Study on the Assessment of the Development Level of Digital Economy in the Yellow River Basin Economic Zone and the Evolution of Time and Space

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Abstract:Based on the Statistical Classification of the Digital Economy and Its Core Industries (2021) and considering the characteristics of the Yellow River Basin Economic Belt, this paper selects 25 secondary indicators from 5 dimensions (digital infrastructure, digital industrialization, industrial digitization, digital innovation and agricultural modernization). A scientific and practical evaluation index system of digital economy development is constructed to accurately measure the digital economy development level of the Yellow River Basin Economic Zone. The entropy weight TOPSIS method was used to calculate the comprehensive evaluation index of the digital economy development level of nine provinces and regions in the Yellow River Basin Economic Belt from 2012 to 2022. On this basis, ArcGIS software is used to draw the visualization map of the digital economic development level of the provinces and regions in each year, measure the relative gap of the digital economic development level with the help of Dagum Gini coefficient method, and portray the absolute gap and dynamic evolution characteristics of the digital economic development level based on the kernel density estimation method. The main conclusions are obtained: 1. Digital economy differences: the Yellow River Basin has significant differences in the level of digital economy, with the east leading and the west lagging behind, affected by multiple factors. 2. Development trend: the digital economy continues to improve from 2012 to 2022, showing a trend of polarization, with the spatial gap gradually narrowing but the differences widening. 3. Changes in the inter-regional differences: the gap in the upstream and downstream digital economy increases and then decreases, and the internal inequalities are decreasing year by year but the widening of inter-regional differences is the main feature.

Keyword:Digital economy; Yellow River basin; space-temporal evolution; Gini coefficie

1. Introduction

At present, the digital economy has become one of the main engines of global economic development. With the rapid development of information technology, the digital economy is playing an increasingly important role around the world. In China, the 14th Five-Year Plan establishes as the core of the national strategy the construction of a new development pattern in which the domestic general cycle is the mainstay and the domestic and international double cycles are mutually reinforcing. In this new development context, the digital economy is regarded as a key force driving the transformation of the economic development model, which is not only shaping the competitive landscape of the global economy, but also becoming an important engine for social progress. As the second largest economy in the world, China's digital economy development is crucial to economic transformation and innovative development. As one of the important economic zones in China, the level of digital economy development in the Yellow River Basin has a direct impact on the competitiveness and sustainable development of the regional economy.

The development of the digital economy is crucial to the flourishing of regional economies. With China's rapid economic growth and accelerated urbanization, central cities and city clusters play an increasingly important role in supporting economic development. The Yellow River Basin, as an important agricultural base and a key economic region in China, plays a pivotal role in the digital economy.

The potential role of digital economy as an important force to promote the sustainable development of the Yellow River Basin cannot be underestimated. Its efficient, green and intelligent features provide a new path for industrial upgrading, resource optimization and ecological governance in the Yellow River Basin. Through big data, cloud computing and other technical means, accurate monitoring and efficient utilization of natural resources in the Yellow River Basin can be realized, thus improving the efficiency of resource utilization. At the same time, the digital economy also helps to promote industrial collaboration and regional integrated development within and outside the Yellow River Basin, and promotes the formation of a green, low-carbon and circular economic development model.

The rise and development of the digital economy has had a profound impact on the economic structure and industrial landscape. With the continuous progress of information technology, the digital economy has become one of the main driving forces of global economic growth. Digital economy not only promotes the upgrading and transformation of traditional industries, but also gives rise to new industries and business forms, and greatly promotes innovation and development. In this context, the digital economy is of great significance to the development of the Yellow River Basin, helping to enhance the competitiveness and sustainable development of the regional economy.

However, due to geographical conditions and historical legacy problems, the economic development of the Yellow River Basin is relatively lagging behind, the industrial structure is not optimized enough, and the innovation ability needs to be improved. As an emerging industry, digital economy is of great significance in promoting the economic transformation and upgrading of the Yellow River Basin. Therefore, an in-depth study of the development status and characteristics of digital economy in the Yellow River Basin is of great significance for the formulation of corresponding policies and the adoption of effective measures. The development of digital economy in the Yellow River Basin faces a series of challenges, including urban-rural differences, insufficient infrastructure development, and talent shortages, which limit the development potential of digital economy and affect the positioning and role of the Yellow River Basin in the new development pattern.

The level of development of digital economy not only reflects the current status of economic development of a region, but also affects its future development direction and potential. As an important economic region in China, the development of digital economy in the Yellow River Basin is of great significance in promoting the transformation and upgrading of the regional economy, improving economic competitiveness and enhancing the innovation ability. Therefore, an in-depth study of the development status and characteristics of the digital economy in the Yellow River Basin, and an exploration of its impact mechanism and path of action on regional economic development are of great significance in promoting the healthy development of the digital economy in the region and the sustainable growth of the regional economy.

This thesis aims to explore the role mechanism of digital economy in the economic development of the Yellow River Basin from the perspective of comprehensively measuring the level of development of digital economy and in-depth analysis of the law of spatial and temporal evolution, and to provide theoretical support and practical guidance for the sustainable development of the region's economy. The rise of digital economy not only brings new development opportunities, but also new challenges and problems. With the advancement of technology and popularization of applications, the development of digital economy in the Yellow River Basin faces many challenges[12], such as digital divide, data security and privacy protection. Therefore, in-depth study of the current situation and problems of the development of digital economy and exploration of solutions are crucial for promoting the digital economy.

This study aims to deeply analyze the development level of digital economy and its spatio-temporal evolution characteristics of nine provinces in the Yellow River Basin between 2012 and 2022. By adopting advanced methods such as kernel density estimation and Dagum's Gini coefficient, it will reveal the development trend and regional differences of the digital economy in the Yellow River Basin, provide scientific decision-making support for the government and policy makers, and promote the healthy, stable and sustainable development of the digital economy in the region and even the whole country. Through comprehensive measurement and in-depth analysis of the development level of digital economy in the Yellow River Basin, it will provide theoretical support and practical guidance for promoting the economic transformation and upgrading of the region[24], and enhancing its competitiveness and sustainable development capability.

2. Literature review

The digital economy is a new type of economic form that promotes economic development by realizing the digital transformation of economic activities through the innovation and application of digital technologies. It covers all areas of production, distribution, exchange and consumption using digital technologies and information networks, and has become one of the main engines of global economic growth. Against this background, the rise of the digital economy in China, the world's largest developing country, is of great significance to its economic transformation and global impact. However, although many studies have been conducted to explore various aspects of the digital economy, in-depth studies on the assessment and spatial change characteristics of the digital economy in specific regions are still insufficient. Therefore, the purpose of this paper is to explore the current status and trends of the development of the digital economy and its spatial change characteristics in specific regions through a review of relevant literature, with a view to providing new perspectives and theoretical support for deepening the understanding of the field.

Kuang Jinsong et al. constructed an index measurement system from the three dimensions of digital economy infrastructure, technology level, and benefit scale, and measured the digital development index at the national and provincial levels from 2005 to 2017[1]. The results show that the digital development of the provinces and regions shows a trend of parallel progress, but the gap is still widening. For their part, Zhou Rongjun et al. took Henan Province as an example and analyzed the digital economy development of 18 prefecture-level cities during the period of 2015-2020[2]. They found that although the overall digital economy maintains steady growth, the development space is limited and the regional differences are significant. In addition, some researchers defined the connotation of digital economy from the macro, meso and micro levels and constructed an evaluation index system[3]. Some scholars also constructed a digital economy evaluation index system from the three dimensions of digital infrastructure, industrial development and environment[4]. They revealed two types of "evolutionary constancy" and "evolutionary regression" in China's regional digital development. Xia Chunfang et al. measured the index data related to the digital economy in the western region through the three-dimensional evaluation system of digital foundation, digital industry, and data environment[14], combined with the entropy value method[5]. Shan Zhiguang et al. established a three-dimensional spatial evaluation system, designing the information cyberspace, entity physical space, and human social space dimensions to expand the space of the digital economy evaluation system[6].

Wang Yanjie et al. (2023)[7], on the other hand, from the perspective of the digital economy, use panel data to measure the industrial concentration of China's digital economy and analyze its evolutionary characteristics. The concentration of China's digital economy industry, digital economy manufacturing industry and digital economy service industry all belong to the very high oligopoly type, with obvious differences in spatial distribution. In addition, digital economy industry concentration has obvious spatial positive correlation, and the radiation and proximity effects of the eastern region can significantly affect the spatial concentration development of digital economy industry in the neighboring regions. Most scholars use panel data to apply Moran′sI index, Markov model, and Terrell index to conduct empirical analysis; Liang Maolin et al. study the evolution of spatio-temporal pattern from the relationship of geo-economy[8]; Wang Yanjie et al. focus on the agglomeration characteristics of digital economy industry; and adopt spatial mismatch correction and spatio-temporal evolution analysis methods to reveal the polarization characteristics of the digital development of the 30 provinces in China. Shen Yang et al, on the other hand, measured the level of digital economy development of 30 provinces from 2013-2019 through global time-series factor analysis[9],they found significant spatial positive correlation among provinces and the gradual evolution of digital foundation, application, innovation and benefits.

In summary, it can be seen that the current research on China's digital economy has been relatively rich, but there are still the following deficiencies. First, after in-depth research and analysis of many papers found that in the measurement of the level of digital economic development[13], these existing methods and indicators are often difficult to comprehensively and accurately reflect the real situation of digital economic development. There is also a lack of specific analysis of the development pattern of specific economic regions, which leads to bias in the assessment of the level of digital economic development. Second, in the study of spatial and temporal evolution often lacks an in-depth exploration of the intrinsic mechanisms and development laws of the digital economy. At the same time, the research scale mainly involves the level of provinces and urban agglomerations, and there are relatively few researches in the scope of watersheds, while watersheds, as a link between different regions, play a key role in the coordination of regional development, and the Yellow River Basin is an important region of China's economic development that plays an important role in the overall development of the overall situation and strategy[10], so it is of practical significance to study the spatio-temporal pattern of the development of the digital economy in this area, but there is a lack of research on the Yellow River Basin at present.

Compared with the existing studies, the innovation of this paper is to absorb the reasonable dimensions of the existing literature to measure the development of digital economy, synthesize the existing evaluation system to assess the digital economy, add the indicators that can reflect the development status of the digital economy in a specific region, combine the actual situation of the digital economy in the Yellow River Basin with the characteristics of the development of the digital economy, and present the level of development of the digital economy in the nine provinces from the visualization of the different time points, and construct a relatively complete and scientific measurement system. scientific measurement system. With the help of Dagum's Gini coefficient, the spatial evolution of digital economy in the basin is analyzed from the perspectives of overall, inter-group and intra-group differences.

3. Research design

Although the deep integration of digital technological innovation with various industries is being promoted in a comprehensive manner[12], the level and characteristics of digital economic development in the Yellow River Basin Economic Belt, as an important agricultural and industrial base in China, have not yet been fully assessed. Therefore, the goal of this study is to construct a comprehensive regional economic development evaluation index system to accurately measure the level of digital economy development in the Yellow River Basin Economic Belt and to deeply analyze its temporal and spatial evolution characteristics.

The Yellow River Basin Economic Belt shows remarkable features in the development of the digital economy, especially in the process of agricultural digitalization and the leadership of scientific and technological innovation. Agricultural production has been digitally managed and monitored through the application of technologies such as the Internet of Things (IoT), big data and artificial intelligence, thus significantly improving production efficiency and product quality. At the same time, investment in science, technology and innovation and the construction of digital infrastructure, such as high-speed broadband networks and intelligent Internet of Things platforms, are also playing an important role in facilitating the flow and sharing of information and enhancing industrial competitiveness and innovation.

In order to scientifically measure the level of digital economy development, this study will adopt entropy weight TOPSIS method as the evaluation method. This method integrates the objective assignment advantage of entropy weight method and the decision distance measurement characteristic of TOPSIS method, so it is suitable for dealing with multi-indicator decision-making problems. Specifically, we will collect relevant data from nine provinces in the Yellow River Basin from 2012 to 2022, including, but not limited to, indicators on the degree of agricultural digitization, investment in science, technology and innovation, and infrastructure construction. These data will be derived from government statistical yearbooks, industry reports[16], and relevant academic studies to ensure the comprehensiveness and reliability of the data. By analyzing these data using the entropy weight TOPSIS method, we will be able to comprehensively assess the level of digital economy development in the Yellow River Basin Economic Belt and gain insight into its spatial and temporal evolution characteristics.

3.1. Measurement indicators

For the scientific evaluation of the development of digital economy in the Yellow River Basin Economic Zone, we have constructed a comprehensive and practical evaluation index system. The system is based on the Statistical Classification of the Digital Economy and its Core Industries (2021), with special consideration of the Yellow River Basin's characteristics such as agricultural modernization and digital innovation. We categorized the evaluation indicators into five first-level indicators and 25 second-level indicators, each of which was strictly screened to ensure its relevance, representativeness and accessibility to the high-quality development of the digital economy. The first-level indicators include digital infrastructure, digital industrialization, industrial digitization, digital innovation and agricultural modernization[15], which together constitute a comprehensive framework for evaluating the development of the digital economy.

Specifically, the digital infrastructure indicator focuses on the construction of information and communication networks and data centers, reflecting the physical foundation for the development of the digital economy. Digital industrialization indicators focus on the development of the electronic information manufacturing and software information service industries, reflecting the scale and benefits of the core industries of the digital economy. Industrial digitization indicators measure the degree of integration of traditional industries with digital technologies, such as the application of smart manufacturing and smart agriculture. Digital innovation indicators cover innovation inputs and innovation outputs, reflecting the innovation vitality in the digital economy. The agricultural modernization indicator highlights the application and promotion of digital technologies in agriculture.

To ensure the accuracy and consistency of the evaluation results, we have strictly defined the definition and calculation methodology of each indicator, and have used diverse data sources, including official statistics, industry reports and academic research. All data have been verified and validated to ensure the reliability of the evaluation results. Although the current indicator system has shown good applicability, we are aware of its limitations, such as the timeliness of data collection and regional differences that may affect the evaluation results. Therefore, future research will further optimize the indicator system to meet the needs of rapid development of digital economy and changes in regional characteristics. These efforts will help to provide a scientific and comprehensive assessment of the digital economy development in the Yellow River Basin, thus guiding relevant policy formulation and practice promotion. In summary, this paper constructs the evaluation indicators of digital economy in the Yellow River Basin as shown in Table 1.

Table 1. System of measurement indicators

LevelOneIndicators	SecondaryIndicators	Unit	Attribute
Digitalinfrastructure	NumberofInternetbroadbandaccessports	million	+
	NumberofInternetbroadbandaccessusers	million	+
	Mobilephonebasestationdensity	pcs/km²	+
	Mobilephonepenetration	Department/100people	+
	Thelengthofthelong-distancefiberopticcableperunitarea	million/km	+
	Fixedinvestmentinthesocialdigitalindustry	million	+

Digitalindustrialization	SoftwarebusinessrevenueasapercentageofGDP	%	+
	InformationtechnologyservicesasapercentageofGDP	%	+
	Numberofemployeesintheinformationserviceindustry	million	+
	ThetotalvolumeoftelecommunicationsservicesasaproportionofGDP	%	+
	Enterprisee-commercetransactionvalue	billion	+
Digitalizationoftheindustry	Proportionofenterpriseswithe-commercetransactionactivities	%	+
	Numberofcomputersusedper100peopleinabusiness	person	+
	Numberofwebsitesper100businesses	piece	+
	DigitalFinancialInclusionIndex	/	+
Digitalinnovation	TheR&Dpersonnelofindustrialenterprisesabovedesignatedsizeareequivalenttofull-timeequivalents	person/year	+
	R&Dexpenditureofindustrialenterprisesabovedesignatedsize	million	+
	NumberofR&Dprojects(topics)ofindustrialenterprisesabovedesignatedsize	item	+
	Thetotalvalueofthetechnologycontractturnover	million	+
	Numberofpatentapplicationsgranted	pieces	+
Modernizationofagriculture	Inspectionofagriculturalproductionenvironment	piece	+
	Degreeofelectrificationofagriculturalproduction	RMB/kWh	+
	Thelevelofexpenditureonagriculture,transportation,andcommunications	%	+
	Thenumberandscaleofruralonlinepayments	/	+
	Retailsalesofconsumergoodsinruralareas	%	+

3.2. Data sources

In this paper, nine provinces (Qinghai, Inner Mongolia, Gansu, Ningxia, Sichuan, Shaanxi, Shanxi, Henan and Shandong) in China's Yellow River Basin Economic Belt between 2012 and 2022 are selected as the research sample. The data required for the study mainly comes from authoritative statistical information such as China Statistical Yearbook, China Tertiary Industry Statistical Yearbook, China Electronic Information Industry Yearbook[13], China Industrial Statistical Yearbook, and Peking University Digital Inclusive Finance Index released in previous years, and also refers to the statistical yearbooks and statistical bulletins of each province. For the problem of missing data in some years, this paper adopts trend extrapolation and interpolation to make up reasonable data to ensure the completeness and accuracy of the study.

4. Development level measurement and spatial and temporal evolution modeling

4.1. Entropy weight TOPSIS method of synthesizing measurements

Because the digital economy involves multifaceted indicators, it is difficult for a single indicator to fully reflect its actual situation. In order to be able to comprehensively consider the development of the digital economy from a multi-dimensional perspective, guide decision-making, identify potential problems, conduct comparative and competitiveness analysis, and provide scientific basis and support for the sustainable and healthy development of the digital economy. This paper adopts a comprehensive evaluation method, the determination of its weight is crucial, and common empowerment methods include subjective empowerment method and objective empowerment method. Subjective empowerment methods, such as the expert scoring method, the Delfin method, and the hierarchical analysis method, rely on subjective empirical analysis and are highly subjective;

while objective empowerment methods, such as the entropy weight method, the principal component analysis method, and the negative correlation coefficient method, are based on the data, and the weights change with the changes in the data. In the previous measurement of the level of digital economic development, scholars have used principal component analysis, NBI index assignment method, and factor analysis method. Considering the special characteristics of digital economic development, it is not appropriate to use subjective assignment method, so we choose objective assignment method to determine the index weights from the data itself. In this paper, we refer to the entropy weight TOPSIS method used by Tao Changqi and Xu Mal (2021)[11]to determine the weights of the evaluation indicators through the entropy weight method, and then determine the ranking of the evaluation indicators through the TOPSIS method by directly utilizing the special technique of ideal solution, which combines the objective assignment advantage of the entropy weight method and the decision distance measurement characteristic of the TOPSIS method, and is suitable for dealing with the multi-indicator decision-making problem. The specific implementation steps are as follows.

First, the dimensionless processing of each indicator. In view of the fact that the indicators selected in the text are all positive indicators, the following processing formula is used uniformly.

$$Z_{ir} = \frac{X_{ir} - min\{X_{1r},\ldots,X_{nr}\}}{max\{X_{1r},\ldots,X_{nr}\} - min\{X_{1r},\ldots,X_{nr}\}} \tag{1}$$

Where X_{ir} and Z_{ir} denote the initialized and processed values of the rth indicator for the ith province, n denotes the number of provinces, and $min\{X_{1r},\ldots, X_{nr}\}$ and $max\{X_{1r},\ldots, X_{nr}\}$ denote the minimum and maximum values in the rth indicator for all provinces.

second，Calculate the information entropy of each indicator:

$$E_r = -k\sum_{i=1}^{n}(Z_{ir}/\sum_{i=1}^{n}Z_{ir})ln(Z_{ir}/\sum_{i=1}^{n}Z_{ir}) \tag{2}$$

Third, obtain the weight values for each indicator:

$$W_r = (1-E_r)/\sum_{i=1}^{R}(1-E_r) \tag{3}$$

where R denotes the total number of secondary indicators and W_r denotes the weight value of the rth indicator.

Fourth, a weighted index for each indicator is obtained:

$$Q_{ir} = W_r \times Z_{ir} \tag{4}$$

where Q_{ir} denotes the weighted index of r indicators for the ith province

Fifth, determine the distance D_{ia} and D_{ib} of each observation region from the optimal and the worst regions.

$$D_i^a = \sqrt{\sum_{r=1}^{R}(Q_{ir}^a - Q_{ir})^2} D_i^b = \sqrt{\sum_{r=1}^{R}\left(Q_{ir} - Q_{ir}^b\right)^2} \tag{5}$$

Among them.

$$Q_{ir}^a = max\{Q_{1r},\cdots,Q_{nr}\}, Q_{ir}^b = min\{Q_{1r},\cdots,Q_{nr}\} \tag{6}$$

Sixth, calculate the comprehensive evaluation index of each object to be evaluated and determine the relative proximity of each observed object to the ideal object C_i.

$$C_i = \frac{D_i^b}{D_i^a + D_i^b} \tag{7}$$

Where C_i is the level of digital economic development of the ith object, and the value range is [0,1]. When C_i is closer to 0, it indicates that the development level of commodity circulation in the region is lower; when C_i is closer to 1, it indicates that the development level of commodity circulation in the region is higher.

4.2. Dagum Gini coefficient

The Dagum Gini coefficient is a key tool for analyzing regional disparities and is particularly important in the analysis of regional levels in the digital economy. It can accurately reveal development level gaps and explore the root causes of differences by decomposing differences based on subgroup samples.

Using the Dagum Gini coefficient, we can quantitatively analyze the differences in digital economy development among the provinces in the Yellow River Basin, and clarify the relative positions of the provinces as well as the extent and sources of the differences[19]. The coefficient decomposes the overall disparity into three parts: inter-domain, intra-region and hyper-variable density, which provides us with a comprehensive and detailed analytical framework and helps us to deeply understand and grasp the regional differences in the level of digital economy development and its mechanisms. The formula for the overall Gini coefficient is as follows:

$$G = \sum_{j=1}^{k}\sum_{h=1}^{k}\sum_{i=1}^{n_j}\sum_{r=1}^{n_h}\left|y_{ji} - y_{hr}\right|/2n^2\bar{y} \tag{8}$$

where G is the overall Gini coefficient, k denotes the sequence number of the region (3 in total), n denotes the total number of provinces (9), i and r are provincial subscripts, nj(nh) is the number of provinces in region j(h), yji(yhr) is the level of the digital economy of province i(r) in region j(h), and $\bar{y}$ is the average of the water value of the digital economy development. Dagum Gini coefficients are further decomposed as follows:

To make the Gini coefficient calculations easier, the regional averages of the levels of digital economic development are ranked in order of size

$$\bar{Y}_h \leq \cdots \bar{Y}_j \leq \cdots \leq \bar{Y}_k \tag{9}$$

The Gini coefficient and the contribution of intra-regional differences in district j are shown below:

$$G_{jj} = \frac{1}{2\bar{Y}_j}\sum_{i=1}^{n_j}\sum_{r=1}^{n_j}\left|y_{ji} - y_{jr}\right|/n_j^2 \tag{10}$$

$$G_w = \sum_{j=1}^{k} G_{jj} p_j s_j \tag{11}$$

The Gini coefficient values and contributions between region j and region h are shown below:

$$G_{jh} = \sum_{i=1}^{n_j}\sum_{r=1}^{n_h}\left|y_{ji} - y_{hr}\right|/n_j n_h\left(\bar{Y}_j + Y\bar{Y}_h\right) \tag{12}$$

$\bar{Y}$ represents the average value of the subgroup digital economy . In addition, to construct the Dagum Gini coefficient subgroup decomposition function, the following variables are further defined:

$$D_{jh} = \frac{d_{jh} - p_{jh}}{d_{jh} + p_{jh}} \tag{13}$$

$$p_{jh} = \int_0^\infty dF_h(y)\int_0^y (y - x)dF_j(x) \tag{14}$$

$$d_{jh} = \int_0^\infty dF_j(y)\int_0^y (y - x)dF_h(x) \tag{15}$$

$$P_j = \mathrm{n}_j / n \tag{16}$$

$$S_j = n_j\bar{Y}_j/n\bar{Y} \tag{17}$$

D_{jh} in equation (13) represents the interaction between subgroup j and subgroup h. D_{jh} in E_q. (15) measures the gap in digital economic development between subgroups, which can be regarded as the mathematical expectation of all y_{ji}-y_{hr}>0 in subgroup j and subgroup h. p_{jh} denotes the hypervariable first-order moments

$$G_{nb} = \sum_{j=2}^{k}\sum_{h=1}^{j-1} G_{jh}(p_j s_h + p_h s_j) D_{jh} \tag{18}$$

The contribution of hypervariable density is:

$$G_t = \sum_{j=2}^{k}\sum_{h=1}^{j-1} G_{jh}(p_j s_h + p_h s_j)(1 - D_{jh}) \tag{19}$$

4.3. kernel density estimation method

Kernel density estimation is a non-parametric estimation method that utilizes a smoothed kernel function to fit the probability density of the sample data and show the intrinsic distribution of the data. The method does not rely on a specific model, the results are robust[20], and it can visualize the distribution, shape and evolution of the development level of the digital economy. This paper applies this method to deeply analyze the dynamic evolution of digital economy in the Yellow River Basin Economic Zone. Its formula is concise but effective, realizing the linear superposition of sample points and bandwidth, and obtaining the continuous kernel density estimation curve through weighted average. Its formula is as follows:

$$f(x) = \frac{1}{Nh}\sum_{i=1}^{N} K\left(\frac{x_i - \bar{x}}{h}\right) \tag{20}$$

where N denotes the number of provinces, :x_i denotes independent and identically distributed observations, $\bar{x}$ denotes the mean of observations, and h denotes the bandwidth.

In this paper, the Gaussian kernel function is used for dynamic estimation, which is formulated as follows:

$$K(x) = \frac{1}{\sqrt{2\pi}} e^{-\frac{x^2}{2}} \tag{21}$$

5. empirical findings

5.1. Measurement of the overall level of development of the digital economy in the basin

Using the entropy-weighted TOPSIS method to analyze the 2012-2022 panel data, the digital economy development index of the nine provinces varies significantly, ranging from 0.193-0.636. Eastern provinces such as Shandong, Henan, and Shaanxi are at a higher level of development due to their well-developed digital infrastructures, large number of leading firms, and active technological innovations, while provinces such as Qinghai and Gansu lag behind in comparison. This difference reflects the different dynamics of provinces in the development of digital economy.

Table 2. 22012-2022 Digital Economy Development Level Score by Province

year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Qinghai	0.212	0.236	0.266	0.346	0.365	0.379	0.492	0.558	0.583	0.558	0.560
Sichuan	0.172	0.153	0.210	0.291	0.344	0.402	0.502	0.652	0.726	0.658	0.591
Gansu	0.267	0.212	0.335	0.380	0.424	0.437	0.510	0.593	0.647	0.588	0.548
Ningxia	0.198	0.166	0.229	0.319	0.332	0.450	0.538	0.617	0.681	0.657	0.609
InnerMongolia	0.305	0.275	0.310	0.294	0.335	0.352	0.376	0.465	0.528	0.644	0.476
Shanxi	0.196	0.225	0.238	0.282	0.319	0.333	0.422	0.447	0.525	0.555	0.648
Shaanxi	0.221	0.201	0.288	0.324	0.375	0.426	0.541	0.622	0.707	0.693	0.583

Henan	0.179	0.158	0.227	0.277	0.313	0.351	0.464	0.552	0.677	0.621	0.581
Shandong	0.169	0.137	0.218	0.294	0.332	0.382	0.516	0.545	0.649	0.620	0.612
Meanvalue	0.213	0.196	0.258	0.312	0.349	0.390	0.485	0.561	0.636	0.622	0.579
Maximum	0.305	0.275	0.335	0.380	0.424	0.450	0.541	0.652	0.726	0.693	0.648
Minimum	0.169	0.137	0.210	0.277	0.313	0.333	0.376	0.447	0.525	0.555	0.476

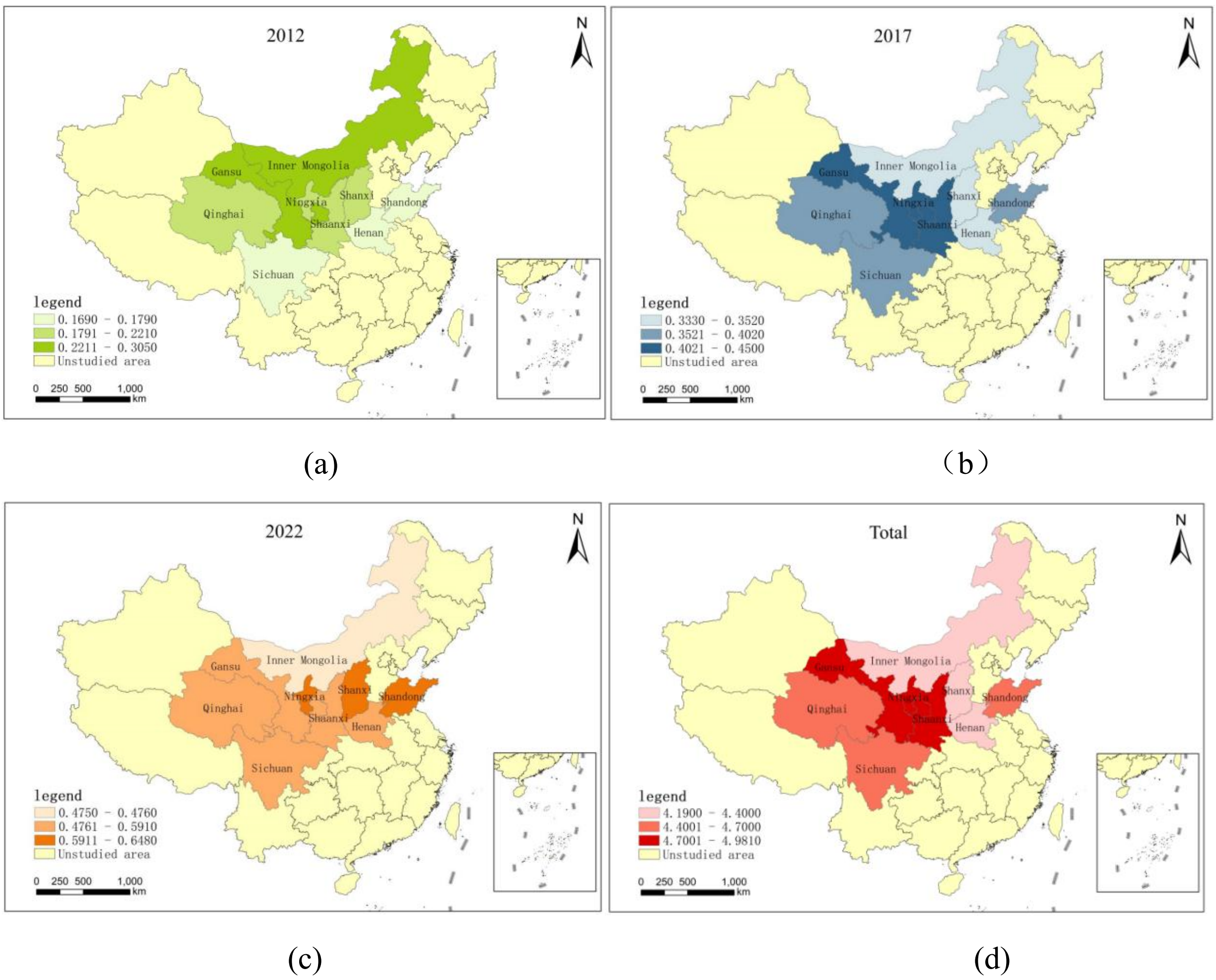

Figure 1. Visual map of the digital economy level of the nine provinces in the Yellow River Basin

The above figure shows the visualization maps of the overall level of digital economy in the Yellow River Basin in 2012 (a), 2017 (b), 2022 (c), and 11 years (d), respectively. In the early stage of digital economy development, the upper Yellow River region, including Gansu, Shaanxi, and Inner Mongolia, demonstrated a high level of digital economy, with a clear advantage over other regions. With the passage of time, regions such as Ningxia and Sichuan have gradually emerged and realized the development and enhancement of the digital economy. By around 2022, the digital economy level of the lower Yellow River regions, such as Henan, Shandong and Shanxi, gradually surpasses that of other provinces, becoming the new high ground of digital economy development in the Yellow River Basin.

Analyzing in-depth the trend of digital economy development in the Yellow River Basin, policy support and resource endowment have promoted the development of digital economy in the initial stage; technological progress and industrial transformation have become the main driving force in the middle stage; and regional economic integration and talent aggregation have played a key role in the near future. Market demand growth, consumption upgrading and infrastructure construction provide strong support. Together, these factors have contributed to the rapid rise and continuous development of the digital economy in the Yellow River Basin, laying the foundation for future economic transformation and upgrading.

5.2. Analysis of the dynamic evolution of the distribution of the level of development of the digital economy

In order to further analyze the trend and spatial evolution characteristics of the digital economy development level of the nine provinces and regions in the Yellow River Basin between 2012 and 2022, this study adopts the three-dimensional dynamic Kernal kernel density form to visualize the digital economy development level scores of the provinces and regions.

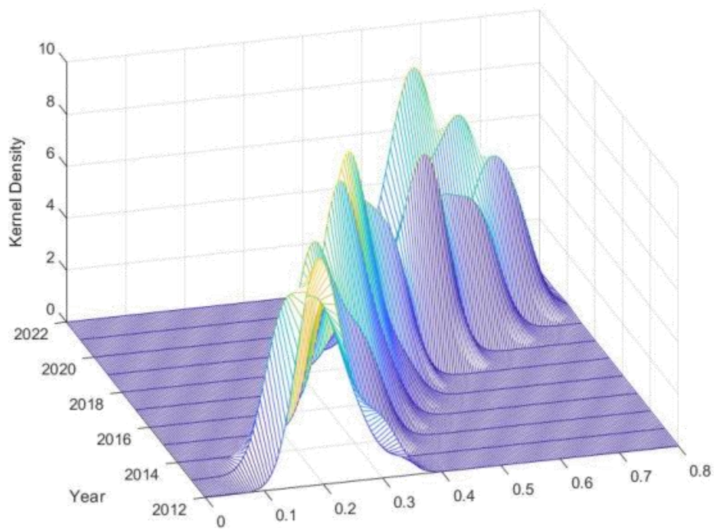

Figure 2. 3 D stereo diagram of nuclear density

The information shown in the root chart indicates that the level of development of China's digital economy has been rising year by year, and the center point of the distribution of the kernel density curve has shifted slightly to the right, signaling a huge potential and space for growth. This change highlights the rise and strong vitality of the digital economy in China's economic system.

At the same time, the peak value of digital economic development in each province rises and the range of wave crests expands, indicating that the level of development tends to be decentralized and more widely distributed. The right trailing phenomenon shows that the digital economy development broadens the ductility and the degree of difference among provinces increases. In the evolution of the wave volume, the level of digital economic development in the nine provinces and regions of the Yellow River Basin is transformed from a single peak to a double peak, and the wave span is flattened to show that there is a trend from non-polarization to bipolarization, with a gradual increase in the number of core provinces. This reflects both the unevenness and the competitive dynamics and potential momentum. In addition, the right trailing phenomenon of the kernel density curve has become shorter year by year, indicating that the spatial gap in the development of the digital economy is narrowing. This is due to policy promotion and market mechanisms, and also reflects synergistic progress and balanced development across regions.

5.3. Characterization of the evolution of regional differences within the basin

According to Dagum's Gini coefficient and its decomposition method, regional differences in the level of digital economic development of the nine provinces in the Yellow River Basin are analyzed, and the results of Gini coefficient measurement are shown in Table 3. In order to more intuitively show the trend of the Gini coefficient and its decomposition[21], the statistical charts of the Gini coefficient for the whole country, intra-region, inter-region and contribution trend are plotted

Table 3 .Results of Dagum's Gini coefficient decomposition

		Within-groupcoefficient			Between-groupcoefficient			Contributionrate(%)		
Year	Overall	Upstream	Downstream	Midstream	Downstream& Upstream	Downstream&Midstream	Midstream &Upstream	Within-groupcontributionrateGw	Between-groupcontributionrateGb	Super-variabledensitycontributionrateGt
2012	0. 108	0. 098	0. 060	0. 105	0. 103	0. 128	0. 120	27. 549%	42. 075%	30. 376%
2013	0. 124	0. 092	0. 085	0. 109	0. 128	0. 167	0. 118	26. 041%	52. 207%	21. 751%
2014	0. 089	0. 103	0. 064	0. 070	0. 104	0. 077	0. 101	29. 578%	24. 735%	45. 687%
2015	0. 055	0. 058	0. 035	0. 028	0. 076	0. 033	0. 075	24. 819%	52. 950%	22. 231%
2016	0. 049	0. 047	0. 040	0. 011	0. 065	0. 034	0. 069	22. 871%	64. 014%	13. 115%
2017	0. 057	0. 032	0. 043	0. 069	0. 046	0. 066	0. 073	27. 899%	27. 460%	44. 641%
2018	0. 057	0. 008	0. 034	0. 081	0. 030	0. 087	0. 085	22. 756%	49. 154%	28. 090%
2019	0. 065	0. 035	0. 030	0. 074	0. 042	0. 087	0. 099	23. 082%	55. 809%	21. 110%
2020	0. 061	0. 049	0. 019	0. 060	0. 044	0. 086	0. 084	22. 807%	57. 070%	20. 123%
2021	0. 040	0. 037	0. 025	0. 037	0. 048	0. 042	0. 042	27. 107%	38. 422%	34. 471%
2022	0. 042	0. 017	0. 012	0. 066	0. 026	0. 055	0. 063	24. 889%	23. 259%	51. 852%

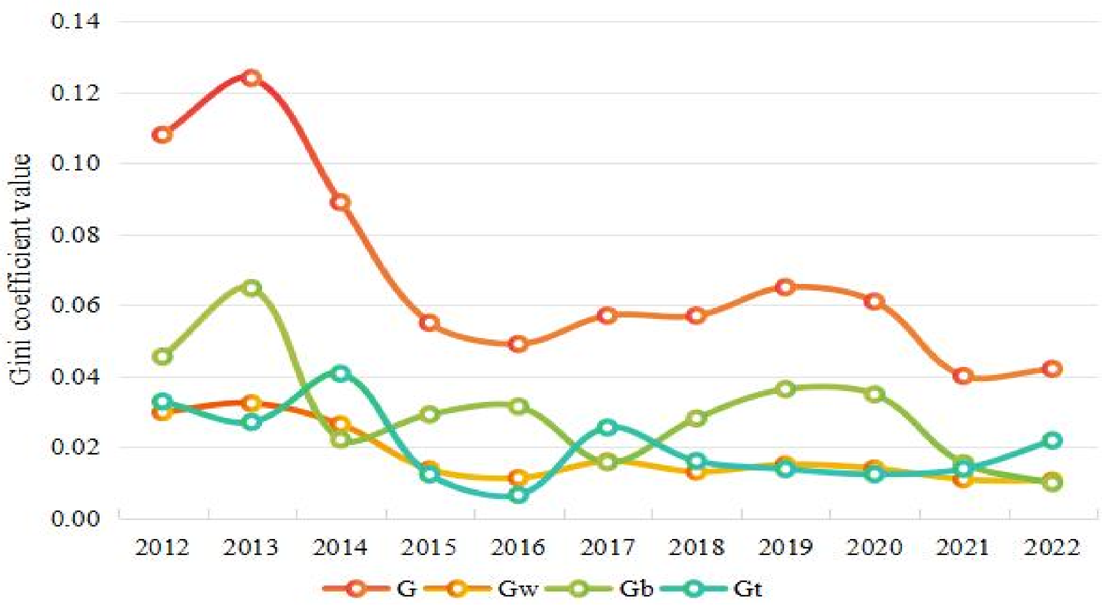

Figure 3. Overall Gini coefficient

In the analysis of overall differences, from the table and figure, it can be seen that the overall Gini coefficient of the digital economy level in the Yellow River Basin from 2012 to 2021 is 0.067, showing a trend of "slight decline - gradual stabilization". Specifically, from 2013 to 2017, the national Gini coefficient decreased from 0.124 to 0.057, indicating that the differences in the level of the digital economy within the basin gradually narrowed during this period; the Gini coefficient was more stable from 2017 to 2019, indicating that the differences in the level of the digital economy as a whole were relatively stable; the Gini coefficient gradually declined from 2019 to 2021, indicating that the differences in the level of the digital economy of the nine provinces in the Yellow River Basin were decreasing. The difference in the level of digital economy is shrinking[22].

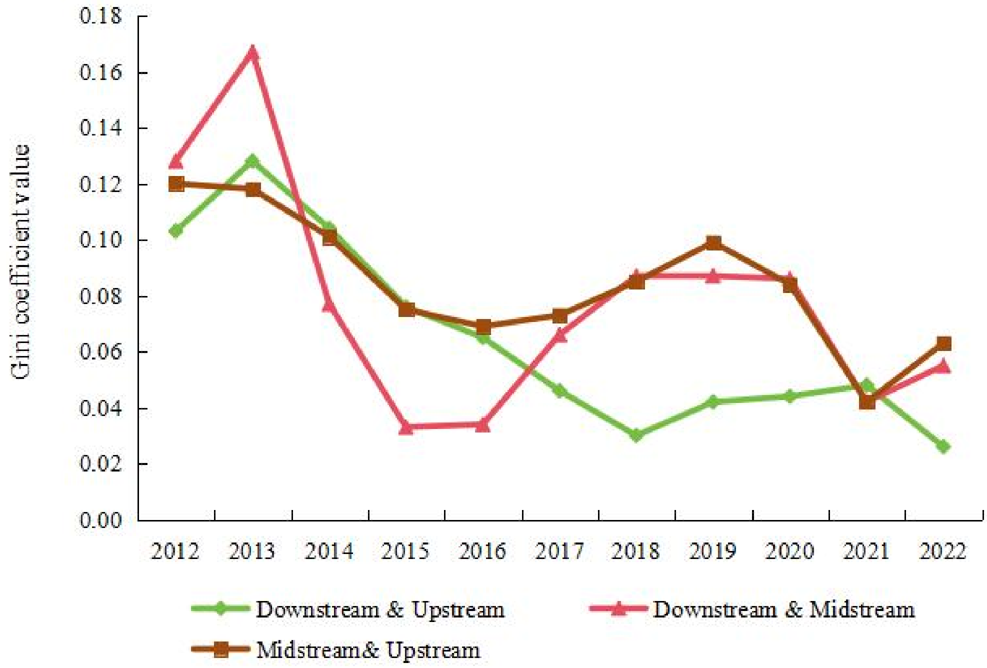

Figure 4. Trends of upper, middle and lower reaches

Inter-regional differences

The Dagum Gini coefficient between upstream and downstream regions fluctuates significantly between 2012 and 2022. It increases slightly from 0.103 to 0.128 initially and then decreases sharply to 0.026, showing an initial small increase followed by a rapid contraction. The Gini coefficient between upstream and midstream is relatively stable, slightly decreasing from 0.120 to 0.118 and then fluctuating little, eventually stabilizing at 0.063 with a slight increase. The Gini coefficient between downstream and midstream increased from 0.128 to 0.167, and then dropped sharply to 0.055, showing a sharp decline after the initial increase. Overall, the gap between the upstream and downstream experienced a first increase and then a decrease, the gap between the upstream and midstream was relatively stable, while the gap between the downstream and midstream increased and then decreased with more significant changes.

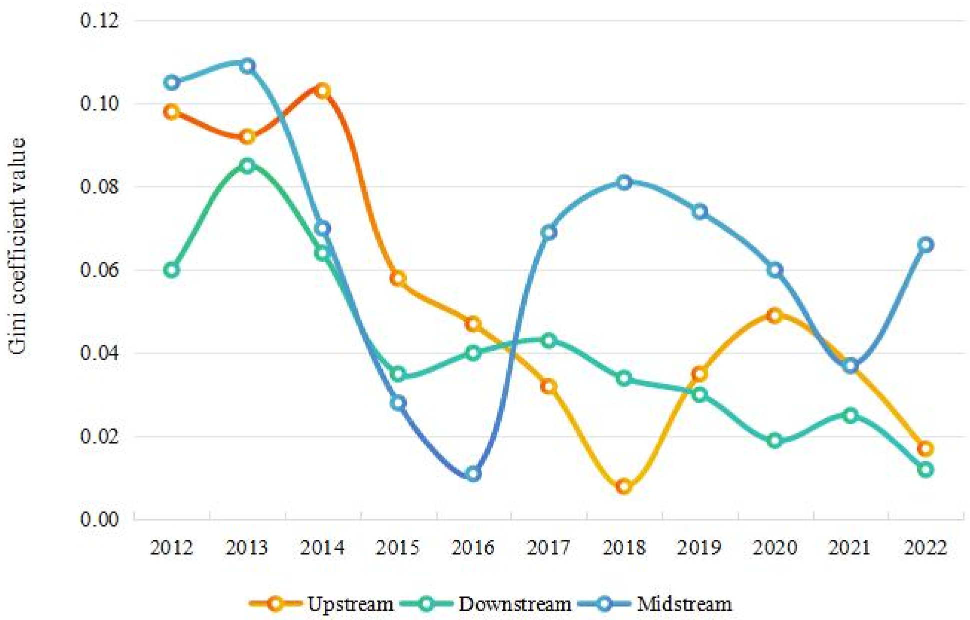

Figure 5. Trends within the region

Intra-regional variations

The Gini coefficient for the upstream region (Qinghai, Sichuan and Gansu) has steadily declined from 0.098 in 2012 to 0.017 in 2022, showing a significant reduction in inequality in the development of the digital economy. This trend reflects the growing economic development of the upstream regions towards balance and inclusiveness. This change is closely related to China's Precision Poverty Alleviation Policy, which has brought more development opportunities to rural areas in the upstream region by strengthening infrastructure construction, education access, healthcare improvement and employment promotion, thereby reducing inequality in the digital economy. The Gini coefficient in the middle reaches (Ningxia, Inner Mongolia, and Shanxi), on the other hand, shows a v-shaped trend, rising from 0.060 in 2012 to 0.085 in 2013, and then gradually falling back to 0.012 in 2022.This change may be influenced by both the inequality factor in the digital economy and the decline of traditional resource-based industries. With the transformation and upgrading of resource-based industries, the economic pattern of the midstream region is undergoing profound changes, and the problem of digital economic inequality is gradually alleviated[23]. The Gini coefficient of downstream regions (e.g. Henan, Shaanxi, Shandong, etc.) is relatively stable, dropping from 0.105 in 2012 to 0.066 in 2022.This is mainly due to the fact that downstream regions have strengthened inter-regional cooperation, optimized the allocation of resources, and promoted the development of complementary economies. At the same time, the adjustment and optimization of the economic structure of downstream regions, especially the rise of emerging and high-tech industries, has provided more local employment opportunities and sources of income, which has helped to narrow the income gap and keep the Gini coefficient relatively stable.

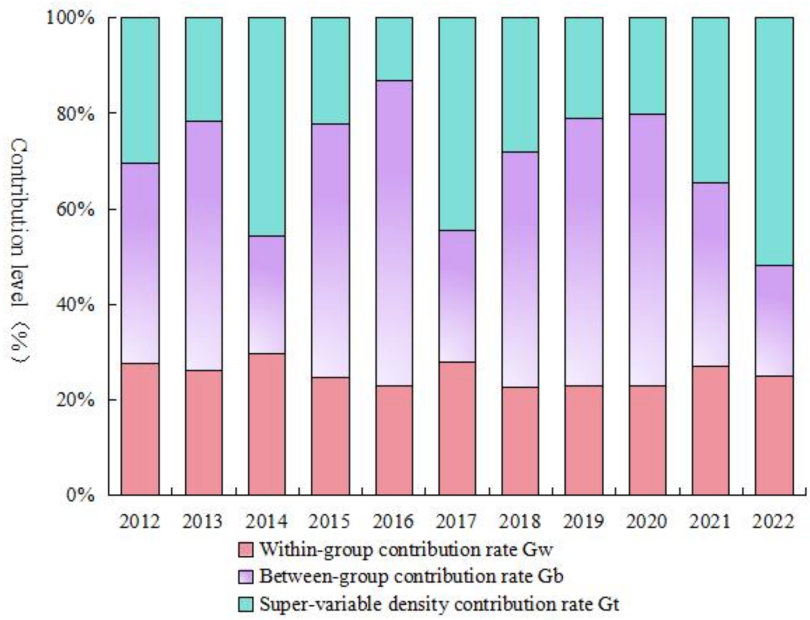

Figure 6. Cumulative contribution rate of the Gini coefficient

Over the past decade, the development of the digital economy in the Yellow River Basin has shown a complex situation. The degree of internal inequality is relatively stable, and the intra-regional contribution of the Dagum Gini coefficient has always been around 0.2555, with no significant trend change. However, inter-regional differences are obvious, and the average value of the contribution of the Dagum Gini coefficient is 0.4474 and has increased, showing a gradual increase-sharp decline-slowly increasing. The average value of hypervariance contribution is 0.3042, which is fluctuating and has a significant impact on the development of digital economy. During the period of 2012-2022, the inter-regional contribution rate and hypervariance density are larger than the intra-regional contribution rate most of the time, and the fluctuation is larger, while the intra-regional contribution rate fluctuates less. Taken together, the spatio-temporal evolution of digital economic development in the Yellow River Basin is characterized by the relative stability of internal inequality, the expansion of inter-regional differences, and the significant fluctuation of hypervariance density. This reveals the complexity and imbalance of the development of digital economy in the Yellow River Basin[24], which requires further strengthening of policy guidance to promote coordinated regional development.

6. Conclusions and recommendations

6.1. research conclusion

Provinces in the Yellow River Basin show significant differences in digital economy development. Eastern provinces such as Shandong, Henan, and Shaanxi have achieved remarkable digital economic development by virtue of policy support, resource advantages, and technological progress, while western provinces such as Qinghai and Gansu are lagging behind. This difference is not only influenced by factors such as resources, technology and industrial transformation, but also closely related to the cultural traditions of the region. The open cultural atmosphere in the eastern provinces promotes innovation and cooperation, creating favorable conditions for the development of the digital economy; in contrast, the western provinces are more conservative in some aspects and less receptive to new industries.

During the period from 2012 to 2022, the overall development of digital economy in the Yellow River Basin shows an upward trend, but the growth rate is limited and there is still huge room for improvement. The development level of each province gradually diverges, the degree of difference increases, and the polarization trend of the digital economy becomes increasingly obvious. It is worth noting that the spatial gap in the level of digital economy development is gradually narrowing, showing a trend of equalization of inter-regional development.

Specifically for the upstream, midstream and downstream regions of the Yellow River Basin, the digital economic development gap shows different patterns of change. The gap between the upstream and downstream regions increases and then decreases, the gap between the upstream and midstream regions is relatively stable, while the gap between the downstream and midstream regions goes through a process of increasing and then decreasing significantly. This change reflects the different strategies and effectiveness of different regions in the development of the digital economy. The inequality in the upstream region decreases year by year, the midstream region shows a v-shaped fluctuating change trend, which may be related to economic restructuring and industrial upgrading, while the downstream region benefits from inter-regional cooperation and optimization of the economic structure, and the Gini coefficient is relatively stable and decreases. Taken together, the development of the digital economy in the Yellow River Basin shows complexity and diversity in spatial and temporal evolution. To promote the balanced development of each region, it is necessary to deeply analyze various influencing factors and strengthen inter-regional cooperation and exchange.

6.2. suggestion

First, for western provinces where the digital economy is lagging behind, tax relief policies can be implemented to reduce the tax burden on enterprises and attract more investment; at the same time, a special fund can be established to support the research and development and innovation of local digital economy enterprises; in addition, financial support can be provided[25], for example, through the establishment of low-interest loans, to help enterprises resolve their financial difficulties. In promoting cooperation between the eastern and western regions, digital economy industrial parks can be set up to attract high-quality enterprises from the east to set up branches in the west, and support the development of the local digital economy through technology export and talent training. Considering that western provinces are more conservative in some aspects and less receptive to new industries, it is recommended to strengthen the popularization of science education and digital cultural literacy in the western region. By means of digital skills training and digital culture promotion activities, the public's awareness and acceptance of the digital economy can be improved, and the endogenous impetus for the development of the digital economy in the western region can be stimulated.

Second，The establishment of special funds should focus on supporting research institutions and enterprises in western provinces to solve their technological bottlenecks and promote innovation in the field of the digital economy. The construction of an innovation platform could include the establishment of a digital economy technology exchange platform to promote technical cooperation and exchanges between different regions, and to jointly overcome key technological challenges. In terms of intellectual property protection, the formulation and enforcement of laws and regulations can be strengthened, a sound intellectual property protection mechanism can be established, and enterprises can be encouraged to increase their investment in and innovation of core technologies.

Thirdly, specific industrial policies can be formulated with regard to the resource endowments and development advantages of different regions, for example, in the eastern region, focusing on the development of high-tech industries such as Internet and e-commerce, while in the central region, efforts can be made to cultivate emerging industries, such as artificial intelligence and big data, while in the western region, special industries focusing on the digital culture industry and eco-agriculture can be developed. Strengthening inter-regional synergies and cooperation can be achieved through the establishment of digital economy industry alliances or cooperation mechanisms to jointly formulate development plans and policies and realize resource sharing and complementary advantages.

Fourth, in terms of infrastructure development, investment in the western region can be increased to improve its network infrastructure and enhance its digitalization level. In terms of public services, digital education and medical platforms can be established, and Internet and artificial intelligence technologies can be used to provide smarter and more personalized services and to promote the benefits of the fruits of the digital economy to a wider range of people.

Fifth,strengthening regulation and governance can be done through the establishment of a digital economy regulatory body to strengthen the supervision and management of the development of the digital economy and to ensure the healthy development of the market order. In terms of data security and personal information protection, relevant laws and regulations can be formulated to regulate the data collection and use behavior of enterprises and protect user privacy and security. Promoting the participation of the government, enterprises and all parties in society can realize the goal of healthy and orderly development of the digital economy by establishing a multi-party cooperation mechanism to form a digital economy governance pattern of common governance and sharing.

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References

[1] Kuang Jinsong,Shi Xuefei,Yang Yi Huang Canchan.2022.A study on the measurement of the level of digital economic development and the pattern of spatial evolution in China's provincial areas,Research in Business（in Chinese）

[2] Zhou Rongjun Zheng Fangyuan.2022.Characteristics of digital economy development level measurement and spatial and temporal evolution in Henan Province, Journal of Luoyang Institute of Technology: Social Science Edition（in Chinese）

[3] Y. Li, R. Jiang, M. Zhang, L. Luo, L. Zhang, 2023.Measurement of the level of high-quality development of China's digital economy and analysis of its spatial and temporal evolution, Statistics and Decision Making（in Chinese）

[4] He Di,Zhao Xuanzhuo Qi Qi.2023.A study on the measurement of China's digital economy development level, spatio-temporal pattern and regional differences,Industrial Technology and Economy（in Chinese）

[5] Xia Chunfang Jia Jubao.2023.Measurement of the level of digital economic development and spatial and temporal evolution in the western region,Shanghai Business（in Chinese）

[6] Shan Zhiguang, Xu Qingyuan, Ma Chaojiang, et al. Evaluation system and outlook of digital economy development based on ternary space theory[J]. Macroeconomic Management, 2020(2):42-49.（in Chinese）

[7] Wang Yanjie,Gao Qijie Yang Rui.2023.A study on industrial agglomeration measurement and spatial and temporal evolution characteristics of China's digital economy,Industrial Technology and Economy（in Chinese）

[8] Liang Maolin, Peng Bangwen, Luo Huasong Hong Juhua.2023.Measurement of China's geo-economic relations with neighboring countries and analysis of the evolution of spatio-temporal patterns, World Geography Research（in Chinese）

[9] Shen Y. Zhou P. F. 2023, Measuring the level of China's digital economy development and analyzing the spatial and temporal patterns, Statistics and Decision-making（in Chinese）

[10] Li Minna, Cai Shu Qin Chenglin. Analysis of economic spatial differentiation patterns in the Yellow River Basin[J] Economic Geography,2011,31(3):379-383.（in Chinese）

[11] TAO Changqi, XU Mal Measurement of China's Innovation Factor Allocation Level under the Threshold of High-Quality Economic Development[J]. Research on Quantitative and Technical Economics,2021,38(3):3~22.（in Chinese）

[12] Wang, M.; Zhu, X.; Yin, S. Spatial–temporal coupling coordination and interaction between digitalization and traditional industrial upgrading: a case study of the Yellow River Basin. *Scientific Reports* **2023,** *13*, 17997.

[13] Lin, K.; Zhang, X.; Hou J. Evaluation of China's provincial digital economy development level and its coupling coordination relationship. *PLOS ONE* **2023**, 18, e0288614.

[14] Li, C.; Peng, W.; Shen, X. Comprehensive evaluation of the high-quality development of the ecological and economic belt along the Yellow River in Ningxia. *Sustainability* **2023,** 15, 11486.

[15] Himthani, P.; Dubey, G. P.; Sharma, B. M.; Taneja, A. Big Data Privacy and Challenges for Machine Learning. 2020 Fourth International Conference on I-SMAC, Palladam, India, 2020, pp. 707-713.

[16] Nie, L.; Bao, X.; Song, S.; Wu, Z. The Impact of the Digital Economy on Total-Factor Carbon Emission Efficiency in the Yellow River Basin from the Perspectives of Mediating and Moderating Roles. *Systems* **2024,** 12, 99. https://doi.org/10.3390/systems12030099

[17] Gao, X. Huang, L.; Wang, H. Spatiotemporal differentiation and convergence characteristics of green economic efficiency in China: from the perspective of pollution and carbon emission reduction. *Environ. Sci. Pollut. Res.* **2023,**30, 109525–109545.

[18] Xu, Z.; Ci, F. Spatial-Temporal Characteristics and Driving Factors of Coupling Coordination between the Digital Economy and Low-Carbon Development in the Yellow River Basin. *Sustainability* **2023,** 15, 2731. https://doi.org/10.3390/su15032731

[19] Du, M.; Huang, Y.; Dong, H.; Zhou, X.; Wang, Y. The measurement, sources of variation, and factors influencing the coupled and coordinated development of rural revitalization and digital economy in China. *PLOS ONE* **2022,** *17*, e0277910.

[20] Tang, L.; Lu, B.; Tian, T. Spatial Correlation Network and Regional Differences for the Development of Digital Economy in China. *Entropy* **2021,** 23, 1575.

[21] Li, C.; Peng, W.; Shen, X. Comprehensive evaluation of the high-quality development of the ecological and economic belt along the Yellow River in Ningxia. *Sustainability* **2023,** 15, 11486.https://doi.org/10.25236/AJBM.2023.052703.

[22] Zhang, W.; Zhao, S.; Wan, X.; Yao, Y. Study on the effect of digital economy on high-quality economic development in China. *PLOS ONE* **2021,** *16* (9), e0257365.

[23] Qing, Y.; Zhao, B.; Wen, C. The Coupling and Coordination of Agricultural Carbon Emissions Efficiency and Economic Growth in the Yellow River Basin, China. *Sustainability* **2023,** 15, 971. https://doi.org/10.3390/su15020971

[24] Liu, J.; Li, X.; Liu, H.; Song, Y. The Spatial and Temporal Evolution Pattern and Influencing Factors of Urban Human Settlement Resilience in Three Provinces of Northeast China. *Land* **2023,** 12, 2161. https://doi.org/10.3390/land12122161

[25] Wang, M.; Zhu, X.; Yin, S. Spatial–temporal coupling coordination and interaction between digitalization and traditional industrial upgrading: a case study of the Yellow River Basin. *Scientific Reports* **2023,** *13* (1), 17997.