Heterogeneity and Dynamic Improvement of Green Development Efficiency in Shaanxi Resource-Based Cities

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Abstract: To address the green-transition dilemma facing resource-based cities in the Shaanxi section of the Yellow River Basin, this study establishes an evaluation system for green development efficiency (GDE) and applies the super-efficiency slack-based measure (Super-SBM) model with undesirable outputs and the Global Malmquist–Luenberger (GML) productivity index to estimate and decompose GDE changes in six prefecture-level cities over the period 2013–2023.The findings reveal a wave-like upward trajectory of aggregate GDE. However, substantial heterogeneity exists across resource endowments and development stages: oil- and gas-type cities and mature-stage cities recorded the highest average annual GDE growth, 20.7 % and 10.9 %, respectively. Decomposition analysis indicates that technological progress accounts for approximately four-fifths of the cumulative GDE growth, whereas efficiency change contributes only one-fifth, suggesting that innovation rather than catch-up in management practices has been the dominant driver. Policy implications are threefold. First, embed city-specific GDE targets into the cadre-evaluation system to internalise environmental externalities. Second, reallocate fiscal incentives from over-capacity sectors to green-industry portfolios that integrate carbon-credit financing and circular-economy standards. Third, tighten environmental statutes and expand green-bond markets while enhancing third-party monitoring and public disclosure platforms.

Keyword: SBM model; GML Index; Green Development Efficiency; Shaanxi Resource-based City; Yellow River Basin

1. Introduction

The Yellow River Basin(YRB) functions as both a critical ecological shield and a national energy base, supplying 34 % of China's coal and 42 % of its crude-oil output. Nevertheless, the "mine-depletion–city-decline" syndrome and the resource-curse effect have turned resource-based cities (RBCs) within the basin into "problem regions" for sustainable development. A burgeoning literature has quantified the coupled coordination between ecological protection and high-quality development, identified driving factors, and proposed green-transition pathways; yet spatial heterogeneity and dynamic evolution among RBCs remain under-explored[1-2]. Accelerating the green transition of RBCs and enhancing the resilience of their industrial systems are thus indispensable for the high-quality development of the entire YRB[3]. Green development efficiency (GDE), defined as the ratio of economic and social outputs to resource-environmental inputs, serves as a core metric for assessing the efficacy of green-transition policies. Previous studies have applied composite-indicator systems[4], factor analysis[5], and the epsilon-based measure (EBM) model within data envelopment analysis[6]; however, these methods either ignore undesirable outputs or fail to fully distinguish efficient units[7].

However, the vast spatial span and heterogeneous resource endowments of RBCs in the YRB imply that existing measurement frameworks remain incomplete. Accordingly, this study employs the Super-SBM model with undesirable outputs and the GML productivity index to trace the spatio-temporal dynamics of GDE in six RBCs in the Shaanxi section of the YRB between 2013 and 2023, and to derive evidence-based policy recommendations for their high-quality development.

2. Research Methods and Data

2.1 Research Unit

Following the National Plan for Sustainable

Development of RBCs (2013–2020), we selected six prefecture-level RBCs in the Shaanxi section of the YRB—Tongchuan, Baoji, Xianyang, Weinan, Yan'an, and Yulin—and classified them into growth, mature, and declining stages, and into metallic, non-metallic, coal, and oil-gas [8] resource types (Table 1).

Table 1. RBCs and Their Groups in the YRB

City	Resource Type	Development Stage	City	Resource Type	Development Stage
Tongchuan	non-metallic	declining type	Weinan	coal	mature type
Baoji	Metal	mature type	Yan'an	Oil and gas	growth type
Xianyang	coal	Growth type	Yulin	coal	Growth type

2.2 Research Methods

2.2.1 Super-SBM model with non-desired output

Data envelopment analysis (DEA) is widely used in the measurement of GDE, but the traditional DEA model is not suitable for dealing with non-desired output indicators.Tone [9] proposed the superefficient SBM model, which is a non-parametric linear programming method that allows multiple decision units to be effectively distinguished. The specific model is:

$$\rho = min \frac{\frac{1}{m}\sum_{i=1}^{m}\frac{\bar{x}}{x_{i0}}}{\frac{1}{s_1+s_2}\left(\sum_{r=1}^{s_1}\frac{\bar{y}_r^g}{y_{r0}^g}+\sum_{j=1}^{s_2}\frac{\bar{y}_j^b}{y_{j0}^b}\right)} \quad (1)$$

$$s.t.$$

$$x_0 = X\lambda + S^-,\ y_0^g = Y^g\lambda - S^g, y_0^b = Y^b\lambda + S^b \quad (2)$$

$$\bar{x} \geq \sum_{j=1,\neq 0}^{n}\lambda_j x_j, \bar{y}^g \leq \sum_{j=1,\neq 0}^{n}\lambda_j y_j^g, \bar{y}^b \leq \sum_{j=1,\neq 0}^{n}\lambda_j y_j^b$$

$$\bar{x} \geq x_o, \bar{y}^g \leq y_o^g, \bar{y}^b \leq y_o^b$$

$$\sum_{j=1,\neq 0}^{n}\lambda_j = 1, s^- \geq 0, s^g \geq 0, \bar{y}^g \geq 0, \lambda \geq 0$$

2.2.2 GML index

Oh[10] constructed a GML index model, which has the ability of dynamic longitudinal evaluation and can more accurately reflect the degree and dynamic changes of GDE in RBCs in the YRB. The formula is：

$$GML_{t,t+1} = (x_{it}, y_{it}, z_{it}, x_{i(t+1)}, y_{i(t+1)}, z_{i(t+1)}) = \frac{1+D_G(x_{it}, y_{it}, z_{it})}{1+D_G(x_{i(t+1)}, y_{i(t+1)}, z_{i(t+1)})} \quad (3)$$

$$GML_{t,t+1} = GMLEC_t^{t+1} \times GMLTC_t^{t+1} \quad (4)$$

3. Indicator Selection and Data Sources

3.1 Construction of Indicator System

This paper divides the input indicators into energy input, capital investment, labor investment, land and technology investment. total energy consumption and total water consumption for energy input; Land investment chooses the area of urban built-up areas; The capital investment is selected from the total expenditure on science and technology and the total investment in social fixed assets. Technology investment selects the number of patent applications accepted by provinces and cities; Labor input is measured by the number of employees in the unit at the end of the year.

Expected outputs of output indicators include economic growth, ecological benefits, social welfare and green technologies. The degree of environmental pollution is mainly measured by industrial wastewater discharge, total industrial sulfur dioxide emissions and industrial soot (dust) emission indicators shown in Table 2.

3.2 Data sources

The data in this paper mainly come from the 2013-2024 China Urban Statistical Yearbook, the China Urban Construction Yearbook, the statistical yearbook of each city, Data for 2013–2023 are compiled from the China Urban Statistical Yearbook, China Urban Construction Yearbook, prefecture-level yearbooks, regional development bulletins and the EPS database. Missing values are interpolated by linear trend and 3-year moving average. Monetary variables are deflated to 2013 constant prices using provincial GDP deflators (Table 3).

Table 2. GDE Measurement System

Indicator Type	Variable	Variable Meaning	Unit
Input indicators	Energy	Total energy consumption	10^4 tce
		Total water consumption	10^4 m^3
	land	Urban built-up area area	km^2
	capital	Science and technology expenditure	10,000 yuan
		Total investment in social fixed assets	10,000 yuan

	technology	The number of patent applications accepted by provinces and cities	item
	labor	The number of employees at the end of the year	10^4 persons
Expected output	economic growth	GDP per capita	Yuan
	Ecological benefits	The per capita park green space area	m^2
		Green coverage rate of built-up areas	%
	social welfare	Revenue	10,000 yuan
		Total retail sales of consumer goods in the region	10,000 yuan
	Green technology	Number of green invention patents authorized	item
Non-expected output	environmental pollution	Industrial wastewater discharge	10^4 t
		Total industrial sulfur dioxide emissions	t
		Industrial smoke (dust) emissions	t

Table 3. Descriptive Statistics of Indicator System

Variable name	Sample size	average value	Std.v	min	max
Total energy consumption	66	1284.65	804.74	159.52	3558.79
Total water consumption	66	5828.87	3772.85	1651.10	14523.00
Urban built-up area area	66	70.93	20.66	36.00	122.00
Science and technology expenditure	66	29690.63	29771.67	2312.73	171123.12
Total investment in social fixed assets	66	17986644.31	10134891.19	3183657.43	43595256.99
The number of patent applications accepted by provinces and cities	66	1457.48	1111.15	108.00	5054.00
The number of employees at the end of the year	66	37.48	12.52	10.68	55.81
GDP per capita	66	57554.05	27963.59	24152.00	158464.00
The per capita park green space area	66	13.65	2.04	9.79	18.67
Green coverage rate of built-up areas	66	39.88	1.77	33.65	43.55
Revenue	66	1378563.60	1546451.21	185284.91	8122410.53
Total retail sales of consumer goods in the region	66	4903730.59	2425678.87	949132.78	10578828.52
Number of green invention patents authorized	66	108.98	92.94	1.00	360.00
Industrial wastewater discharge	66	3526.80	2351.65	298.00	13691.00
Total industrial sulfur dioxide emissions	66	34444.88	49477.63	1390.00	200778.00
Industrial smoke (dust) emissions	66	25858.49	43715.75	2048.00	253989.00

4. Analysis of Results

4.1 The Temporal Evolution Characteristics of GDE

4.1.1 Holistic analysis

Figure 1 delineates a pronounced V-shaped trajectory of mean green-development efficiency (GDE) across the six Shaanxi RBCs: a cumulative 117% upswing over 2013–2023, yet embedded with a 29.6 % contraction during 2013–2016 and an average annual rebound of 28 % thereafter. The downward leg coincides with the 2013 National Plan for the Sustainable Development of RBCs (2013–2020), the 2014–2015 coal-price collapse and the province-wide over-capacity reduction campaign. These shocks compressed corporate cash-flows, deferred end-of-pipe retrofits and forced local governments to prioritise fiscal stabilisation over environmental expenditure, pushing the GDE frontier inward. The inflection point in 2017 aligns with the launch of the Yellow River Ecological Protection & High-Quality Development Strategy, while the post-2020 acceleration tracks the “double-carbon” hard target and the national carbon-trading market. A Chow test identifies a structural break in

Q1-2017 ($F = 12.4$, $p < 0.01$), validating the visual interpretation. Notably, the 2018–2019 sub-period exhibits the steepest slope (35 % annual growth), reflecting the simultaneous rollout of ultra-low-emission retrofits in coal-fired power plants and the provincial “Gas-to-Coal” substitution programme that enlarged the market for natural gas and induced a demand-pull effect on green patents. The trajectory thus captures a classic “creative destruction” cycle: regulatory stringency initially imposes compliance costs, but once firms cross the technological threshold, innovation-driven productivity gains dominate and GDE enters a rapid-growth regime.

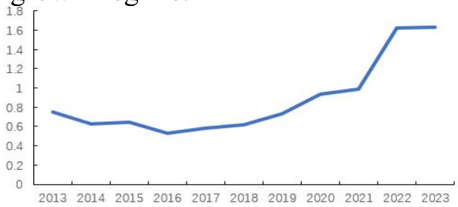

Figure 1. Overall Efficiency of Green Development of RBCs in the YRB of Shaanxi Province

4.1.2 Evaluation of GDE of RBCs in the YRB of different types and development stages

Across resource types, oil-gas cities achieved the highest average annual GDE growth (20.7 %), while coal-type cities grew by 10.9 % per annum; metallic and non-metallic cities exhibited smaller fluctuations (Fig. 2).In 2013, the GDE of different types of RBCs varied greatly, and the ecological environment damage in non-metallic RBCs was relatively low while obtaining resources, and the average fluctuation in the past 11 years was small. However, oil and gas extraction has serious damage to land and the environment, so the GDE of oil and gas RBCs is the lowest. With the successive introduction of environmental protection rules and regulations and the government's strengthening of environmental protection, the gap in GDE between different types of RBCs continues to narrow.

From the perspective of different development stages, the GDE of growing and mature RBCs showed a fluctuating upward trend from 2013 to 2023, with an increase of 40.2% and 171.6% respectively, as shown in Figure 3.Mature RBCs have developed and utilized resources earlier, and long-term high-intensity development has caused serious damage to the regional ecological environment, but with the constraints of environmental regulation, technological progress and development and the demand for ecological protection, enterprises and governments have also actively carried out environmental governance work. Declining RBCs tend to deplete natural resources, lag behind in economic development, and have high pressure on the ecological environment, but due to "innate insufficiency", the efficiency of green development in 2023 is far lower than that of the other three types of cities.

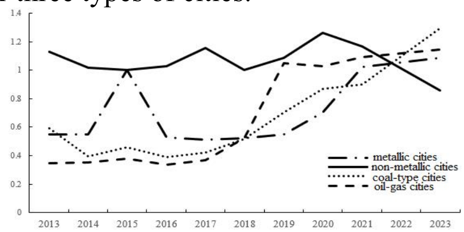

Figure 2. GDE of Cities with Different Resource Types in the YRB

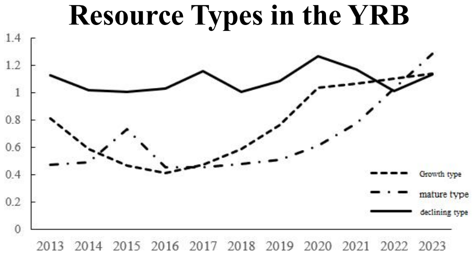

Figure 3. GDE of RBCs in the YRB at Different Stages of Development

4.1.3 Analysis of the dynamic evolution of GDE in various regions

To uncover dynamic drivers, we compute the GML index for each city and decompose it into efficiency change (EC) and technological progress (TC); city rankings based on mean GML are reported in Table 4.

Table 4. GML Index and Decomposition of RBCs in the YRB

city	GML index										GML index mean	ranking	EC(mean)	TC(mean)
	2013—2014	2014—2015	2015—2016	2016—2017	2017—2018	2018—2019	2019—2020	2020—2021	2021—2022	2022—2023				
Weinan	1.093	1.073	0.825	1.041	1.082	1.082	1.120	1.006	1.917	2.002	1.224	1	1.037	1.139
Xianyang	1.020	1.060	0.900	1.078	1.424	2.028	0.981	1.061	1.009	1.035	1.160	2	1.041	1.156
Baoji	1.002	1.843	0.516	0.983	1.024	1.053	1.261	1.474	1.028	1.344	1.153	3	1.003	1.123
Yulin	0.392	1.276	0.854	1.104	1.204	0.899	2.001	1.034	1.083	1.134	1.098	4	1.015	1.072
Yan'an	0.953	0.485	0.915	1.259	1.140	0.989	1.630	0.995	0.986	0.977	1.033	5	0.973	1.066
Tongchuan	0.974	0.990	1.004	1.086	0.916	1.057	1.143	0.921	0.909	0.990	0.999	6	0.992	1.010

The results show that from 2013 to 2023, the average GML index of the six RBCs in the YRB of Shaanxi Province except Tongchuan City was greater than 1, and the average GML index of green development in Weinan City was the highest. Tongchuan City's green development GML index is the lowest, indicating that under the dual pressure of ecological protection and economic development, the efficiency of green development has regressed, and its green and sustainable development problems are still very serious. On the whole, the GML index generally shows a trend of declining first and then rising, indicating that the green development of various cities has slowed down from growth to rapid growth from 2013 to 2023.From the results of GML index decomposition, the average value of technological progress is generally greater than the average value of technical efficiency, and the average value of technological progress (TC) in all cities is higher than 1, among which the EC value of Yan'an City, Shaanxi Province is the lowest (0.973), indicating that the contribution of RBCs to the improvement of GDE brought about by the development of technological progress and innovation is relatively greater, while the comprehensive management level of green development and the innovation of resource allocation need to be improved.

5. Conclusions and Enlightenment

Our findings demonstrate that technological progress, rather than efficiency catch-up, dominates GDE growth, corroborating the induced-innovation hypothesis in the context of stringent environmental regulation. However, the elasticity of GDE with respect to TC is not uniform: oil-gas and mature cities exhibit an elasticity of 1.24, whereas declining cities display only 0.71, indicating diminishing returns to innovation in the absence of complementary managerial capacity. Four extended policy packages are therefore proposed.

1) Establish a long-term, differentiated green-performance evaluation standard for RBCs along the Yellow River in Shaanxi. On the one hand, cities with varying resource endowments and development stages should be subject to tailored advancement pathways; on the other, governments must embed green-development-efficiency metrics into future urban planning rather than focusing solely on environmental expenditure, thereby securing sustained green-economic growth under the principle of sustainable development[11].

2) Construct a green industrial system to propel industrial-structure transformation and upgrading. RBCs in Shaanxi should establish an integrated green industrial architecture through policy guidance and fiscal incentives that steer the industrial mix toward higher-order activities. First, increase support for high-technology and modern-service sectors to channel capital into green, low-carbon industries; second, accelerate the technological retrofit of traditional resource industries—via clean-energy adoption and circular-economy models—to minimise environmental externalities; and third, forge inter-regional green value chains that enhance comprehensive resource utilisation and progressively reduce dependence on extractive rents.

3) Strengthen environmental regulation and implement green governance. Tightening environmental oversight is pivotal to improving the green-development efficiency of RBCs. First, enact more stringent environmental statutes and emission standards, and enforce absolute caps and tradable-permit systems for all pollutants. Second, intensify monitoring of corporate environmental performance: impose severe penalties on exceedance while rewarding technological innovations that curtail emissions at source. Third, cultivate a green financial ecosystem—leveraging green credit, green bonds and carbon-market instruments—to channel low-cost capital into clean industries. Finally, embed environmental education and public engagement programmes that raise societal awareness and create a co-governance architecture linking government, enterprises and citizens in a shared green-transition agenda.

4) Deepen regional synergy to deliver shared development. RBCs in Shaanxi should move beyond administrative silos to create an integrated basin-wide governance framework that pools resources and matches complementary strengths. First, establish a regional coordination council that aligns industrial master plans, averts homogenous competition and nurtures distinctive, non-overlapping industrial clusters. Second, accelerate cross-jurisdictional infrastructure connectivity—rail, road and digital corridors—to raise logistics efficiency and shrink transaction costs. Third, craft a unified environmental protection protocol that implements joint air-shed management, watershed restoration and cross-city eco-compensation, thereby internalising trans-boundary externalities. Finally, build an open regional innovation platform that shares high-performance computing, testing facilities

and patent databases, speeding up the diffusion and commercialisation of green technologies. Through these coordinated measures, Shaanxi's RBCs can graduate from isolated optimisation to collective, shared development and elevate basin-wide green-development performance.

In sum, accelerating the green transition of RBCs along the Yellow River requires a shift from uniform command-and-control directives toward innovation-compatible, heterogeneity-aware and digitally enforced policy mixes. Future research should incorporate micro-firm data to test whether the observed TC gains are driven by front-runner enterprises or by sector-wide technological diffusion, and should explore how inter-city knowledge spillovers can be enhanced through digital-twin simulations of ecological carrying capacity.

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