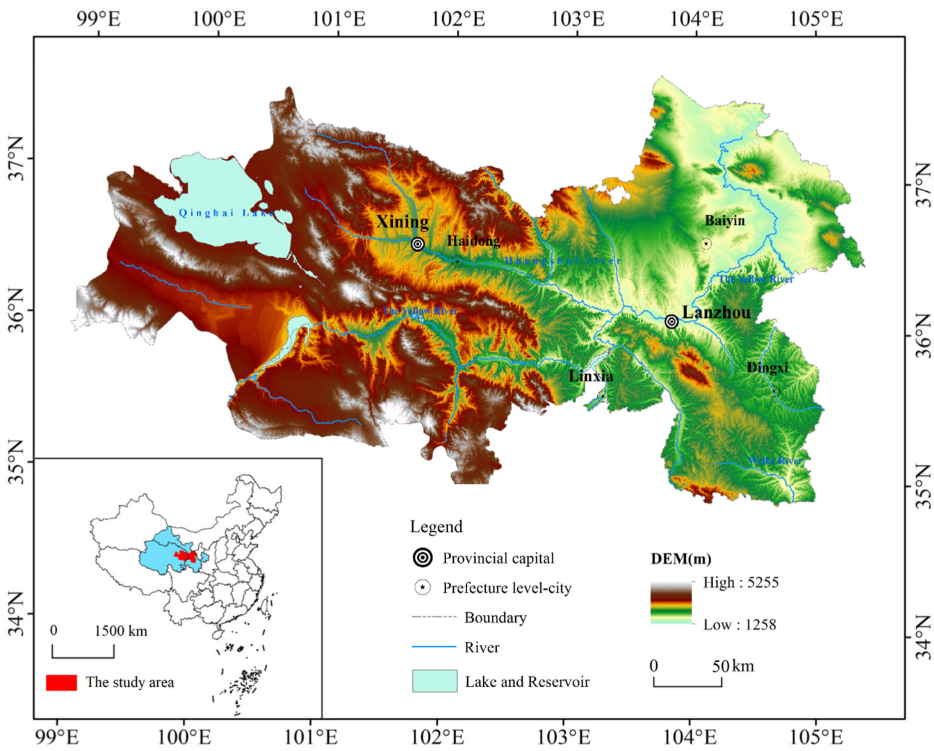

Figure 1. Diagram of the study area.

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 a 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 is an essential strategic support for maintaining China's ecological security and is situated in the crucial zone of transition from the first to the second terrain in China. It contains significant ecological security barriers such as the Source Region of Three Rivers, Qilian Mountains, and Gannan Plateau. Water provision services refer to the interception, infiltration, and storage of precipitation by ecosystems through their unique structures and water interactions, and the effective regulation of water circulation through evapotranspiration. The water provision services of the LXUA play an important role in mitigating surface runoff, supplementing groundwater, mitigating seasonal fluctuations in river water flow, and ensuring water source quality. Meanwhile, vegetation can effectively reduce the impact of precipitation on soil. Plant roots are intertwined with the soil, which can effectively fix the soil. The soil conservation services are crucial to reduce soil erosion, maintain soil fertility, prevent and control desertification, and reduce the occurrence of geological disasters such as landslides and debris flows. Carbon fixation services refer to the conversion of atmospheric carbon dioxide into organic carbon through photosynthesis, which are fixed in the plants or soil. Carbon fixation services can reduce the concentration of greenhouse gases such as carbon dioxide in the atmosphere, which plays an important role in maintaining the carbon oxygen balance and slowing down global warming. Integrated ecosystem services are the overall manifestation of various service functions and an important indicator reflecting the quality and condition of regional ecosystems. These four types of ecosystem services 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 the four aspects of water provision, soil conservation, carbon fixation, and integrated ecosystem services were selected for assessment. The analysis framework is shown in Figure 2.

Table 1. Indicators of urbanization quality.

Functional Layer	Indicator Layer	Attribute	Weight
Economic development level	Per capita GDP (RMB)	+	0.0422
	Per capita retail sales of consumer goods (RMB)	+	0.0368
	Per capita investment in fixed assets (RMB)	+	0.0454
	The proportion of tertiary industry (%)	+	0.0396
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	+	0.0504
	Number of public buses per 10,000 people	+	0.0379
	Gross Domestic Product (RMB 10,000)	+	0.0299
	Number of enterprises with considerable scale	+	0.0466
Urban–rural relations	Average income ratio between urban and rural residents	−	0.0359
	Average consumption expenditure ratio between urban and rural residents	−	0.0396

The process of urbanization is one of the most important manifestations of the development and evolution of human society. The ecosystem is a natural background and supporting system for the subsistence and multiplying of human beings. Urbanization is closely related to ecosystems, and both are important components of the regional man–land system. The impact of urbanization on the ecosystem is bidirectional, with both negative stress and positive promotion effects. The coercive effect of urbanization on the ecosystem refers to the phenomenon of environmental pollution, imbalance between resource supply and demand, reduction of biodiversity, and degradation of ecosystem functions when the amount and speed of waste discharged by cities into the hinterland environment through production and living reach or exceed the speed of ecological environment decomposition and digestion. The promoting effect of urbanization on the ecosystem refers to the investment of more resources such as technology, funds, and manpower into urban economic construction activities within the range of ecological environment capacity and carrying capacity. Through policy intervention and the promotion of clean production technology, the economic development mode is transformed, resource utilization efficiency is improved, pollution emissions are reduced, citizens' lifestyles are transformed, the low-carbon and green development of cities is achieved, and the quality of the living environment is improved. The ecosystem also has a positive and negative impact on urbanization. On the one hand, resources such as water, soil, energy, and minerals mainly constrain urban scale, affect urban layout, limit urban industrial structure, and influence the speed of urbanization development, thereby exerting constraints on various aspects of urbanization; on the other hand, ecosystem services such as water provision, soil conservation, and carbon fixation are fundamental for supporting and guaranteeing conditions for urban development and residents' lives.

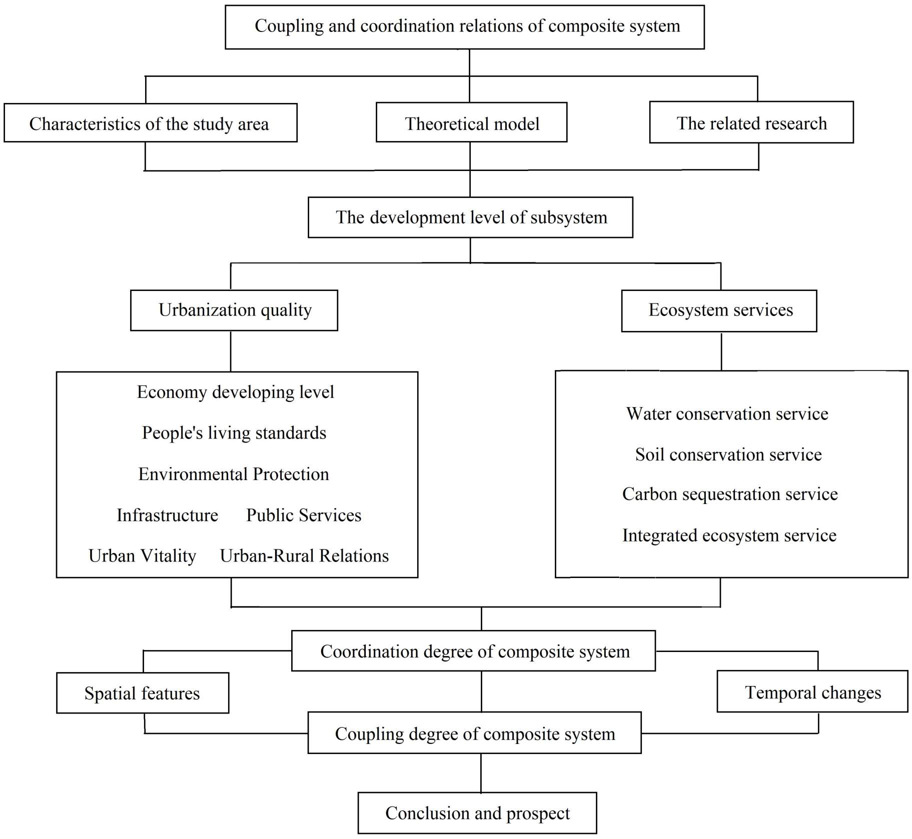

Figure 2. Analysis framework.

2.3. 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 accessed on 22 August 2022) (Figure 3).

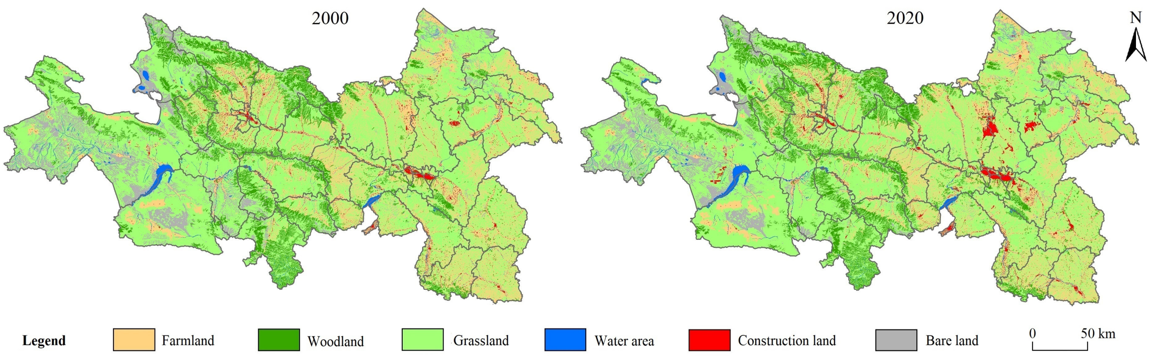

Figure 3. Land-use types of LXUA in 2000 and 2020.

The socio-economic data used in this study were mainly obtained from "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. Meteorological data, including temperature, precipitation, water pressure, etc., were obtained from the China Metrological Data Service Centre (http://data.cma.cn accessed on 28 August 2022), and the local 5-year average meteorological data were taken for the calculation considering the interannual fluctuation of the data. the soil data were sourced from National Earth System Science Data Center (http://www.geodata.cn accessed on 12 September 2022).

2.4. Methods

2.4.1. Exponential Efficacy Function Model

In previous studies, the linear efficacy function model was usually used to standardize the data. The linear efficacy function model defines the change of indicators as "uniform change", which is a relatively simplified form of processing. 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 law of diminishing marginal utility. It will then be more challenging to maintain the indicator's growth or progress. The derivative of exponential efficacy function model is a lower convex function about independent variable. In practical applications, the exponential efficacy function model 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 the theoretical minimum value, x^h is the theoretical maximum value. The parameters A and B can be determined by the critical points. When the index value and the theoretical minimum are the same, according to the linear efficacy function method, set d = 60, then A = 60. When the index value and the theoretical maximum are the same, set d = 100, then $B = -\ln 0.6$ [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 according 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:

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

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

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

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

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

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

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. The 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 the InVEST model. The model is based on the Budyko water and heat coupling equilibrium assumption, taking into account factors such 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 Z_{ij} denotes the annual water yield of land-use type j in grid i (mm). $AETi_j$ 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 is the calculation formula:

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

where SD denotes the amount of soil conservation ($\text{t}\cdot\text{hm}^{-2}\cdot\text{a}^{-1}$). R is rainfall erosivity ($\text{MJ}\cdot\text{mm}\cdot\text{hm}^{-2}\cdot\text{h}^{-1}\cdot\text{a}^{-1}$). K is soil erodibility ($\text{t}\cdot\text{hm}^{2}\cdot\text{h}\cdot\text{hm}^{-2}\cdot\text{MJ}^{-1}\cdot\text{mm}^{-1}$). 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 ($\text{t}\cdot\text{hm}^{-2}\cdot\text{a}^{-1}$). C_{above} is the aboveground carbon storage ($\text{t}\cdot\text{hm}^{-2}\cdot\text{a}^{-1}$). C_{below} is the underground carbon storage ($\text{t}\cdot\text{hm}^{-2}\cdot\text{a}^{-1}$). C_{soil} is the density of soil organic matter ($\text{t}\cdot\text{hm}^{-2}\cdot\text{a}^{-1}$). C_{dead} is carbon storage of litter ($\text{t}\cdot\text{hm}^{-2}\cdot\text{a}^{-1}$).

d. Integrated ecosystem services

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

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

where ES_i is the ecosystem services of the i-th grid cell. $\boldsymbol{\sigma_{ik}}$ is the amount of the k-th ecosystem services on 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

Originally a physical concept, coupling refers to the phenomenon of two or more systems affecting each other through various interactions. The coupling degree can describe influence between systems or elements. The coupling action determines the state and structure of the system when it reaches the critical region, which determines the trend of the system from disorder to order. The impact of urbanization quality and ecosystem services interaction is defined as the coupling degree, which reflects the order of the system and the interaction strength 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. According to the value range of the coupling degree, it can be divided into four stages. When the CD is below 0.3, the system is in the low coupling stage; when the CD is between 0.3 and 0.5, the system is in the antagonistic stage; when the CD is between 0.5 and 0.8, the system is in the running-in stage; and when the CD is between 0.8 and 1.0, the system is in the high coupling stage. 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 formula is as follows:

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

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

The coupling degree can indicate the strength of interaction between urbanization quality and ecosystem services, but it is not possible to judge whether the coupling status is benign or not. When the development level of both systems is low, a high coupling degree can still be obtained. The degree of coordination adds a development coefficient to the degree of coupling, which is a composite reflection of the order of internal structure and the external scale of the system, 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 [44], 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 the 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 the LXUA was 12.47 million, accounting for 40% of the total population of Gansu and Qinghai, among which the urbanization rate of the resident population in Lanzhou and Xining was 83.1% and 78.63%, respectively. In terms of distribution pattern, the urbanization quality of the 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, in the eastern and western cores of the urban agglomeration (Figure 4). 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 the Haibei urban area and Ping'an of the Haidong urban area, which had increased to more than 0.4; and 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 an urbanization quality higher than 0.6 in 2020 in Dingxi, Hainan or Huangnan urban areas within the city cluster.

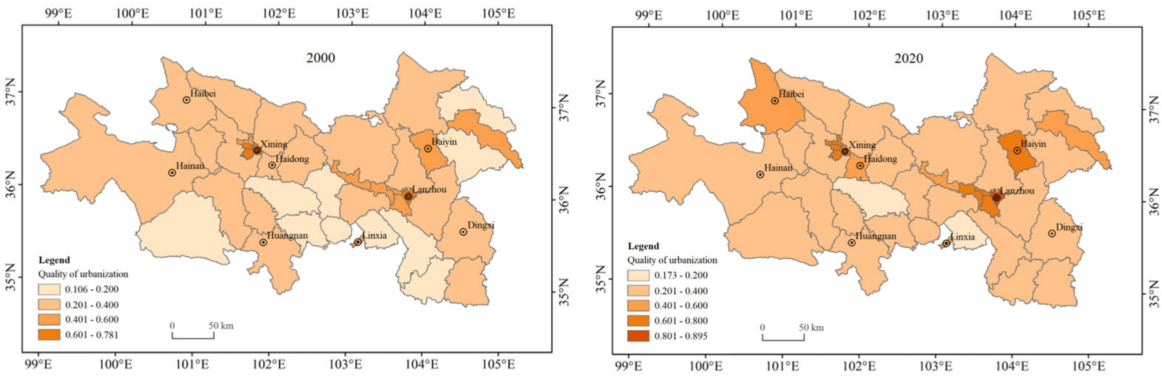

Figure 4. Urbanization quality of the LXUA in 2000 and 2020.

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 0.536, while that of Xining was 0.539. 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 had scores 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 an 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 need to be strengthened.

In terms of temporal changes, the average urbanization quality of the counties in the LXUA was 0.328 in 2000, rising to 0.404 in 2020, with an overall increase of 23.17% 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%; and that of Yongdeng, Anding, Longxi, Lintao, Yongjing, Huangyuan and Huangzhong increased by more than 30%, mostly in the eastern Gansu section of the urban cluster (Figure 5). 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 a 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.

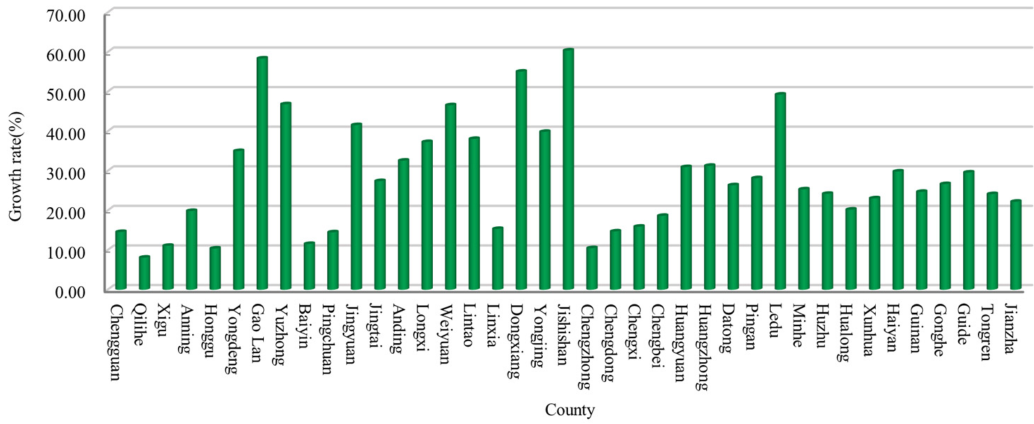

Figure 5. Growth rate of urbanization quality in the LXUA from 2000 to 2020.

3.1.2. Ecosystem Service Subsystem

Water provision services refer to the ability of an ecosystem to intercept or store water resources from rainfall. From 2000 to 2020, the water provision services of the 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 services.

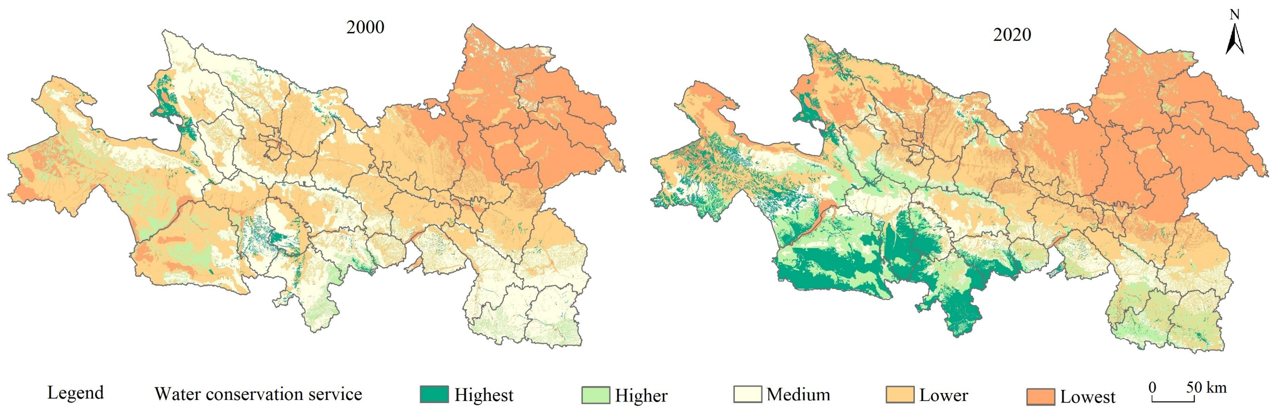

Figure 6. Water provision service of LXUA in 2000 and 2020.

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 (Figure 7). 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 that was slightly higher in the middle and lower in the east and west.

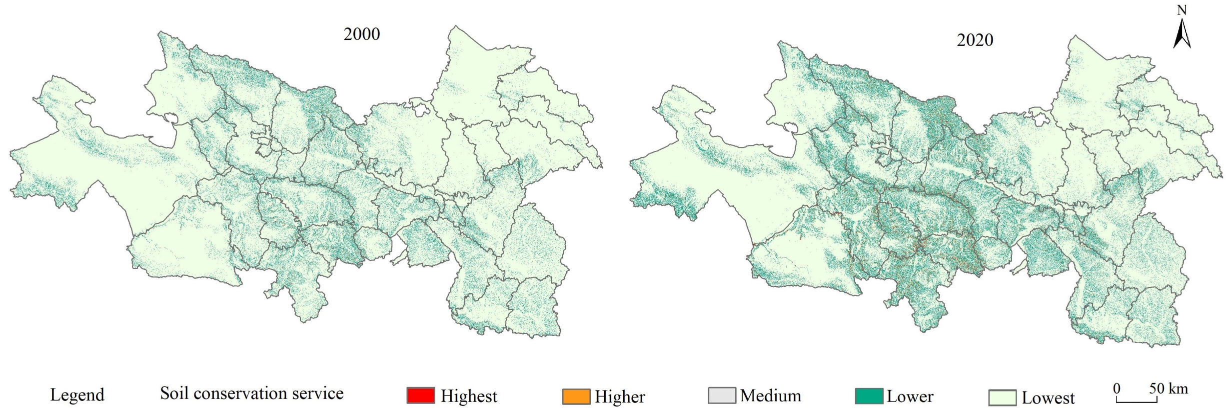

Figure 7. Soil conservation service of LXUA in 2000 and 2020.

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 the photosynthesis of green plants and the other is the 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 (Figure 8). 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 values were staggered, and the trend of "fragmentation" and "fragmentation" was obviously intensified.

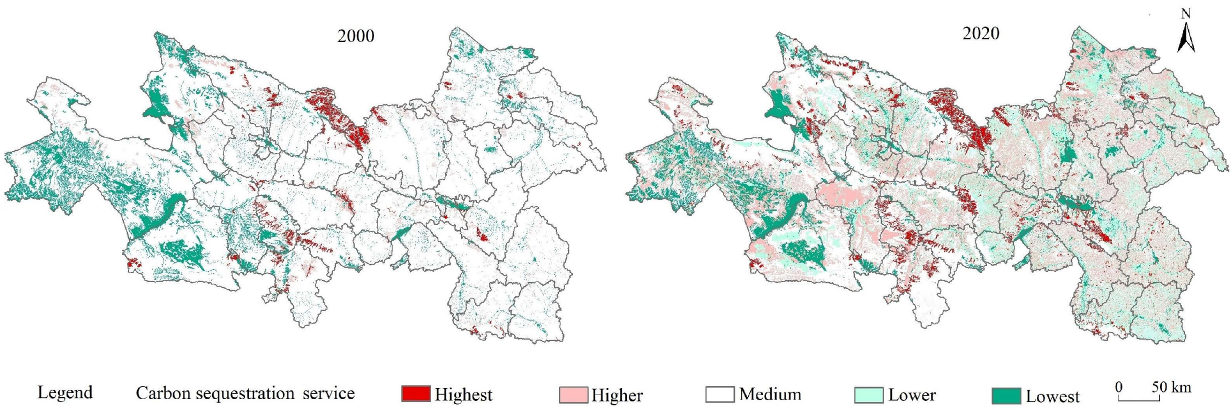

Figure 8. Carbon fixation service of LXUA in 2000 and 2020.

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 the 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 2500 m 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. Their vegetation coverage was high, their root system was developed, and their ability to conserve water and soil was strong. Compared with 2000, the area of high-value ecosystem services 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 freshwater resources in China. Driven by the National Sanjiangyuan Ecological Protection and Construction Phases I and II, the forest coverage and wetland area in the region has increased significantly in the past two decades. The service level of regional integrated ecosystem had been significantly improved.

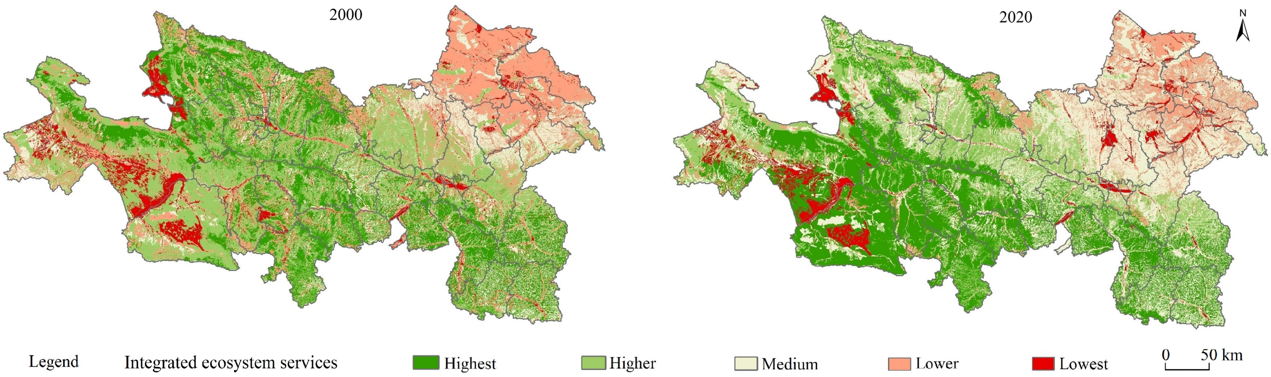

Figure 9. Integrated ecosystem services of LXUA in 2000 and 2020.

In 2020, the higher-value areas of ecosystem services were 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 are relatively low in elevation and have 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 were located in the northeast of the LXUA, including Baiyin and Yongdeng, Gaolan and Yuzhong of the 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 the water area and 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 at 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 areas 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 [45], the CD is between 0.6 and 0.8, indicating that the system is in the running-in stage; and if the CD is between 0.8 and 1.0, the system is in a high coupling stage.

The CD between urbanization quality and ecosystem services in the LXUA was 0.793 in 2000 and 0.842 in 2020, with an overall growth of 6.18% over the past two decades. In terms of changes in each county, 31 counties in the urban agglomeration showed 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, that the overall evolution trend of the subsystems is consistent, and that the interaction is close. The CD of the eight counties 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.

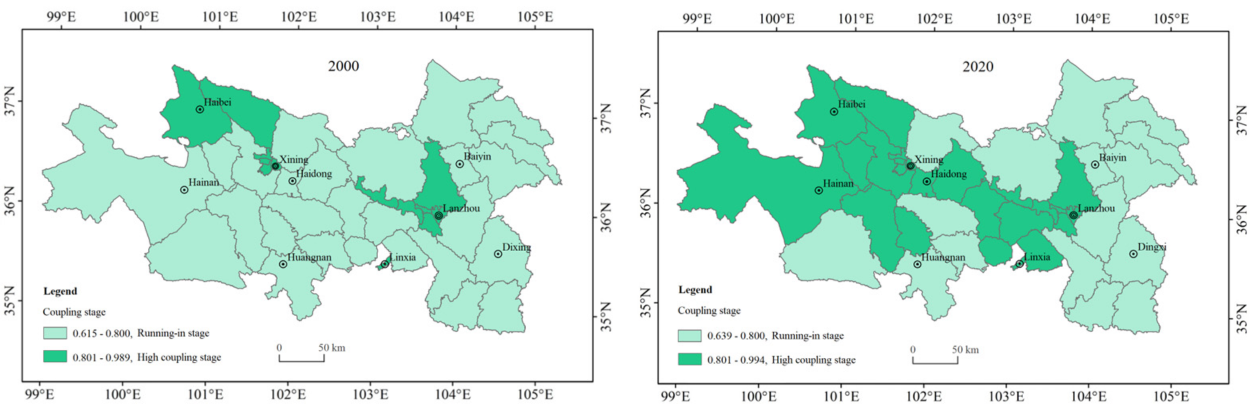

Figure 10. The coupling degree of composite ecosystem in LXUA in 2000 and 2020.

From the perspective of distribution pattern, in 2020, the CD of the Qinghai area in the west of the LXUA was higher than in the east. In 2020, there were 15 counties with a CD above 0.8, which were in a high coupling stage, mainly concentrated in Xining Haidong and Linxia urban areas. The CD of 24 counties was between 0.6 and 0.8, which indicates 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 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.

Table 2. Classification criteria for coordination degree.

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 0.464. In 2020, it was 0.493, an overall increase of 6.25%. 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 6 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.

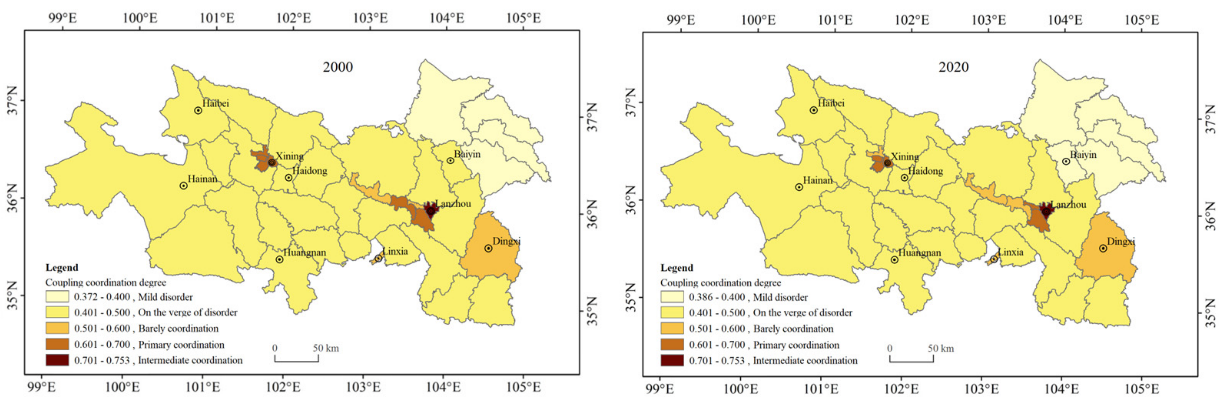

Figure 11. Coupling coordination degree of composite ecosystem in LXUA in 2000 and 2020.

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 problems of industrial isomorphism and homogeneous competition in each county are more prominent. At the same time, the overall scale of each county is relatively small, mostly small- and medium-sized towns with less than 500,000 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 the LXUA, adjacent to the Tengger Desert in the north. The climate is relatively dry, with an annual rainfall of 180~450 mm and annual evaporation of 1500~1600 mm, 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 and mainly composed of silty sand, with developed vertical joints, 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, which were 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 tasks of energy conservation and carbon reduction are 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

By comparing previous studies, we believe that evaluating the scale of urbanization solely from population, economy, and land is not comprehensive in Northwest China. The assessment must consider aspects such as people's living standards, environmental protection, infrastructure, public service, urban vitality, and urban–rural relations. More than 60% of counties had an urbanization quality below 0.4 in 2020, indicating that the overall quality of urbanization in the LXUA is still low. It is necessary to change the development mode of simply pursuing the urbanization scale and focus on improving the quality and efficiency of urbanization. In the current research, statistical indicators are often used to evaluate the environmental condition, which can lead to higher evaluation results, reduce the spatial continuity, and enhance the mutability of the data. It is hard to reflect the real ecological status of the region using the evaluation results. Based on multivariate data and the InVEST model, we found that the overall spatial pattern of ecosystem services in the LXUA shows an increasing trend from northeast to southwest, while the level of ecosystem services is relatively low in city-and-town concentrated areas. The two systems in general show a "high coupling–low coordination" development status. This indicates that urbanization quality and ecosystem services are closely related, and the feedback effect is obvious in the northwest arid area. Many counties are still the antagonistic stage and the running-in stage between urbanization and ecosystems, and the overall coupling coordination degree is relatively low. It is necessary to reduce the negative impact of industry and life on ecosystems through policies, funds, technology, and other means.

The coupling mechanism between urbanization and ecosystems is very complex. This study starts from two aspects of urbanization quality and ecosystem services, and the evaluation and analysis of the composite system may still be incomplete. Subsequent research will continue to be supplemented and improved. The study area for this article is the LXUA. What are the different coupling mechanisms between this area and other regions? Whether the conclusions obtained in this study are applicable to other urban agglomerations, as well as other spatial scales at home and abroad, requires further research and verification in the future.

We found that there are significant differences in the development level of subsystems and the coupling coordination degree of composite systems in different regions. Each county should adopt measures suiting local conditions. The construction of public green space such as parkland, square land and urban protection greenbelt 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. Counties on the verge of disorder should rely on ecological security barriers such as the three-rivers source area 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. Each county should actively improve its infrastructure and public services to enhance the quality of the county's residential environment. On the one hand, mild-disorder counties should strengthen their combat of desertification and water loss and governance of soil erosion, as well as reduce environmental risk and pollutant emissions. On the other hand, these counties should repair the abandoned mines, actively build the circular economy industrial system, and promote the green transformation of the economy and society.

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 the LXUA and explored the coupling coordination relationship between them. This study is important to clarify the coevolution mechanism of the man–land areal system in the Upper Yellow River. The results of the study can pro-vide decision support and a theoretical basis for the ecological protection and high-quality development of the Yellow River Basin. The main conclusions are as follows:

(1) In 2020, the urbanization quality of the LXUA presented a barbell shaped "dual core" distribution pattern, with the insufficient development of secondary cores and prominent problems in 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 ser-vices 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) The relationship between the urbanization quality and ecosystem services in the LXUA is strong and the interaction is significant. The CD in 2020 was 0.844, with a growth rate of 6.3% over the past twenty years. Fifteen counties were in the run-in stage, and 24 counties were in the highly coupled stage in the LXUA. The CD of most counties was increasing, and the reduced areas were mainly concentrated in the centers of various cities.
(4) For the counties within the LXUA, there is a lot of room to promote the coordination relationship between urbanization quality and ecosystem services. The CCD of the composite system in 2020 was 0.495. 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 analytical framework of the article is a guide to explore the evolution mechanism of the man-earth areal system in Northwest China. However, as the connotations of urbanization and ecosystem services continue to be enriched, an indicator system may still not be comprehensive. In our subsequent research, we will continue to supplement and improve them.

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Abbreviations

LUXA	Lanzhou-Xining urban agglomeration
CD	Coupling degree
CCD	Coupling coordination degree

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