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Measurement and optimization paths of the multidimensional development levels of counties in the Yellow River Basin: based on the sustainable livelihoods framework

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The Yellow River Basin (YRB) faces intense man-land conflicts. However, existing studies rarely focus on the comprehensive and multidimensional development levels in the YRB, and there is a lack of refined county-level studies, making it difficult to fully support the implementation of ecological protection and high-quality development strategy in the YRB. Under the Sustainable Livelihoods Framework, the spatial distribution, differences, and correlation characteristics of the multidimensional development levels of counties in the YRB are disclosed. This is achieved by comprehensively utilizing geospatial, socio-economic, and other multi-source data in combination with methods such as the entropy weight method, the Theil index, and spatial analysis. Optimal development paths are proposed with a focus on the development types of counties. The findings are as follows: (1) Counties in the YRB have a low overall multidimensional development level, presenting a spatial distribution pattern of "high in the east and low in the west" overall. In terms of each dimension, the average value ranking of lower reach > middle reach > upper reach is observed in each dimension; the exception is the financial dimension (with the ranking of middle reach > lower reach > upper reach). (2) Differences between counties in the development indices vary across different dimensions. The differences in the multidimensional development indices and in the development indices of each dimension (except for the natural dimension) are mainly attributable to differences between counties within each reach. Differences between reaches are non-significant. (3) The multidimensional development levels of counties in the YRB and their development levels in each dimension show strong spatial correlation. And significant counties are mainly identified as LL-type (clusters of low value areas) and HH-type (clusters of high value areas). (4) Depending on the measurement results and advantageous factors of the county multidimensional development index, counties are classified into four development types: weak development type, single-dimension-led development type, potential coordinated development type, and multidimensional coordinated development type. Based on this classification, targeted optimal development paths are proposed with a focus on the specific characteristics of different development types. The research findings can provide effective scientific support for ecological protection and high-quality development in the YRB.

KEYWORDS

multidimensional development, sustainable livelihood, optimization path, county, Yellow River Basin

1 Introduction

The Yellow River, China's second-longest river, flows from western to eastern China and is known as the "Mother River". The Yellow River Basin (YRB) serves not only as a critical ecological security barrier but also as an important hub for population activities and economic development. It plays an important strategic role in China's overall economic development and ecological civilization construction efforts. However, limited by historical and natural conditions, the YRB has a vulnerable ecological environment and relatively backward socio-economic development. It is one of the regions in China where the conflict between humans and the environment is most acute (Wang et al., 2020). It is worth noting that five of China's 14 concentrated and contiguous poverty-stricken areas involve the YRB, which is inevitably a key and challenging area for the implementation of new urbanization and rural revitalization strategies (General Office of the State Council of the People's Republic of China, 2021). In 2019, the ecological protection and high-quality development of the YRB were elevated to the level of a major national strategy, imposing explicit requirements for man-land, urban-rural, and spatial coordinated development in the basin (Li et al., 2020). Counties are not only the basic units of state governance and national socio-economic development but also an important fulcrum in advancing new urbanization and rural revitalization strategies in a coordinated way. Counties serve as a connecting link between higher and lower levels of governance, between different sectors, as well as between urban and rural areas (Xu, 2022). The high-quality development of counties is of great importance for promoting the two-way free flow of production factors between urban and rural areas, expanding domestic demand, and smoothing the circulation of the national economy. In this sense, an objective and accurate understanding of the comprehensive development levels of counties in the YRB can provide an important basis for their high-quality development.

Regional development is a key area of research in human geography and regional science, and how to quantitatively depict and evaluate regional development levels has long been a major focus of both governmental agencies and the academic community (Xu et al., 2016). Initially, scholars mostly measured regional development levels using single economic indicators such as Gross Domestic Product (GDP) and Gross National Product (GNP), or from single economic dimensions such as economic structure and economic scale (Mishan, 1967; Liu, 2006). With socio-economic development and the further advancement of research, other dimensions of regional development, such as natural environments, education, medical care, public services, and social security, have attracted more and more attention (Zhu, 2021). Academic research on regional development both in China and internationally has gradually shifted from single-indicator, unidimensional measurement to multi-indicator, multidimensional measurement (Silva and Ferreira-Lopes, 2014; Cao et al., 2021; Li et al., 2022). Scholars argued that benign interaction and coordinated development should be realized at the regional level in economic, social, environmental, and other dimensions. Accordingly, scholarly understanding of regional development has become more systematic and multidimensional. In terms of the research scale, while existing studies involve different spatial scales, they mainly remained at national, provincial, and municipal levels. With the wide application of big data, relevant quantitative studies at county, town, and village levels have become increasingly diverse in recent years (Jiang et al., 2020; Zhang et al., 2024).

Sustainable livelihoods frameworks (SLFs) originated from sustainable development theory (Sen, 1981) and have garnered extensive attention in geography, where the man-land relationship is a central theme (Zhao, 2017). Among the various SLFs, the theory-driven and problem-oriented framework proposed by the former British Department for International Development (which includes environmental vulnerability, five types of livelihood capital (i.e., human, social, physical, financial, and natural), structural and process transformation, livelihood strategies, and livelihood outcomes) has been widely used in practical research (Department for International Development, 1999). As a core element of the SLF, livelihood capital, with its diverse connotations, has been widely applied in studies of multidimensional poverty and sustainable development at both individual and regional levels. Specifically, scholars earlier investigated the poverty status, livelihood strategy choices, and their sustainability at the individual/household level based on livelihood capital, exploring how different types of livelihood capital contribute to improving living conditions and enhancing quality of life (Nikuze et al., 2019). Later, scholars criticized the tendency of livelihood capital to focus on individuals/households while ignoring regions involved; consequently, livelihood capital evaluation was extended into the regional level to monitor regional sustainable development more effectively. For example, based on the five types of livelihood capital, Erenstein et al. (2010), Donohue and Biggs (2015), and Berchoux and Hutton. (2019), Berchoux et al. (2020) studied the poverty or development characteristics across different regions, including the Indo-Gangetic Plain, the ecological regions of Nepal, and the Mahanadi Delta region of India. Similarly, studies by Chinese scholars on livelihood capital also mostly stressed the people-oriented micro scale (Yan et al., 2022; Xiang et al., 2023; Xia et al., 2023). Inspired by international studies, Chinese scholars have discussed issues such as regional development, poverty, and the quality of poverty alleviation based on multidimensional livelihood capitals (Zhu, 2021; Guo et al., 2021; Luo et al., 2022), focusing on the macro policies of the state or the realities of regional

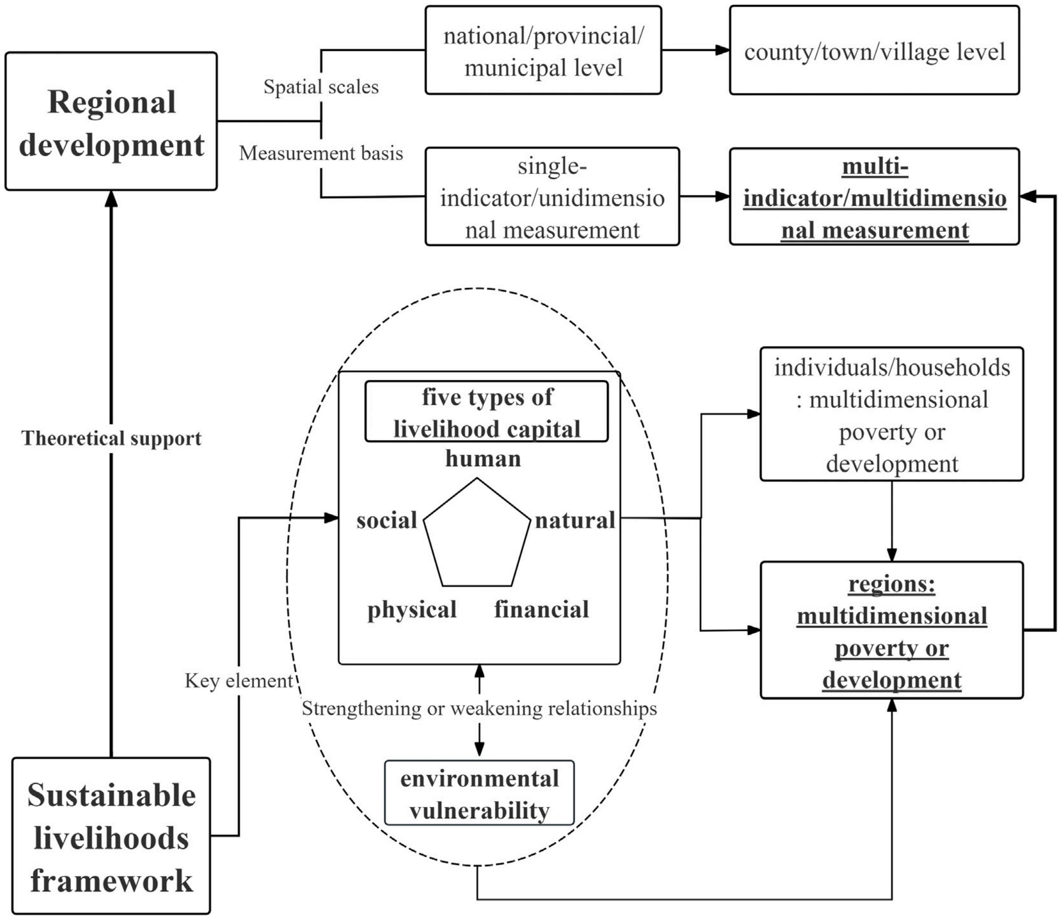

FIGURE 1
The theoretical framework.

development. Although these studies differ in subject matter, they are both diverse and unified, as they are based on the same internal logic—that is, a comprehensive measure of the regional multidimensional development index. At the same time, some scholars argued that there were direct or indirect strengthening or weakening relationships between environmental vulnerability and regional livelihood capitals (Liu and Xu, 2015; Pan et al., 2018; Xu et al., 2021), they comprehensively depicted the multidimensional development status of regions based on six dimensions of five types of livelihood capital and environmental vulnerability. In this sense, regional research based on SLF provides effective theoretical support for the evaluation of regional multidimensional development levels (Figure 1).

Existing studies on the YRB mostly analyzed its development characteristics from the perspective of a single dimension (such as economy, industry, or ecology) or the coupling coordination relationship between two dimensions (Deng et al., 2021; Chen et al., 2022; Zhao et al., 2022; Yang and Zhang, 2022; Qian-Ming and Ji-Xia, 2024), however, research rarely paid adequate attention to its multidimensional comprehensive development. In terms of research scale, relevant literature largely focused on provincial and municipal levels, and there is a lack of refined county-level studies that can effectively support the high-quality development of the YRB. Therefore, in this paper, counties in the YRB are taken as the research object. A multidimensional indicator system is constructed based on SLF to analyze the multidimensional development levels and spatial differentiation characteristics of counties in the YRB. Based on summarizing the development types of counties, targeted optimal development paths are proposed, with the aim to provide scientific support for the high-quality development of counties in the YRB.

The remainder of this paper is organized as follows: Section 2 introduces the study area, research methods and data sources. Section 3 analyzes the results. Section 4 presents the discussion, and Section 5 concludes the research.

2 Research methods and data sources

2.1 Overview of the study area

The Yellow River has a total length of 5,464 km. It originates from the northern foot of the Bayan Har Mountains on the Qinghai-Tibet Plateau and flows in a "几"-shaped path through nine provincial-level administrative regions: Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shanxi, Shaanxi, Henan, and Shandong. The river eventually empties into the Bohai Sea at Dongying, Shandong

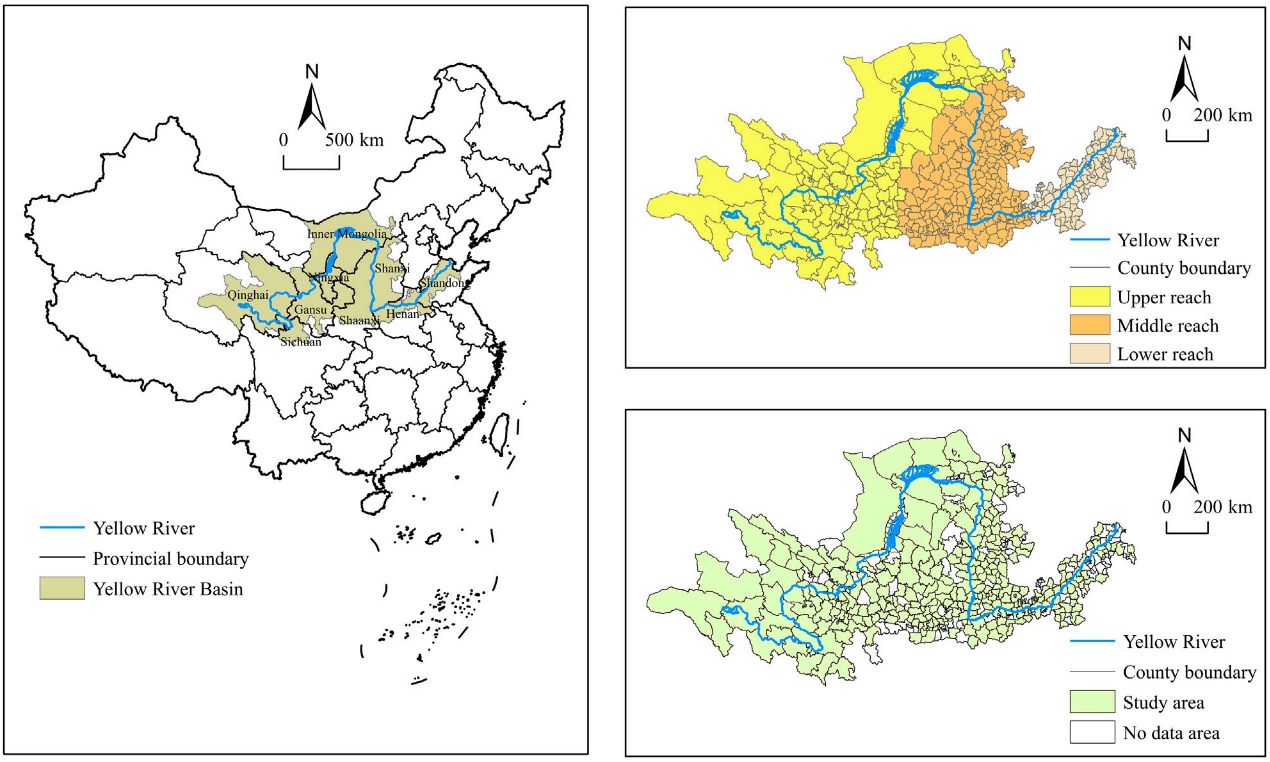

FIGURE 2
Scope of the YRB.

Province (General Office of the State Council of the People's Republic of China, 2021). Depending on the natural environments and hydrological conditions of the areas through which the Yellow River runs, it is divided into upper, middle, and lower reaches by Hekou Town in the Inner Mongolia and Taohua Valley in Henan. The regions through which the Yellow River flows, or its associated irrigation areas, are commonly referred to as the YRB. Referring to the methods of Qin and Ma (2012), and Qiao et al. (2020), this paper defines the scope of the YRB as follows: the scope of the natural basin, delineated by the Yellow River Conservancy Commission of the Ministry of Water Resources and the irrigation districts along the lower reach of the Yellow River. Counted according to the names of the county-level administrative units under China's administrative divisions at the end of December 2019, the YRB involves a total of nine provincial-level administrative regions, 71 prefecture-level administrative units, and 483 county-level administrative units. County-level administrative units occupy a total area of 1.25 million km^2. Due to the severe lack of statistical data in some municipal districts and to ensure comparability between county-level units, this paper selects 318 county-level administrative units (hereafter referred to as "counties" or "county"), excluding all municipal districts, as the final research units (Figure 2).

2.2 Research methods

2.2.1 Indicator system construction

The five types of livelihood capital are the core elements of the SLF and are fundamental to understanding regional development and poverty (Zhao, 2017). At the same time, there are direct or indirect strengthening or weakening relationships between environmental vulnerability and regional livelihood capitals. Therefore, based on SLF and existing relevant research results (Liu and Xu, 2015; Liu and Xu, 2016; Pan et al., 2018; Zhou et al., 2018; Xu et al., 2021; Luo et al., 2022), the construction of the indicator system starts with the five types of livelihood capital and environmental vulnerability. At the same time, considering the development requirements of counties in the YRB and following the principles of scientificity, typicality, comprehensiveness, accessibility, and quantifiability, an indicator system for measuring multidimensional development index (MDI) is constructed. This indicator system is composed of six dimensions and 27 indicators, aiming to provide a comprehensive representation of the counties' multidimensional development levels (Table 1).

Human capital refers to the human resources a county possesses, primarily evaluated from population size and population quality. The number and density of the permanent resident population reflect the population size, while the labor force and educational attainment represent the quality of the population.

Social capital refers to the social resources that can be utilized or possessed for county development. It is mainly assessed from aspects such as market opportunities available to the county, the degree of external connections, the level of attention received, and the state of social activities within the county. Among these, the level of population urbanization and the development of non-agricultural industries reflect the county's stage of social development. The

TABLE 1 Indicator system for measuring the MDI of counties in the YRB.

Dimension	Indicator	Indicator attribute	Weight
Human capital (H)	Size of permanent resident population (X1)	+	4.52%
	Density of permanent resident population (X2)	+	7.08%
	Proportion of labor force population (15–59 years old) (X3)	+	1.90%
	Proportion of population with a junior high school degree or above (X4)	+	2.83%
Social capital (S)	Urbanization rate (X5)	+	2.56%
	Proportion of the output value of non-agricultural industries (X6)	+	1.99%
	Driving distance to the prefecture-level city (X7)	-	1.79%
	Page views ranking of the government website (X8)	-	2.68%
	Nighttime light index (X9)	+	7.87%
Physical capital (*P*)	Railway mileage per unit area (X10)	+	5.71%
	Highway mileage per unit area (X11)	+	3.18%
	Per capita number of beds at medical and health institutions (X12)	+	2.72%
	Per capita number of beds at social welfare institutions (X13)	+	3.90%
	Number of industrial enterprises above designated size (X14)	+	6.78%
Financial capital (F)	Per capita GDP (X15)	+	4.03%
	Per capita revenue from the national general public budget (X16)	+	6.41%
	Per capita disposable income (X17)	+	2.90%
	Per capita balance of savings deposits (X18)	+	2.68%
	Per capita retail sales of consumer goods (X19)	+	3.52%
Natural capital (N)	Per capita cultivated land area (X20)	+	4.68%
	Drainage density (X21)	+	4.20%
	Average temperature in 2001–2020 (X22)	+	2.65%
	Average rainfall in 2001–2020 (X23)	+	2.69%
	Net primary productivity of plants (X24)	+	2.53%
Environmental vulnerability (E)	Average elevation (X25)	-	2.63%
	Average slope (X26)	-	2.83%
	Topographic relief (X27)	-	2.74%

higher the levels of these two indicators, the more market opportunities the county possesses (Liu and Xu, 2015). The driving distance to the nearest prefecture-level city reflects the county's accessibility and external connectivity; the number of visits to the county government's website indicates the level of attention the county receives. The nighttime light data reflects the intensity of human social activities within the county. The stronger the nighttime light data, the greater the development vitality of the county, which can help the county better access resources and promote social coordination (Xu et al., 2021; Liu et al., 2023a).

Physical capital refers to the basic conditions for maintaining socio-economic activities in a county, represented by the relevant indicators of infrastructure, public service facilities, and the production conditions of major enterprises. Specifically, this includes infrastructure indicators such as railway and highway mileage, public service facility indicators like the number of healthcare institutions and social welfare establishments, as well as enterprise production indicators such as the number of industrial enterprises above a designated size.

Financial capital refers to the economic development capacity of a county, measured by the relevant indicators of income, savings, and disposable income. Specific economic indicators include GDP, public budget revenue, disposable income, savings account balances, and total retail sales of consumer goods.

Natural capital refers to the natural resources or conditions a county possesses, represented by the relevant indicators of cultivated land resources, water resources, temperature and rainfall conditions, and plant productivity.

Environmental vulnerability refers to the sensitivity and fragility of a county's natural environment in response to external pressures and disturbances. A vulnerable environment often indicates that the ecosystem of that county is under higher stress or is more difficult to recover after damage. Indicators such as elevation, slope, and topographic relief can be used to reflect the environmental vulnerability of the county (Pan et al., 2018).

2.2.2 Measurement of MDI of counties

Under the constructed indicator system, weights are assigned to various indicators using the entropy method according to the indicator data matrix composed of m counties to be evaluated and n evaluation indicators (Table 1). Thus, the MDI of counties in the YRB is calculated using the following formula:

$$MDI_i = \sum_{j=1}^{n} x_{ij}^{'} w_j \times 100$$

where MDI_i denotes the MDI of the county i, $x_{ij}^{'}$ denotes the normalized value of the indicator j of the county i, and w_j denotes the weight of indicator j. Similarly, the score of a single dimension (SDI_i) can also be calculated by this method according to the specific indicators included in the dimension.

2.2.3 Spatial analysis methods

Spatial analysis methods are primarily used to examine the spatial distribution and spatial correlation characteristics of county development levels in the YRB. In this study, we use the Jenks Natural Breaks method provided by ArcGIS to classify the development levels of counties into five categories: high-value areas, relatively high-value areas, medium-value areas, relatively low-value areas, and low-value areas. This method maximizes inter-class differences and minimizes intra-class differences, making it possible to intuitively identify key breakpoints in the data, comprehensively revealing relative disparities and spatial distribution patterns in development across the YRB (Jenks and Caspall, 1971). We also employ global spatial autocorrelation (Global Moran's I) and local spatial autocorrelation (Local Moran's I) to analyze the overall spatial correlation and specific spatial correlation patterns of county development levels. Global spatial autocorrelation measures whether there is an overall correlation in the distribution of county development levels (Cliff and Ord, 1981). Local spatial autocorrelation further explores spatial heterogeneity, identifying specific spatial correlation types by classifying significant county locations into High-High and Low-Low clusters (indicating counties with similar high or low values grouped together) and High-Low and Low-High outliers (indicating counties where high values are surrounded by low values or low values are surrounded by high values, respectively), while pinpointing their exact locations in the spatial context (Anselin, 1995).

2.2.4 Measurement of differences in county development levels

The Theil Index is employed to analyze the differences in the county development levels in the YRB. The strength of Theil Index lies in its ability to decompose the overall regional differences into internal and external differences across different spatial scales (Wang et al., 2019). In this study, the overall differences in the county development levels in the YRB are decomposed into the differences between counties within each reach, as well as the differences between the reaches. The calculation formulas are as follows:

$$T = \frac{1}{m} \sum_{q} \sum_{i} \frac{y_{qi}}{\mu} log \frac{y_{qi}}{\mu}$$

$$T = \sum_{q} \frac{m_q \mu_q}{m\mu} \frac{1}{m_q} \sum_{i} \frac{y_{qi}}{\mu_q} log \frac{y_{qi}}{u_q} + \frac{1}{m} \sum_{q} m_q \frac{\mu_q}{\mu} log \frac{\mu_q}{\mu} = T_W + T_B$$

$$CT_W = \frac{T_W}{T} \times 100\%$$

$$CT_B = \frac{T_B}{T} \times 100\%$$

in the formulas, T represents the overall Theil Index (i.e., overall differences), T_W signifies the Theil Index of intra-reach differences (i.e., differences between counties within each reach), T_B indicates the Theil Index for inter-reach differences (i.e., differences between the reaches), CT_W is the contribution rate of internal differences within the three reaches, CT_B represents the contribution rate of differences between the three reaches. m represents the number of counties, q represents the specific reach (i.e., upper reach, middle reach, lower reach), m_q denotes the number of counties within each reach, i represents the county, y_{qi} represents the MDI or SDI of county i within reach q, μ denotes the mean of MDI or SDI for all counties in the YRB, μ_q represents the mean of MDI or SDI for counties in the reach q.

2.2.5 Identification of the development types of counties

An accurate identification of the development type of a county is of great importance to clarify the development direction of the county, optimize its resource allocation, and support its high-quality development. Standard deviation is an important measure of data dispersion. Adding a certain multiple of the standard deviation to the mean can represent values slightly above the average level in a data-set, which are generally understood as the better-performing portion of the overall distribution. Thus, we follow the method used in existing literature that identifies the dominant functions or development advantages of regions (Liu et al., 2011; Liang et al., 2023), specifically applying the "mean +0.5 times the standard deviation" as the criterion to determine the development advantages of counties in the Yellow River Basin. When the development index value of a county in a dimension is greater than the sum of the average development index value of all counties in this dimension and 0.5 times the standard deviation, this dimension is referred to an advantageous dimension of the county. The development type of the county is then identified according to the number of advantageous dimensions possessed by the county. To be specific, a county without an advantageous dimension is classified under the weak development type; a county with only one advantageous dimension is classified under the single-dimension-led development type; a county with 2–3 advantageous dimensions is classified under the potential coordinated development type; a county with ≥4 advantageous dimensions is classified under the multidimensional coordinated development type.

It is worth noting that, as this study involves three classification systems for counties in the YRB, a comparison of these three systems has been made in Table 2.

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TABLE 2 Comparison of classification system for counties in the YRB.

Classification name	Basis for the classification	Classification results	Content using this classification
Value grade types	Jenks Natural Breaks	high-value area, relatively high-value area, medium-value area, relatively low-value area, and low-value area	spatial distribution characteristics of development levels
Spatial correlation types	local spatial autocorrelation	HH-type, LL-type, HL-type and LH-type	spatial correlation characteristics of development levels
Development types	mean +0.5 times the standard deviation, the number of advantageous dimensions	weak development type, single-dimension-led development type, potential coordinated development type, and multidimensional coordinated development type	classification of county development types and optimal development paths

2.3 Data sources

The data involved in this paper can be divided into four types: basic geographical information and remote sensing data, station monitoring data, socio-economic statistics, and network data, all of which correspond to the year 2020. Basic geographical information and remote sensing data: Vector data on administrative district boundaries, traffic, and water systems are derived from the National Catalogue Service for Geographic Information (https://www.webmap.cn/commres.do?method=result100W). Based on these data, the railway mileage per unit area, highway mileage per unit area, and river length of each county are obtained. DEM data (90 m resolution) and land use data (30 m resolution) are obtained from the Geographical Information Monitoring Cloud Platform (http://www.dsac.cn/). Based on these data, the average elevation, average slope, topographic relief, and cultivated land area of each county are obtained. The data on net primary productivity of plants (500 m resolution), which are MOD17A3 synthetic data, are extracted from the Level-1 and Atmosphere Archive and Distribution System Distributed Active Archive Center of NASA (https://ladsweb.Nascom.Nasa.gov). Nighttime light data are derived from the Earth Observation Group under the National Oceanic and Atmospheric Administration (https://eogdata.mines.edu/products/vnl/). To obtain stable nighttime light data, through data clipping and projection transformation (500 m resolution), the national cell pixel radiation threshold were set to 472.86, and cells with a negative pixel value were removed to calculate the nighttime light data of each county in 2020. Station monitoring data: Temperature and rainfall data are extracted from the China Meteorological Data Network (http://data.cma.cn/). The annual average temperature and rainfall data of each county are obtained by performing spatial interpolation on the data collected by meteorological stations throughout the country from 2001 to 2020 and calculating average statistics by counties. Socio-economic statistics: Population-related indicators are extracted from the Seventh National Population Census of China in 2020. The remaining socio-economic indicators are mainly derived from the China County Statistical Yearbook (2021). In specific cases, the data extracted from relevant provincial and municipal statistical yearbooks or the Statistical Communiqué of the People's Republic of China on the National Economic and Social Development serve as supplement. Network data: The data on the driving distance to the nearest prefecture-level city are obtained from the driving path planning interface of Amap (https://lbs.amap.com/api/webservice/guide/api/direction/). The data on the page views ranking of the government website are extracted from the SimilarWeb platform (https://www.similarweb.com). The platform has more than 1,000 data sources, ensuring data quality and the accuracy of the analysis. Website quality can be efficiently compared and assessed by analyzing website traffic information (e.g., traffic ranking and traffic source) and user stickiness (e.g., time on site and bounce rate).

3 Results

3.1 Spatial distribution characteristics of development levels

First, the development index measurement method is adopted to calculate the MDI of each county in the YRB, as well as its SDI in the following six dimensions: human, social, physical, financial, natural, and environmental. Depending on their MDI or SDI values, counties are then divided into five grades according to the Jenks Natural Breaks method: high-value areas, relatively high-value areas, medium-value areas, relatively low-value areas, and low-value areas. Finally, their results are visualized spatially using ArcGIS (Figure 3).

From an MDI perspective, counties in the YRB have a low overall multidimensional development level, with an average MDI of only 0.30. The total proportion of high-value areas and relatively high-value areas is only 30.50%. Overall, there is a spatial distribution pattern of "high in the east and low in the west". Quantitatively, the proportions of high-value areas, relatively high-value areas, medium-value areas, relatively low-value areas, and low-value areas are 8.49%, 22.01%, 28.93%, 26.73%, and 13.84%, respectively. Spatially, the high-value areas and relatively high-value areas of MDI are concentrated in the middle and lower reaches of the YRB, and only 3.09% of the counties involved are located in the upper reach. For example, Zhongmu County, Huantai County, and Guangrao County in the lower reach and Yima City, Gongyi City, and Xinmi City (county-level) in the middle reach all ranked among the top 10 in terms of MDI. Simultaneously, all low-value areas are distributed in the upper reach. For example, Gande County, Chengduo County, Jiuzhi County, and Dari County are all ranked among the bottom 10. The average MDI scores of the upper, middle, and lower reaches are 0.22, 0.31, and 0.39, respectively. Because of the vulnerable ecological environment and weak infrastructure, the destitute areas in the upper reach of the YRB are contiguous. More than 70% of the counties there belong to the concentrated and contiguous poverty-stricken areas

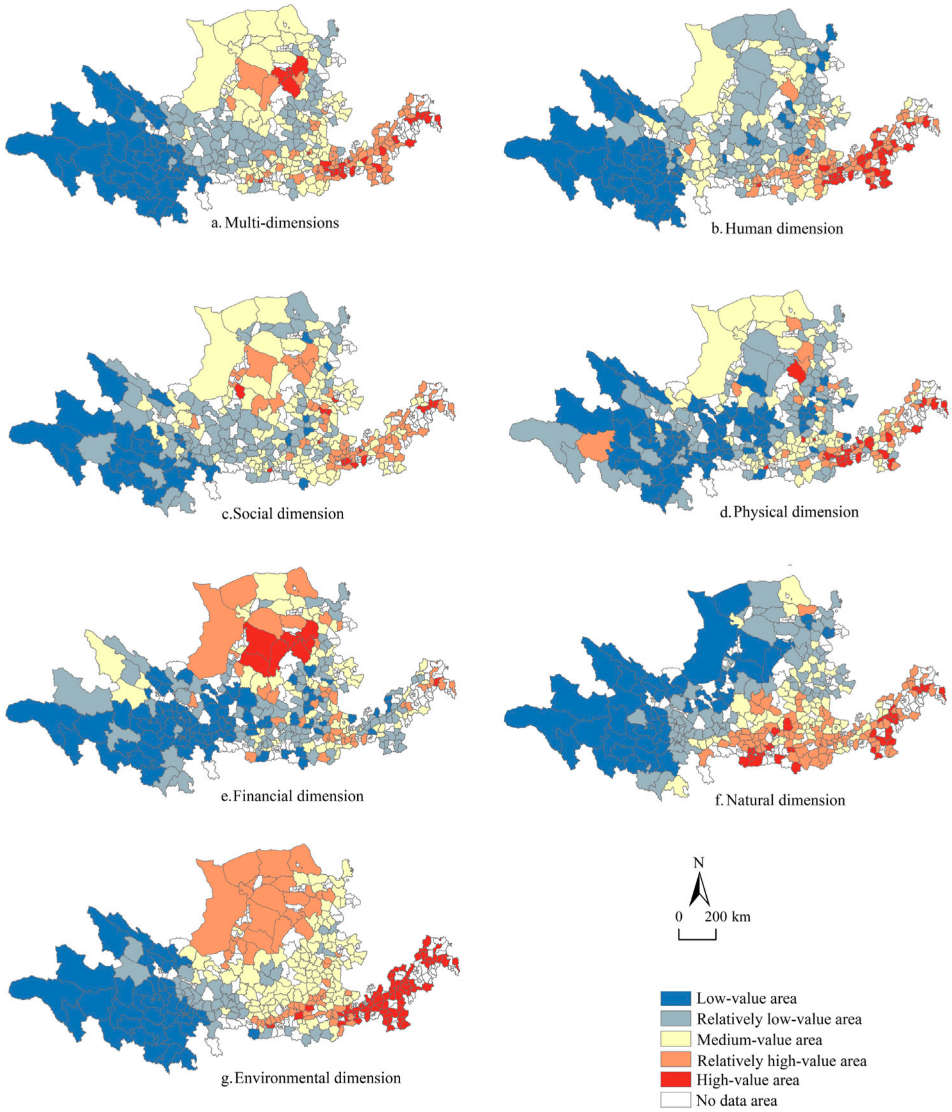

FIGURE 3
Spatial distribution characteristics of development levels of counties in the YRB. **(A)** Multi-dimensions. **(B)** Human dimension. **(C)** Social dimension. **(D)** Physical dimension. **(E)** Financial dimension. **(F)** Natural dimension. **(G)** Environmental dimension.

designated by the Chinese government, including the Tibetan areas in Qinghai, Sichuan, Yunnan and Gansu provinces, and the Liupanshan Mountain area. The lower reach is dominated by plains and hills, characterized by a dense population, concentrated cities, convenient infrastructure, and high overall development levels. The middle reach involves the mountainous areas of the Lvliang Mountains and the Qinba Mountains (the Funiu Mountains) and other concentrated and contiguous poverty-stricken areas. Several counties face the problems of scarcity of water resources, poor coupling of soil and water elements, and complicated geological conditions. The middle reach is somewhere between the upper and lower reaches in terms of multidimensional development levels.

In terms of each dimension, the average value ranking of lower reach > middle reach > upper reach is observed in each dimension, except for the financial dimension (which shows the ranking of middle reach > lower reach > upper reach). Specifically, the average score of the human dimension is 0.04; its high-value areas are mainly located in lower-reach Shandong Province and Henan Province, each of which has a large population and enjoys great advantages in population size and density. Low-value areas are mainly located in the areas populated by ethnic minorities in upper-reach Qinghai Province and Gansu Province. Each of these provinces has a vast territory sparsely populated by a poorly educated population. The average score of the social dimension is 0.06, and its two extreme-value areas, i.e., high-value areas and low-value areas, account for a low proportion. To be specific, its high-value areas are dispersed in six provinces in the upper, middle, and lower reaches, while its low-value areas are concentrated in Qinghai Province and Gansu Province. Counties of this type have been confined within a relatively isolated socio-economic environment for a long time; therefore, human activities in these counties are relatively limited, have a low intensity, and the overall social development is recessive. The average score of the physical dimension is 0.04, and the low-value areas and relatively low-value areas of this dimension involve a substantially expanded scope, accounting for more than 50% of the total number of counties. However, they are still concentrated in the middle and upper reaches of the YRB, suggesting that counties in these two reaches generally have weak public services and infrastructure and need to improve their infrastructure construction. The average score of the financial dimension is 0.04, and the total proportion of its low-value areas and relatively low-value areas is further expanded (exceeding 60%), involving the upper, middle, and lower reaches. Its high-value areas only involve eight counties, including Ejin Horo Banner, Jungar Banner, and Otog Banner. Counties of this type are rich in coal resources and have high levels of regional economic development as well as living standards for people. The average score of the natural dimension is 0.06. The spatial distribution of value areas at each grade is relatively concentrated, and the spatial distribution pattern of "high in the east and low in the west" is more apparent. The lower reach is rich in cultivated land resources because of its superior water, soil, climatic, and biological conditions, but, as the river reaches progress upstream, its ecological environment becomes increasingly vulnerable. The average score of the environmental dimension is 0.06. Its high-value areas and relatively high-value areas are mainly distributed in the North China Plain, the Hetao Plain, and the Guanzhong Plain, and other areas with low topographic relief. Many low-value areas and relatively low-value areas are clustered around the mountainous areas of the Bayan Har Mountains, the Liupan Mountains, and the Lvliang Mountains.

3.2 Differences in development levels and spatial correlation characteristics

3.2.1 Differences in development levels

The Theil index is calculated and decomposed for the MDIs and SDIs of each dimension (Table 3). The differences among the upper, middle, and lower reaches in these regards are further compared. The results show that the differences between counties in SDIs vary across different dimensions, and that the six dimensions can be ranked in descending order of differences as follows: financial > physical > human > environmental > natural > social. The differences between counties' MDIs are close to those in the development indices of natural and social dimensions. The decomposition of the Theil index shows that the differences in MDIs and SDIs of each dimension (except for the natural dimension) are mainly attributable to intra-reach differences. That is, the differences between counties within each reach are larger than the differences between the three reaches. From the perspective of the contribution rate of intra-reach differences to the overall differences, the financial dimension has the highest contribution rate (91.225%), followed by the social, physical, and human dimensions; the environmental and natural dimensions have the lowest contribution rates (54.789% and 42.668%, respectively). This contribution pattern suggests that the intra-reach differences in the development indices of environmental and natural dimensions are relatively small, mainly because counties within each reach have similar natural environments. The comparison results among the three reaches indicate that the differences in the MDIs and SDIs of each dimension increase in the following order: lower reach < middle reach < upper reach. Specifically, the upper and lower reaches show the most substantial differences in the SDIs of the financial dimension, while the middle reach presents the most substantial differences in the SDIs of the physical dimension.

3.2.2 Spatial correlation characteristics

Both global and local autocorrelation analyses are performed on the MDIs of counties in the YRB and their SDIs in each dimension using Global Moran's I and Local Moran's I. The results show that, in global autocorrelation analysis (Table 4), Global Moran's I pass the 1% significance test for both the MDIs of counties in the YRB and their SDIs in each dimension. This result suggests that the multidimensional development levels of counties in the YRB and their development levels in each dimension are spatially strongly correlated, indicating that there is significant spatial correlation. Additionally, the correlation of counties' SDIs for the social and financial dimensions is weaker than that of other dimensions. Local autocorrelation analysis can detect specific spatial correlation types and their exact locations. Accordingly, significant counties are divided into the four types of HH, LL, HL and LH (Figure 4). Counties identified in multiple dimensions and different dimensions are mostly of type LL (statistically significant clusters of low value areas) or type HH (statistically significant clusters of high value areas). Most of LL-type counties belong to the upper reach of the YRB that used to be key poverty alleviation counties designated by the government. They are mostly distributed in concentrated and contiguous poverty-stricken areas. HH-type counties largely belong to the middle and lower reaches of the YRB. A comparison of the analysis results of different dimensions shows that the distribution of LL-type and HH-type counties in the physical, natural, and environmental dimensions is relatively consistent with that of MDI, i.e., there is spatial coherence, showing a "contiguous" pattern. Notably, the two types of counties in the natural dimension involve wider scopes: The scope of LL-type counties extends eastward, while that of HH-type counties extends westward. In the human dimension, LL-type counties form a spatial pattern of "one big one and three small ones" in the middle and upper reaches of the YRB, involving seven provincial-level regions of Qinghai, Gansu, Sichuan, Ningxia, Inner Mongolia, Shaanxi, and Shanxi. In the social and financial dimensions, especially the financial dimension, HH-type counties are more dispersed than those in other dimensions, involving six provincial-level regions of Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan, and Shandong.

3.3 Classification of county development types and optimal development paths

Depending on the number of advantageous dimensions possessed, counties in the YRB are classified into the following four development types: weak development type, single-dimension-led development type, potential coordinated development type, and multidimensional coordinated development type (Figure 5). On this basis, targeted optimal development paths are proposed with a focus on the specific characteristics of different development types.

TABLE 3 Theil index and its decomposition for the MDIs and SDIs of counties in the YRB.

	T	T_B	CT_B	T_W	CT_W	T_U	T_M	T_L
Multi-dimensions	0.037	0.017	46.112%	0.020	53.888%	0.043	0.016	0.007
Human dimension	0.054	0.020	37.893%	0.033	62.107%	0.054	0.032	0.015
Social dimension	0.036	0.008	22.970%	0.027	77.030%	0.060	0.018	0.010
Physical dimension	0.130	0.035	27.177%	0.095	72.823%	0.112	0.110	0.050
Financial dimension	0.137	0.012	8.775%	0.125	91.225%	0.218	0.100	0.083
Natural dimension	0.037	0.021	57.332%	0.016	42.668%	0.042	0.010	0.004
Environmental dimension	0.048	0.022	45.211%	0.026	54.789%	0.077	0.015	0.001

TABLE 4 Global Moran'I of MDIs and SDIs of counties in the YRB.

	Multi-dimensions	Human dimension	Social dimension	Physical dimension	Financial dimension	Natural dimension	Environmental dimension
Moran'I	0.514	0.521	0.295	0.453	0.235	0.495	0.570
Z-score	36.348	36.981	20.990	32.134	16.924	35.049	40.294
p-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000

3.3.1 Weak development type

Counties of this type exhibit a lack of dominant advantageous dimensions, accounting for 40.88% of the total number of counties. They are primarily characterized by low-value and relatively low-value areas and are mainly distributed in the middle and upper reaches of the YRB. Notably, 80% of these counties were once key poverty alleviation counties designated by the government. These counties face several challenges, including limited resource and environmental carrying capacity, underdeveloped infrastructure and public service facilities, weak industrial foundations, human resource shortages, and a persistent tension between ecological protection and socio-economic development. As a result, their MDIs show significant potential for improvement. To address these challenges, it may be beneficial for them to explore local development characteristics, coordinate available resources, and create dominant advantages to stimulate development. Specifically, they could prioritize ecological protection and restoration while working to improve the quality of the ecological environment (Liu et al., 2023b). Strengthening infrastructure and improving basic development conditions would also be important for supporting growth. Meeting the population's needs in health, education, and other essential services, as well as enhancing public service capacity, could improve overall living conditions (Ma and Yang, 2024). Leveraging local resources to foster green development in key sectors such as agriculture, processing, and tourism could help drive economic growth (Gao and Zheng, 2024). Engaging with national initiatives such as the Belt and Road Initiative, promoting regional cooperation, and leveraging the advantages of regional central cities could further stimulate development (Chen et al., 2023). Additionally, counties that have exited poverty may focus on consolidating and expanding their poverty alleviation gains while integrating these efforts with rural revitalization strategies to foster endogenous growth and improve their overall development levels (Ma and Mu, 2024).

3.3.2 Single-dimension-led development type

Counties of this type have a single advantageous dimension, accounting for 19.81% of the total number of counties, with most falling within medium-value areas. These counties are mainly located in the middle reach of the YRB. Based on the specific advantageous dimension, these counties can be further classified into H type, S type, *P* type, F type, N type, and E type counties, each named after the advantageous dimension. For counties in these categories, the focus could be on reinforcing their primary development advantages while also addressing the growth of other dimensions to promote more balanced, multidimensional development. Specifically, H-type counties, with strong human capital advantages, could benefit from leveraging regional labor resources, fostering collaboration between the labor economy and local industries, and utilizing modern information technology to enhance the value of human capital (Xie et al., 2023). S-type counties, with distinct locational advantages and strong social development vitality, could more actively engage in the integrated development of nearby metropolitan areas or urban agglomerations, revitalize local resources, improve infrastructure, promote industrial transfer, and strengthen economic linkages both domestic and international (Chen et al., 2023; Li et al., 2024). P-type counties, which have relatively favorable basic conditions for socio-economic development, might focus on further boosting local development drivers and enhancing the momentum for growth (Ma and Yang, 2024). F-type counties, whether resource-rich or resource-exhausted areas, face significant pressures for sustainable development. Resource-rich counties may prioritize green development alongside resource and energy production, while also considering comprehensive ecological governance. These counties might explore pathways for transformation that prioritize low-carbon, green, and sustainable growth (Pang et al., 2024). In contrast, resource-exhausted counties could consider developing substitute

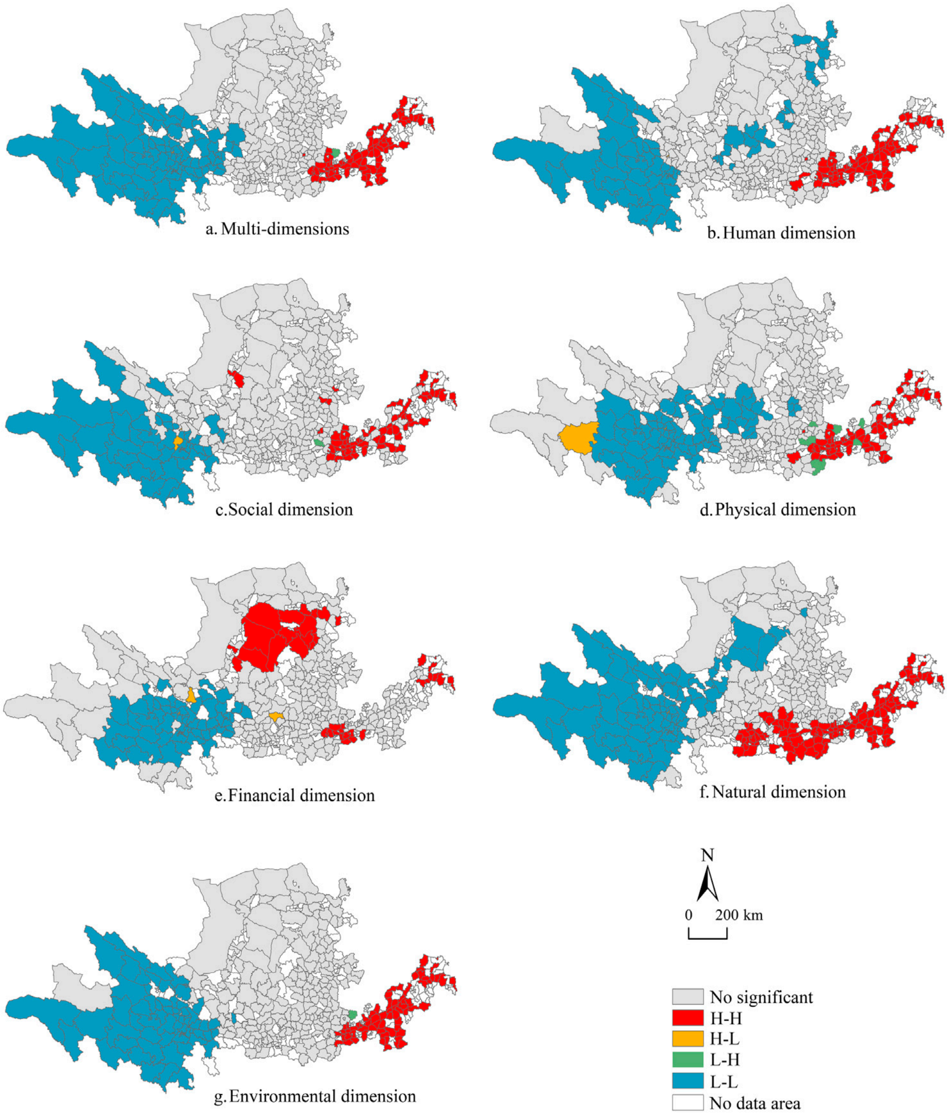

FIGURE 4
Spatial correlation characteristics of development levels of counties in the YRB. **(A)** Multi-dimensions. **(B)** Human dimension. **(C)** Social dimension. **(D)** Physical dimension. **(E)** Financial dimension. **(F)** Natural dimension. **(G)** Environmental dimension.

industries, diversifying their industrial base, and advancing ecological restoration and environmental remediation in mining areas (Cui et al., 2024). N-type counties, primarily mountainous regions with abundant plant resources, could consider developing characteristic agriculture, enhancing local agricultural products, and promoting the integration of agriculture with other sectors, such as industry and services (Gao and Zheng, 2024). E-type counties, mostly traditional plain agricultural counties with long-standing history and culture, are important grain-producing regions. It could be beneficial to promote moderate-scale agricultural operations and extend the agricultural industrial chain (Lu et al., 2021).

3.3.3 Potential coordinated development type

Counties of this type have 2–3 advantageous dimensions, predominantly consisting of medium-value areas and relatively high-value areas. They account for 18.24% of the total number of counties, with 18 distinct combinations of advantageous dimensions, including H-N-E, S-P-F, H-P-E, S-F, H-E, F-E, *etc.* In addition to maintaining their development advantages, counties of this type may also focus on addressing weaker areas to support multidimensional coordinated development. As counties of this type involve 18 combinations of advantageous dimensions, only H-N-E and S-F (two combinations covering large numbers of counties) are taken as examples to explore the optimal development paths. From a shared perspective, both H-N-E and S-F counties face the common challenge of limited physical capital, which is also a widespread issue among many counties in the potential coordinated development type. To address this, it may be necessary to prioritize infrastructure development, with an emphasis on meeting practical needs and promoting urban-rural integration. This could enhance public service delivery

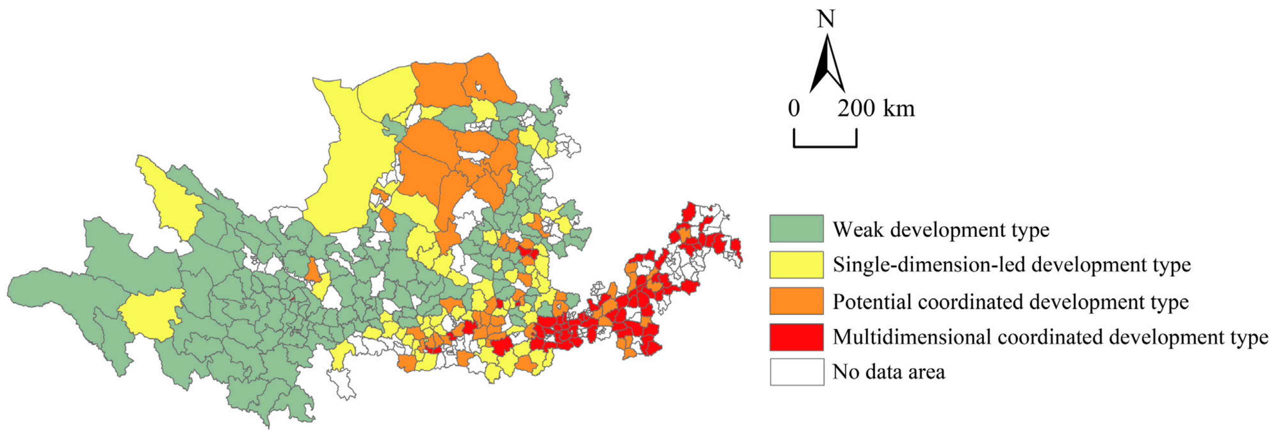

FIGURE 5
Development types of counties in the YRB.

and improve the infrastructure environment, thus supporting socio-economic development (Ma and Yang, 2024). When examined individually, H-N-E-type counties possess rich human resources and favorable agricultural conditions but are constrained by low social vitality and limited economic strength. In response, these counties may explore diversifying agricultural functions, improving the quality of agricultural development, promoting the growth of secondary and tertiary industries, optimizing industrial structure, advancing new urbanization, and facilitating the integration of the agricultural labor force into local industries (Lu et al., 2021). By contrast, S-F counties may prioritize the protection and restoration of the ecological environment as a foundation for promoting industrial transformation through green development (Liu et al., 2023a). Additionally, these counties might benefit from enhancing the employment environment to attract and retain talent, while improving living conditions to support sustainable development (Jin et al., 2022; Xie et al., 2023).

3.3.4 Multidimensional coordinated development type

Counties of this type have ≥4 advantageous dimensions, and are dominated by relatively high-value areas and high-value areas. These counties account for 21.07% of the total number of counties and are mainly distributed in the middle and lower reaches of the YRB. They involve 13 combinations of advantageous dimensions, including H-S-P-F-N-E, H-S-P-N-E, S-P-F-N-E, and H-S-N-E, *etc.* Counties of this type may focus on strengthening their development advantages and building high-quality development demonstration areas, which could serve as models for other counties in the YRB to achieve multidimensional coordinated development. Data from this study shows that only 44.78% of these counties have a clear advantage in the financial dimension, while at least 77% exhibit strengths in other dimensions. This suggests that the financial dimension represents a relative weakness for these counties. To address this imbalance and further enhance economic development, these counties could focus on optimizing the allocation of production factors between urban and rural areas, supporting industrial transformation and upgrading, and strengthening industrial platforms to foster sustainable growth (Khan and Cui, 2022).

4 Discussion

As the basic units of state governance and socio-economic development, counties play a pivotal role in the country's economic, social, ecological, and cultural systems. The healthy development of counties is crucial for the sustainable development and stability of the entire nation. With the comprehensive implementation of the ecological protection and high-quality development strategy in the YRB, the coordinated development of human-environment relationships in the basin has increasingly attracted attention from both academia and local governments. Therefore, based on SLF and by comprehensively utilizing geospatial, socio-economic, and other multi-source data, this study assesses the multidimensional development levels and spatial differentiation characteristics of counties in the YRB from six dimensions (i.e., human, social, physical, financial, natural, and environmental) and proposes targeted optimal development paths. This study is of great significance for promoting human-environment, urban-rural, and spatial coordination in the YRB, and the research findings can provide effective scientific support for ecological protection and high-quality development in the region.

Compared with previous studies, the potential innovations of this research are as follows: On the one hand, although this study builds on previous research that measured multidimensional development or poverty levels based on the five types of livelihood capital and environmental vulnerability under SLF, it further optimizes and refines the selection of specific indicators. This is mainly reflected in the use of the latest data from Seventh National Population Census of China to represent the characteristics of population size and quality of counties under the dimension of human capital, which ensures that the population-related data is more accurate and up-to-date. Under the social capital dimension, the study uses page views of the government websites to represent external attention to counties, which is a reasonable application of internet big data. This approach combines big data with traditional small data to represent regional development levels more comprehensively. On the other hand, compared with previous studies related to the development of the YRB, which were mostly conducted at the prefecture-level scale and focused on single dimensions such as economy, industry, or ecology, or the coupled coordination of two dimensions, this research is conducted at the county-level scale, offering a more refined scale of analysis. Moreover, it incorporates more diverse dimensions, providing more precise support for the promotion of the ecological protection and high-quality development strategy of the YRB.

The findings of this study have broad potential for practical application. Firstly, the results of the multidimensional development level measurement and optimization paths for counties can provide a scientific basis for local governments in the YRB when formulating medium- and long-term development plans. This will help counties tailor their policies to local conditions, allocate resources efficiently, and promote coordinated economic, social, and ecological development. Secondly, the results of this research can also provide theoretical support for the design and implementation of ecological protection projects, poverty alleviation policies, and regional development strategies, facilitating effective cooperation and coordination among various stakeholders to achieve sustainable development goals for the region. Finally, the methodology of this study is not only applicable to the YRB but can also be extended to similar regions globally that face comparable contradictions in resource environments and socio-economic development. The experiences and conclusions drawn from this research can serve as a reference for these countries in formulating relevant policies.

However, this study also has certain limitations. On the one hand, due to the non-continuous nature of some indicator data—such as population census data, which is conducted every ten years—the educational attainment and working-age labor force of the permanent resident population involved in this study cannot be updated annually. Additionally, some indicators, such as elevation, slope, and topographic relief, show little change across years. Therefore, this research analyzes the multidimensional development status of counties in the YRB based solely on cross-sectional data, which does not fully reflect the dynamic changes in county development processes. On the other hand, due to workload restrictions, this study offers no field research on typical counties of different types as case studies, for which there is a lack of details about the multi-dimensional development modes and paths for different types of counties.

5 Conclusion

Firstly, an MDI measurement indicator system is constructed for counties in the YRB under the SLF. Then, the multidimensional development levels and spatial differentiation characteristics of these counties are analyzed. On the basis of identifying the advantageous factors of county MDI, counties are classified into four development types. Finally, targeted optimal development paths are proposed. The main conclusions are as follows:

(1) Counties in the YRB have an average MDI of 0.30 and a low overall multidimensional development level, presenting a spatial distribution pattern of "high in the east and low in the west" overall. In terms of each dimension, the average development index of each dimension falls within the range of 0.04–0.06. And the average value ranking of lower reach > middle reach > upper reach is observed in each dimension, except for the financial dimension (which shows the ranking of middle reach > lower reach > upper reach).

(2) Significant development differences exist between counties in the YRB in the financial and physical dimensions. The differences in MDIs and SDIs of each dimension (except for the natural dimension) are mainly attributable to differences between counties within each reach, while the differences between reaches are non-significant. From the perspective of the distribution in the three reaches, the most significant differences in the development indices are observed between counties in the lower reach.

(3) The multidimensional development levels of counties in the YRB and their development levels in each dimension are strongly correlated spatially. And significant counties identified across multiple and different dimensions are predominantly LL-type, mainly located in the upper reach of the YRB and previously key national-level poverty-stricken counties, and HH-type, primarily situated in the middle and lower reaches of the YRB.

(4) Counties in the YRB are classified into four development types, namely, weak development type, single-dimension-led development type, potential coordinated development type, and multidimensional coordinated development type. Counties of the weak development type may seek to cultivate dominant advantageous dimensions to stimulate development. Those of the single-dimension-led development type could focus on reinforcing their primary development advantages while also addressing the growth of other dimensions. Counties of the potential coordinated development type might focus on addressing weaker areas to foster more balanced development. Those of the multidimensional coordinated development type could serve as models, demonstrating the benefits of integrated, multidimensional development.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

LC: Conceptualization, Formal Analysis, Data curation, Writing–original draft. LM: Methodology, Data curation, Validation, Formal Analysis, Writing–review and editing. JQ: Conceptualization, Project administration, Funding acquisition, Writing–review and editing, Supervision. XL: Methodology, Visualization, Software, Writing–review and editing.

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