

Digital Economy Empowering Green Development Welfare: Empirical Evidence from Resource-Based Cities in the Yellow River Basin (Postprint)

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Abstract

Enhancing green development welfare represents the ultimate objective of green development, with the digital economy exerting dual effects on regional green development. Building upon a systematic analysis of the theoretical mechanisms through which the digital economy influences green development welfare, this study employs panel data from 36 resource-based cities in the Yellow River Basin spanning 2013–2022, utilizing a two-way fixed effects model and a spatial Durbin model to empirically examine the impact, heterogeneous effects, and spatial spillover effects of the digital economy on green development welfare. The findings reveal: (1) Regarding spatiotemporal evolution, the overall level of green development welfare remains relatively low, temporally exhibiting a smooth ‘S’-shaped upward trend, and spatially presenting a pattern characterized primarily by medium-low level block distribution, with high-level point distribution as a supplement. (2) Concerning impact relationships, the digital economy at the resource-based city level in the Yellow River Basin demonstrates a significant enhancing effect on regional green development welfare, a result that remains robust after conducting robustness tests. (3) In terms of heterogeneous effects, the promotional effect of the digital economy is most pronounced in growth-type resource-based cities. (4) With respect to spatial spillover, the impact of the digital economy on green development welfare exhibits positive spatial spillover effects, where both direct and total effects are significantly positive, while the indirect effect is significantly negative. These research findings can facilitate the formation of synergy between the digital economy and green development welfare in the region, thereby advancing the realization of Chinese-style modernization featuring harmonious coexistence between humans and nature.

Full Text

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Abstract

Improving green development welfare represents the ultimate objective of green development, while the digital economy exerts dual effects on regional green development. Based on a systematic analysis of the theoretical mechanisms through which the digital economy influences green development welfare, this study employs panel data from 36 resource-based cities in the Yellow River Basin spanning 2013–2022. Using a two-way fixed effects model and a spatial Durbin model, we empirically examine the impact of the digital economy on green development welfare, along with its heterogeneous effects and spatial spillovers. The findings reveal that: (1) Regarding spatiotemporal evolution, the overall level of green development welfare remains relatively low, showing a smooth N-shaped upward trend over time and a spatial distribution pattern dominated by medium-low level clusters with high-level points as supplements. (2) In terms of impact relationships, the digital economy at the resource-based city level in the Yellow River Basin significantly enhances regional green development welfare, an effect that remains robust after a series of robustness tests. (3) Concerning heterogeneous effects, the digital economy's promotional effect is most pronounced in growing resource-based cities. (4) Regarding spatial spillovers, the digital economy exhibits a positive spatial spillover effect on green development welfare, with both direct and total effects being significantly positive, while the indirect effect is significantly negative. These results can help the region forge synergy between the digital economy and green development welfare, thereby advancing Chinese-style modernization characterized by harmonious coexistence between humanity and nature.

Keywords: digital economy; green development welfare; Yellow River Basin; resource-based cities

1 Theoretical Mechanisms

The digital economy refers to a series of economic activities that use data resources as key production factors, modern information networks as important carriers, and the effective use of information and communication technology as an important driving force for improving efficiency and optimizing economic

structure. According to endogenous growth theory, technological progress is the source of sustainable economic growth, and technological innovation is an important means of technological progress. The path of technological innovation determines the degree to which innovation influences social production methods and welfare levels.

1.1 Digital Economy Enhances Watershed Green Development Welfare by Accelerating New Quality Productive Forces Formation

Using green wealth supply as endogenous driving force forms the basic condition and development potential for improving green development welfare, including natural capital, physical capital, and human capital. The digital economy has the potential to enhance productivity levels and reorganize the qualitative attributes of the three productivity factors, providing disruptive and cutting-edge green data elements and technologies for forming and developing new quality productive forces. Compared with traditional production factors, green data exhibits non-rivalrous use, ubiquitous spatiotemporal presence, non-independent production, and easy carrier transmission.

According to the environmental quality utility function, when green labor or green capital inputs using the same green data increase, and unit green data utilization rate or average output improves, this means that with other inputs held constant, obtaining more green data makes green productivity more advantageous, increases wages for green innovation-type workers, and generates increasing welfare benefits through scale and scope effects. Green technology has universal applicability, dynamic evolution, and innovation complementarity. Green technological progress enables workers to master more skills with reduced difficulty, accelerating the transition of general workers to green innovation-type workers. The basic paradigm of labor materials becomes innovative, allowing for reprogramming, access, and self-reinforcement, enabling green digital innovation to enter a virtuous cycle. The fundamental logic of labor objects changes, bringing high liquidity to green digital products, new generativity to green digital platforms, and strong flexibility to green digital users, allowing consumers to obtain more positive environmental quality utility.

Therefore, the digital economy enhances green development welfare by forming new quality productive forces, improving the efficiency of natural capital acquisition and use, accelerating physical capital accumulation speed, and increasing the contribution ratio of human capital.

1.2 Digital Economy Enhances Watershed Green Development Welfare by Strengthening “Three Lives” Externalities Management

Using green economic quality as external thrust represents the key measure and fundamental requirement for improving green development welfare. Economic activities require carriers including production, living, and ecological spaces. Production spaces acquire products and provide functional venues. The digital

economy, through industrial digitalization, digital industrialization, and digital technology, promotes more sufficient and efficient resource intensification, information aggregation, and factor mobility in production space industries. Living spaces guarantee life services and emphasize people-oriented development. The digital economy promotes full-scenario digital technology applications, making daily life aspects such as housing, medical care, and education more intelligent and convenient, enhancing humanistic comfort, health, and wisdom in living spaces. Ecological spaces increase greenery, reduce pollution, and ensure safety. The digital economy can obtain ecological environment data in real-time, effectively and comprehensively, build full industrial chains for energy resources, strengthen digital supervision, improve resource utilization efficiency across all links, and bring about clear waters and lush mountains.

The Environmental Kuznets Curve has been validated to show that green technology progress effects biased toward energy conservation and clean production can explain why pollution levels decline with economic growth. The digital economy's characteristics of low energy consumption, low material consumption, and low emissions can achieve green production and lifestyle patterns and social environment inclusiveness, bringing more high-quality employment opportunities, improving living standards, and enhancing economic resilience.

Therefore, the digital economy enhances green development welfare by strengthening "three lives" externalities management, promoting intensive and efficient production space industries, fostering humanistic and livable living spaces, and ensuring natural ecological spaces with clear waters and lush mountains.

1.3 Digital Economy Reduces Watershed Green Development Welfare by Distorting Welfare Attention Allocation

Using green consumption preferences as innovation vitality represents the driving source and main means for improving green development welfare. The digital economy can reshape the allocation pattern of tangible elements represented by green consumption preferences through intangible elements represented by attention. The more public attention, intensity, and duration focused on green development welfare, the lower the information costs for enterprise production and government decision-making, the more accurate the information obtained, and the greater the investment in green development welfare fields. However, driven by herd mentality and catalyzed by the digital economy, public preferences converge and cognitive convergence occurs, social class status differentiation cognition is strengthened, generating relative deprivation feelings, subjective status identity shifts downward, objective economic status rises, creating utility expectation waiting, potentially producing a bad money drives out good effect, thereby amplifying the public's attention degree on welfare concerns, distorting green preferences and environmental demands, leading to resource misallocation or over-allocation. In the green development welfare field, this causes green consumption crowding, increases government pressure on ecological and livelihood construction, and triggers low efficiency in green policy internal friction.

Therefore, the digital economy reduces green development welfare by distorting welfare attention allocation, weakening public energy consumption levels, amplifying enterprise green innovation and environmental demands, causing government resource misallocation or over-allocation, and lowering green development welfare.

2 Study Area and Methods

2.1 Study Area Overview

Resource-based cities constitute an important urban type with numerous quantities and prominent problems in China, characterized by high dependence on natural resource extraction and primary processing and a large share of resource-based industries in the industrial system. Under the requirements of green, low-carbon, and high-quality development, resource-based cities undertake multiple national security tasks including development and ecology. The Yellow River Basin is an important ecological barrier and economic zone in China, as well as an energy development industrial belt, concentrating more than 50% of the nation's resource-based cities and accounting for 36 in the basin. Resource-based cities in the Yellow River Basin contribute approximately 70% of the nation's coal resource output, providing important support for rapid national economic development. However, these cities face severe resource curse negative energy and prominent ecological security pressures in the region, with more urgent needs for a beautiful ecological environment than other regions, and the status of ecological environment quality in the happiness index continuously highlighted. Improving green development welfare in resource-based cities is essential for ecological protection and high-quality development in the Yellow River Basin. This paper selects data from resource-based cities in the Yellow River Basin as empirical evidence to test the relationship and mechanisms between the digital economy and green development welfare, which has typical representativeness, demonstration effect, and reference value.

2.2 Methodology

2.2.1 Measurement Method for Green Development Welfare in Yellow River Basin Resource-Based Cities Indicator System Construction:

Green development welfare refers to changes in residents' current welfare levels due to green development and the capacity for sustainable improvement in future welfare levels. This paper defines it as the process of breaking through the "welfare threshold" trap within the "ecological threshold" during coordinated "production-living-ecology" development, compensating for and reducing ecological and environmental costs paid for economic growth in an ecologically sustainable manner, and ultimately effectively exchanging for quality of life, transformed development potential, and happiness gains or losses for humanity.

Different from green development level, green development welfare measurement stands from a welfare perspective, measuring maximized welfare utility based on minimized resource consumption, from three basic output indicators: green wealth supply, green economic quality, and green consumption preference (Table 1), to measure the green development welfare level of resource-based cities in the Yellow River Basin.

Evaluation Method: Referencing Zou Weiyong et al.'s research, we adopt the entropy weight method to extract indicator information and avoid subjective preferences and empirical limitations in determining weight coefficients.

1) Data standardization processing:

$$\text{For positive indicators: } x'_{ij} = \frac{x_{ij} - \min_j}{\max_j - \min_j}$$

$$\text{For negative indicators: } x'_{ij} = \frac{\max_j - x_{ij}}{\max_j - \min_j}$$

Where: $i = 1, 2, 3, \dots, n$ represents the number of evaluation objects; m represents the number of indicators; x_{ij} represents the value of the j th indicator for the i th evaluation object; \max_j and \min_j represent the maximum and minimum values of the j th indicator.

2) Determination of weight coefficients:

$$\text{Calculate the entropy value for each indicator: } e_j = -\frac{1}{\ln n} \sum_{i=1}^n p_{ij} \ln p_{ij}$$

$$\text{Calculate information entropy redundancy: } d_j = 1 - e_j$$

$$\text{Calculate each indicator's weight: } w_j = \frac{d_j}{\sum_{j=1}^m d_j}$$

Where: e_j is the entropy value of the j th indicator; p_{ij} is the proportion of the i th evaluation object under the j th indicator; d_j is the information entropy redundancy; w_j is the weight coefficient.

3) Comprehensive score for each sample:

$$GDB_i = \sum_j w_j x_{ij}$$

2.2.2 Test Model for Digital Economy Impact on Green Development

Welfare Based on theoretical mechanism analysis, to examine the impact of the digital economy on green development welfare in Yellow River Basin resource-based cities, we construct a two-way fixed effects econometric model for testing, drawing on studies by Liu Minlou, Lü Yue, et al.:

$$\ln GDB_{it} = \alpha + \beta \ln DE_{it} + \gamma_i X_{it} + \delta_i + \varepsilon_t + \mu_{it}$$

Where: i and t represent city and year; GDB_{it} (dependent variable) represents green development welfare level; DE_{it} (core explanatory variable) represents digital economy development level; X_{it} represents control variables; α , β , γ_i represent model parameters, coefficient of the digital economy development level term, and control variable coefficients respectively; δ_i , ε_t , μ_{it} represent city fixed effects, year fixed effects, and random disturbance terms respectively.

Considering that the impact of digital economy development on green development welfare in Yellow River Basin resource-based cities may have spatial

spillover effects, we further establish a spatial econometric model:

$$\ln GDB_{it} = \rho W \ln GDB_{it} + \alpha + \beta \ln DE_{it} + \phi_i X_{it} + \theta W \ln DE_{it} + \varphi_i W X_{it} + \delta_i + \varepsilon_t + \mu_{it}$$

Where: ρ is the spatial lag parameter of green development welfare; W is the inverse distance spatial weight matrix; ϕ_i is the control variable coefficient.

2.3 Variable Selection

Core explanatory variable: Digital economy development level. We comprehensively measure the digital economy development level of Yellow River Basin resource-based cities using five indicators: digital financial inclusion development, internet penetration rate, related employment situation, related output situation, and mobile phone penetration rate.

Control variables: Economic development level ($\ln Gdp$) affects employment opportunities and income sources, measured by per capita GDP; Financial development level ($\ln Finance$) affects high-quality living demands, measured by the ratio of financial institution deposit and loan balances to GDP; Urbanization level ($\ln Urban$) affects residents' quality of life, measured by population density per square kilometer; Opening-up level ($\ln Fdi$) affects public service quality such as education and medical care, measured by the ratio of actual utilized foreign investment to regional GDP; Industrial structure affects growth efficiency and resident wages, measured by the ratio of tertiary industry to secondary industry value-added.

2.4 Data and Sample

We use panel data from 36 cities in the Yellow River Basin from 2013–2022 as the research sample. Referring to the “National Sustainable Development Plan for Resource-Based Cities (2013–2020)” and the “Yellow River Basin Comprehensive Plan (2012–2030),” and considering data availability (Laiwu City was merged into Jinan City in 2019), we ultimately selected 36 resource-based cities in the study area. Based on resource security capacity and sustainable development capacity, they are classified into growing (7 cities: Dongying, Ordos, Yulin, Yan’ an, Qingyang, Xianyang, Wuwei), mature (19 cities: Dongying, Tai’ an, Jining, Hebi, Datong, Xinzhou, Yangquan, Jinzhong, Changzhi, Jincheng, Pingdingshan, Lüliang, Linfen, Yuncheng, Sanmenxia, Weinan, Pingliang, Baoji, Jinchang), declining (6 cities: Jiaozuo, Tongchuan, Wuhai, Shizuishan, Baiyin), and regenerative (4 cities: Zibo, Luoyang, Baotou, Zhangye) types.

Main economic variables are sourced from the “China City Statistical Yearbook,” “China Urban Construction Statistical Yearbook,” and “China Statistical Yearbook” for 2013–2022, as well as national economic and social development statistical bulletins, environmental condition bulletins of each city, and the China Digital Financial Inclusion Index compiled by the Peking University Digital Finance Research Center and Ant Financial. Missing data are supplemented

using interpolation and extrapolation methods. To reduce heteroskedasticity, all variables are logarithmically transformed. Descriptive statistics are presented in Table 2.

3 Results

3.1 Spatiotemporal Evolution Analysis

3.1.1 Spatiotemporal Evolution Process Figure 2 illustrates the spatial evolution process of green development welfare in Yellow River Basin resource-based cities in typical years. Overall, the green development welfare level of these cities is relatively low. From a temporal perspective, the green development welfare level shows a smooth N-shaped upward trend, with the index steadily increasing year by year. Taking the beginning and end periods as examples, the cities with the largest and smallest increases are Baotou and Zhangye, respectively. From a spatial perspective, the green development welfare level exhibits a pattern of “medium-low level clusters as the main distribution, supplemented by high-level point distributions.” Specifically, low-level cities increased from 6 (Pingliang, Baoji, Datong, Xinzhou, Yangquan, Weinan, Tongchuan) to 7 (Baiyin, Yan’ an, Yangquan, etc.); medium-level cities account for about 50% of the entire sample, sporadically distributed across various regions; high-level cities remained stable at 4 (Jining, Tai’ an, Zibo, Dongying).

[Figure 2: see original paper]

3.1.2 Spatial Distribution Characteristics and Center of Gravity Shift

Table 3 presents the standard deviation ellipse parameters and elliptical center of gravity movement trajectory for green development welfare in Yellow River Basin resource-based cities from 2013–2022, revealing four dynamic characteristics: (1) The impact direction of regional resource-based city green development welfare is primarily east-west. During the study period, the azimuth angle increased from 38.28° to 52.93° , with a change amplitude of 38.28%, indicating that the main development direction remains east-west oriented. (2) The spatial distribution shows an “east strong, west weak” pattern, with the center of gravity shifting eastward. The average length of the long semi-axis during the study period is 2.3 times that of the short semi-axis. Over time, the long semi-axis, short semi-axis, and ellipse area all show a decreasing trend, indicating that the green development welfare index is increasingly concentrated in the east-west direction spatially. The center of gravity moved from Linfen and Lüliang to Jinzhong, always remaining in the eastern region of the geographical center. (3) The unbalanced spatial distribution pattern has not changed. During the study period, the shape index remains below 0.5, indicating relatively uneven spatial distribution of green development welfare, meaning certain regional disparities exist among Yellow River Basin resource-based cities.

[Figure 3: see original paper]

3.2 Impact of Digital Economy on Green Development Welfare

Table 4 presents regression results for the impact of the digital economy on regional green development welfare. The estimated coefficient of the digital economy is significantly positive at the 1% level, indicating that the digital economy can effectively enhance green development welfare levels in regional resource-based cities. Economic development level produces a positive effect on welfare improvement, with each 1% increase in per capita GDP raising welfare levels by 0.23%. However, due to the strong dependence on local natural resources in Yellow River Basin resource-based cities, using the environment as an economic price likely leads to negative externalities of GDP growth, thereby negatively impacting green development welfare. Industrial structure upgrading also produces a positive effect on welfare improvement, likely because the digital economy promotes the elimination or transformation of traditional industries into new industries, reducing transaction costs and improving labor productivity. However, this effect is not significant, indicating that green transformation in resource-based cities remains urgent. The estimated coefficient of financial development level is significantly negative at the 5% level, becoming insignificant after gradually adding “opening-up level” and “industrial structure” control variables, possibly because enhanced data availability in the financial sector and related technological progress have alleviated financial repression and financing discrimination issues, weakening the inhibitory effect on green technology transformation efficiency. Similarly, urbanization level and opening-up level produce negative effects on welfare improvement, with the former being more significant, likely because accelerated urbanization leads to resource constraints, population concentration, and intense competition under resource constraints, creating greater pressure, and may absorb energy-intensive, highly polluting industries from abroad, forming technological dependence and reducing welfare.

3.3 Robustness Test

Table 5 presents robustness test regression results. After winsorization, the digital economy development level still has a significant positive effect on green development welfare. Using entropy weight TOPSIS to recalculate weights for green development welfare levels, using principal component analysis to re-measure city-level digital economy development indicators, and changing the two-way fixed effects model to a benchmark regression model all confirm that digital economy development significantly enhances green development welfare. Although regression coefficients and significance levels show some differences, the signs and significance levels remain basically consistent with the previous model, indicating that the constructed index system can effectively measure green development welfare levels and digital economy development levels in Yellow River Basin resource-based cities, and the econometric results are robust.

3.4 Heterogeneity Analysis

Due to the particularity of natural conditions, economic development, and social history in cities, resource-based cities differ in resource security potential, resource development stage, and green development transformation needs, leading to significant differences in challenges and opportunities regarding digital economy development and welfare level improvement. Table 6 presents the impact of the digital economy on green development welfare across four types of resource-based cities: growing, mature, declining, and regenerative. The effect is most obvious in growing cities. Growing cities are in the rising stage of resource development, with greater potential in natural capital, physical capital, and human capital, relatively complete functions in production, living, and ecological spaces, and more reasonable welfare attention allocation such as public energy conservation awareness and enterprise green innovation enthusiasm. Strengthening the deep integration of data technology in these cities can better leverage the green value of the digital economy. However, the digital economy's enhancement effect on green development welfare in mature, declining, and regenerative cities is not significant, with the impact effect following the pattern "declining > regenerative > mature." This may be because mature cities, while in a stable resource development stage, already show negative externality effects, with increasingly severe problems of single industrial structure, environmental pollution, and ecological destruction. Declining cities face resource depletion, economic weakness, talent outflow, and many overlapping issues, being in a green development transformation bottleneck period. Regenerative cities still have relatively low levels of industrial structure sophistication, with high-tech industry development lagging, urgently needing to improve opening-up levels and accelerate green and low-carbon transformation.

3.5 Spatial Effect Test

During the sample period, the global Moran's I of green development welfare levels in regional resource-based cities shows a fluctuating trend of "decrease-increase," with almost all passing significance tests (Table 7), indicating spatial correlation. The spatial Durbin two-way fixed effects model shows the highest fit and credibility, making it the optimal model (Table 8). The spatial lag coefficient of the digital economy is significantly negative, indicating that urban digital economy development has significant spatial effects, meaning local digital economy development has a significant inhibitory effect on green development welfare in neighboring regions.

From the effect decomposition, both the direct and total effects of the digital economy are significantly positive, while the indirect effect is significantly negative, indicating the existence of a negative spatial spillover effect.

4 Conclusions and Recommendations

4.1 Conclusions

- (1) **Spatiotemporal evolution:** The overall level of green development welfare in Yellow River Basin resource-based cities is not high. Temporally, it shows a smooth N-shaped upward trend; spatially, it presents a pattern of “east-west differentiation, north-south similarity,” with future growth potential still concentrated in eastern regions.
- (2) **Impact relationship:** Digital economy development in Yellow River Basin resource-based cities significantly enhances green development welfare levels, and this conclusion remains valid after a series of robustness tests.
- (3) **Heterogeneous effects:** The digital economy’s promotional effect on green development welfare is most significant in growing resource-based cities, with impact effects on other types following the pattern “declining > regenerative > mature.”
- (4) **Spatial spillovers:** Green development welfare in Yellow River Basin resource-based cities has spatial autocorrelation. The digital economy has a positive spatial spillover effect on regional welfare levels, with both direct and total effects significantly positive, but the indirect effect significantly negative, indicating an inhibitory effect on improving green development welfare in neighboring areas.

4.2 Recommendations

- (1) **Consolidate green development achievements and improve the efficiency of digital economy green welfare transformation.** During the study period, the transformation effect of green development achievements into people’s welfare in Yellow River Basin resource-based cities was not obvious and spatially uneven. Therefore, in the green development process, we must take green development welfare level improvement as the fundamental goal, introduce relevant policies benefiting people’s livelihood, encourage social capital investment in environmental infrastructure, ensure effective welfare output transformation, achieve absolute decoupling of economic growth from resource consumption, and alleviate environmental pollution and ecological destruction in resource-based cities.
- (2) **Build a new infrastructure system and leverage the green value of digital economy data-technology elements.** During the study period, the digital economy could generate “digital dividends” by spawning new quality productive forces, strengthening “three lives” externalities management, and allocating welfare attention. Therefore, we should increase the integration of digital infrastructure with ecological environment infrastructure, promote the transformation and upgrading of traditional ecolog-

ical environment infrastructure, build an ecological environment big data system, achieve full coverage of environmental quality, pollution source, and ecological condition monitoring, digitize green development achievements, and enable more accurate welfare transformation evaluation.

- (3) **Formulate tailored strategies and expand the spatial spillover effect radius of the digital economy.** During the study period, the digital economy significantly improved welfare in growing resource-based cities in the Yellow River Basin and had positive spatial spillover effects on local areas. Therefore, we should classify cities by welfare level: for high or relatively high-level cities, continue optimizing the urban “three lives” spatial environment and promote green scientific research achievement transformation; for medium-level cities, strengthen co-construction of green innovation platforms with higher-level cities; for low or relatively low-level cities, re-coordinate the relationship between economic development and ecological and livelihood welfare.

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