# Spatial Evolution and Regional Disparities Measurement and Decomposition of Green Development Efficiency in China's Eight Economic Zones

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**Abstract.** This study analyzes the spatial and temporal evolution of green development efficiency (GDE) in China's eight comprehensive economic zones from 2011 to 2021. Using an improved Super-SBM Data Envelopment Analysis model that includes undesirable outputs, the study measures regional GDE accurately. The Theil index is used to assess and decompose regional disparities within and between these zones. Results show that GDE increased nationwide, with clear spatial differences: central China leads, followed by eastern, and then western regions. The Middle Yellow River zone experienced the most significant improvement, reaching the highest efficiency by 2021. Eastern China, the Middle Yangtze River, and Northwest zones lag behind with considerable potential for growth. The Theil index indicates that overall regional disparities in GDE have declined, mostly due to shrinking differences within regions. However, since 2019, disparities between regions have slightly increased. Northern China has the largest internal efficiency gap, mainly because of uneven provincial development. Policy recommendations include improving national green policies, increasing investments in green technology and industry, and enhancing regional collaboration tailored to local strengths. These actions can help achieve more balanced and sustainable green development across China's diverse economic zones.

**Keywords:** Green development efficiency (GDE); Super-efficiency SBM Model; Eight economic zones; Theil Index

## 1 Introduction

Since China's reform and opening up, its economy has rapidly developed, but this fast growth has resulted in resource shortages and ecological issues becoming prominent. According to World Bank data, China has become the world's second-largest economy and the largest energy consumer and carbon emitter, which contrasts with its per capita resource scarcity and fragile ecology[1]. To address these challenges, China proposed the green development concept in 2015, emphasizing circular economy, low carbon,

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and sustainability, aiming to promote transformation toward a low input, low emission, and high output economic model. Accurate evaluation of green development levels is critical for both government and academia to scientifically tailor regional green development paths and achieve coordinated economic and environmental progress.

## 2 Literature Review

### 2.1 Research Progress on Multi-Scale Green Development

Existing research covers multiple geographic scales including global, national, provincial, urban agglomerations, and county levels. Internationally, scholars compare green development levels of OECD countries[2], ASEAN[3], and Belt and Road countries[4]. Provincial-level studies in China focus on all 30 provinces[5], constructing evaluation systems. Urban agglomeration studies, like those on the Yangtze River Economic Belt[6], Yellow River Basin[7], Beijing-Tianjin-Hebei[8], and Pearl River Delta[9], reveal spatial heterogeneity using stochastic DEA and cloud models. At the county level, Rong-bo [10] explored the driving effect of ecological function zone policies on the green development of counties, filling the gap in micro-scale research. In terms of industrial dimensions, distinctive evaluation systems have been formed in fields such as industry[11], agriculture[12]. However, cross-sector research suffers from fragmented indicator systems and comparability issues.

### 2.2 Measurement Methods of Green Development

Quantitative research on green development mainly adopts two paradigms: efficiency measurement and index system construction. Compared to traditional efficiency measurements, GDE involves environmental constraints in the input-output framework, aiming for minimizing resource consumption and environmental cost while maximizing economic output - a dual-objective optimization. Data Envelopment Analysis (DEA) is the mainstream technique, with advances including two-stage DEA[13], three-stage DEA[14], slack-based measure (SBM)[15], Super-SBM[16], and super-EBM models[17] improving accuracy. Index systems integrate economic, ecological, social, and governance dimensions, based on frameworks like WCED, OECD, UNEP, and China's CCIEE and WWF. However, issues remain such as redundant indicators and data limitations at micro levels. Scholars often customize indicators with entropy weighting approach[18], factor analysis[19], and AHP[20], but heterogeneity reduces cross-study comparability.

Current research limitations include: (1) Polarized scales (macro national/provincial vs. local micro units) without meso-level economic zone analysis; (2)Non-standardized methods limiting comparability; (3) Lack of spatial perspective ignoring regional heterogeneity and spatial correlations.

This paper innovates by considering eight integrated economic zones rather than traditional east-middle-west divisions, improving DEA models with four dimensions

(capital, labor, technology, energy), and combining dynamic efficiency trends with spatial effects to elucidate spatial-temporal heterogeneity and decomposition of green development differences.

# 3 Methodology and Data

## 3.1 Super-Efficiency SBM Model Incorporating Undesired Outputs

The traditional SBM model may yield multiple efficient decision-making units (DMUs) with efficiency value 1, which cannot be ranked further. The Super-SBM model improves this by ordering efficient DMUs properly, better reflecting real GDE in China.

$$\theta^* = \min_{\lambda, s^-, s^+} \frac{1 + \frac{1}{m}\sum_{i=1}^{m} \frac{s_i^-}{x_{io}^t}}{1 - \frac{1}{q+h}\left(\sum_{r=1}^{q} \frac{s_r^+}{y_{ro}^t} + \sum_{k=1}^{h} \frac{s_k^-}{b_{ko}^t}\right)}$$

$$\text{s.t. } x_{io}^t \geq \sum_{t=1}^{T} \sum_{j=1, j\neq o}^{n} \lambda_j^t x_{ij}^t - s_i^- \quad i = 1,2,\ldots,m;$$

$$y_{ro}^t \leq \sum_{t=1}^{T} \sum_{j=1, j\neq o}^{n} \lambda_j^t y_{rj}^t + s_r^+ \quad r = 1,2,\ldots,q;$$

$$b_{ko}^t \geq \sum_{t=1}^{T} \sum_{j=1, j\neq o}^{n} \lambda_j^t b_{kj}^t - s_k^- \quad k = 1,2,\ldots,h;$$

$$\lambda_j^t \geq 0(\forall j), s_i^- \geq 0(\forall i), s_r^+ \geq 0(\forall r), s_k^- \geq 0(\forall k)$$

In the equation: $\theta^*$ represents the GDE score; x denotes input factors, while y and b represent desirable and undesirable output factors respectively; m, q, h indicate the number of indicators for inputs, desirable outputs, and undesirable outputs; i, r, k correspond to decision-making units (DMUs) for inputs, desirable outputs, and undesirable outputs; $s_i^-$, $s_r^+$, $s_k^-$ are slack variables for inputs, desirable outputs, and undesirable outputs; $\lambda_j^t$ is the weight vector. When $\theta^* \geq 1$, the evaluated production decision-making unit is relatively efficient; When $\theta^* < 1$, the evaluated DMU is relatively inefficient, indicating efficiency losses that can be improved by optimizing input quantities, desirable outputs, and undesirable outputs to enhance GDE.

## 3.2 Theil Index

Theil index measures spatial disparities in GDE across the eight economic zones in China, capturing total inequality (0–1, smaller values mean less disparity). It is decomposable into within-region and between-region components, revealing main sources of differences.

$$T = \frac{}{k}\sum_{q=1}\left(\frac{}{\bar{S}} \times ln\frac{}{\bar{S}}\right)$$

$$T_{\mathrm{p}} = \frac{1}{k_p}\sum_{q=1}^{k_{\mathrm{p}}}\left(\frac{S_{pq}}{\bar{S}_p} \times ln\frac{S_{pq}}{\bar{S}_p}\right)$$

$$T = T_w + T_b = \sum_{p=1}^{8}\left(\frac{k_p}{k} \times \frac{\bar{S}_p}{\bar{S}} \times T_p\right) + \sum_{p=1}^{8}\left(\frac{k_p}{k} \times \frac{\bar{S}_p}{\bar{S}} \times ln\frac{\bar{S}_p}{\bar{S}}\right)$$

$$C_w = \frac{T_w}{T}$$

$$C_b = \frac{T_b}{T}$$

$$C_p = \frac{S_p}{S} \times \frac{T_p}{T}$$

In the above equation: T, $T_p$, $T_w$, and $T_b$ represent the Theil indices of green development at the national level, regional level, intra-regional level, and inter-regional level respectively, reflecting the disparities in green development at corresponding scales. $C_w$, $C_b$, and $C_p$ denote the contribution rates of intra-regional, inter-regional, and sub-regional variations respectively, indicating how internal differences, external differences, and sub-regional disparities influence the total variation. p, q, and k represent region, province, and number of provinces respectively, with $k_p$ indicating the number of provinces in region p. S and $\bar{S}$ represent the aggregate and average national green development levels respectively. $S_p$, $S_q$, and $S_{pq}$ denote the aggregate green development level of provinces within region p, the green development level of province q, and the green development level of province q within region p respectively. $\bar{S}_p$ represents the average green development level of region p.

### 3.3 Study Units, Evaluation System, and Data Sources

China is divided into eight integrated economic zones, grouping provinces by geographic and economic similarities (Table 1). The evaluation system adopts input indicators from capital, labor, technology, and energy, converted to constant 2011 prices to eliminate price effects, with output indicators including technological output, ecological benefits, and pollution measured through the entropy method (Table 2). Data is sourced from official yearbooks: China Statistical Yearbook, Energy Statistical Yearbook, Science and Technology Statistical Yearbook, Environment Statistical Yearbook covering 2012-2022.

**Table 1.** Eight comprehensive economic zones in China

| | Economic zone | Province |
|---|---|---|
| Zone 1 | Northeast China | Liaoning, Jilin, Heilongjiang |
| Zone 2 | Northern China | Beijing, Tianjin, Hebei, Shandong |
| Zone 3 | Eastern China | Shanghai, Jiangsu, Zhejiang |
| Zone 4 | Southern Coastal Area | Fujian, Guangdong, Hainan |
| Zone 5 | The middle region of the Yellow River | Shanxi, Inner Mongolia, Henan, Shaanxi |
| Zone 6 | The middle region of the Yangtze River | Anhui, Jiangxi, Hubei, Hunan |
| Zone 7 | Southwest China | Guangxi, Chongqing, Sichuan, Guizhou, Yunnan |
| Zone 8 | Northwest China | Gansu, Qinghai, Ningxia, Xinjiang |

**Table 2.** Input-Output Indicators

| | Indicator type | | |
|---|---|---|---|
| | 1st-level indicator | 2nd-level indicator | 3rd-level indicator |
| Input indicators | Capital input | Capital stock | Investment in fixed assets |
| | Labor input | the number of employees | |
| | Technical Input | full-time equivalent of R&D personnel | |
| | Energy input | total energy consumed | Convert into standard coal |
| | economic output | Regional GDP | |
| Output indicators | Technological output | R&D technological output | The number of scientific and technological papers published |
| | | | The number of published scientific and technological works |
| | | | The number of patent authorizations |
| | Ecological benefit | Ecological environment index | Forestry area |
| | | | Afforestation area |
| | | | Green area |
| | Environmental pollution | environmental pollution index | Sulfur dioxide emissions |
| | | | Chemical oxygen demand |
| | | environmental pollution index | General industrial solid waste |

# 4 Spatial-Temporal Evolution of GDE in China's Eight Economic Zones

## 4.1 Temporal Evolution

From 2011 to 2021 (Table 3), the average GDE among zones ranged between 0.57 and 0.86, showing clear differences. Initially, Northeast and Southwest zones had relatively higher efficiency; by 2021, central zones improved significantly. The national average efficiency exhibits a "W"-shaped upward trend, with Northeast, Southwest, and Southern Coastal zones consistently outperforming national and other zones, contributing greatly to overall development. Northern China showed a "U"-shaped trend. Middle Yellow River region experienced a slow decline initially, then rapid rise peaking at 1.02 in 2021 (highest among all zones). Eastern China, Middle Yangtze River, and Northwest China lag behind, indicating room for improvement (fig. 1).

**Table 3.** Average of GDE of eight economic zones and the whole nation

| | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | Mean | Rank |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Zone1 | 0.81 | 0.73 | 0.72 | 0.75 | 0.93 | 0.84 | 0.88 | 1.05 | 0.84 | 0.98 | 0.89 | 0.86 | 1 |
| Zone2 | 0.82 | 0.75 | 0.73 | 0.71 | 0.70 | 0.60 | 0.62 | 0.69 | 0.65 | 0.75 | 0.80 | 0.71 | 5 |
| Zone3 | 0.63 | 0.62 | 0.57 | 0.57 | 0.59 | 0.59 | 0.65 | 0.71 | 0.79 | 0.88 | 0.92 | 0.68 | 7 |
| Zone4 | 0.77 | 0.71 | 0.78 | 0.62 | 0.73 | 0.69 | 0.79 | 0.76 | 0.88 | 1.03 | 0.88 | 0.79 | 3 |
| Zone5 | 0.68 | 0.65 | 0.63 | 0.60 | 0.68 | 0.60 | 0.71 | 0.89 | 0.77 | 0.87 | 1.02 | 0.74 | 4 |
| Zone6 | 0.59 | 0.56 | 0.58 | 0.60 | 0.66 | 0.66 | 0.69 | 0.72 | 0.73 | 0.89 | 0.84 | 0.68 | 6 |
| Zone7 | 0.73 | 0.66 | 0.70 | 0.70 | 0.84 | 0.76 | 0.82 | 0.81 | 0.85 | 0.99 | 0.94 | 0.80 | 2 |
| Zone8 | 0.66 | 0.45 | 0.47 | 0.43 | 0.45 | 0.49 | 0.52 | 0.63 | 0.70 | 0.83 | 0.64 | 0.57 | 8 |
| China | 0.71 | 0.64 | 0.65 | 0.62 | 0.70 | 0.65 | 0.71 | 0.78 | 0.78 | 0.90 | 0.87 | 0.73 | |

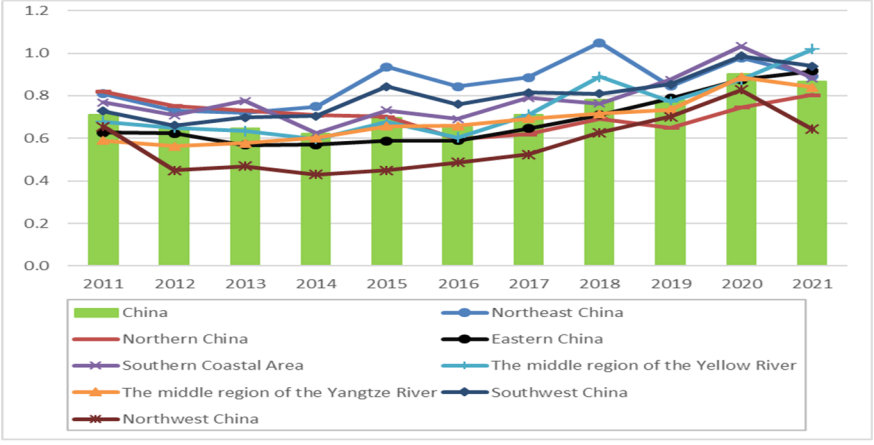


**Fig. 1.** Time-series evolution patterns of GDE in eight economic zones

### 4.2 Spatial Evolution

Using ArcGIS, five efficiency levels were defined (Fig.2): high (>0.9), good (0.8-0.89), medium (0.7-0.79), poor (0.61-0.69), and inefficient (<0.6). Comparing 2011 and 2021, the latter shows significant improvements, with five zones upgrading to higher performance grades. The Middle Yellow River, Eastern China, and Southwest shifted from poor/medium to high efficiency. The Middle Yangtze River rose from inefficient to good. Spatial distribution reveals a clear "central > eastern > western" pattern by 2021, indicating strong concentration of high-efficiency zones in central China, moderate in east, and low in west, with a shift of GDE from east to west over time.

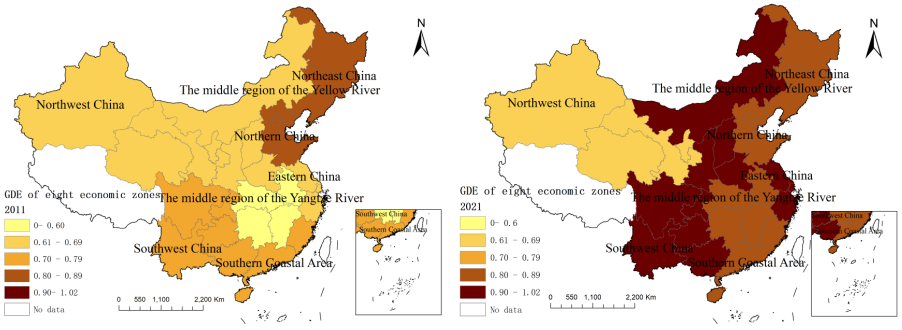


**Fig. 2.** Spatial patterns of average GDE in eight comprehensive economic zones.

## 5 Measurement and Decomposition of Regional Disparities in GDE

### 5.1 The Theil Index of China's GDE and Its Evolution

It can be seen from Table 4 and Figure 3 that the disparities in China's GDE during the research period can be divided into two stages. In the first stage (2011-2019), the Theil Index showed a significant downward trend, with an average annual decline of 6.9%, which indicates that the disparity in China's GDE is gradually narrowing. In the second stage (2019-2021), the Theil Index showed an upward trend, with an average annual growth rate of 4.0%, which indicates an increase in regional disparities. Throughout the research period, the Theil index showed a fluctuating downward trend, which indicates that as the GDE of China continues to improve, the disparities in China's GDE gradually decreases.

The contribution rates of within-group and between-group differences to the GDE of China have the following two characteristics: First, within-group disparities are the main contributors to the disparities in China's GDE. Second, the gap in the contribution rate of disparities between and within regions to the total differences has gradually narrowed.

**Table 4.** The Theil index and decomposition

| | T | $T_w$ | $T_b$ | $C_w$ | $C_b$ |
|---|---|---|---|---|---|
| 2011 | 0.0595 | 0.0534 | 0.0062 | 89.65 | 10.36 |
| 2012 | 0.0570 | 0.0457 | 0.0112 | 80.26 | 19.74 |
| 2013 | 0.0543 | 0.0432 | 0.0111 | 79.51 | 20.49 |
| 2014 | 0.0507 | 0.0386 | 0.0122 | 76.03 | 23.97 |
| 2015 | 0.0592 | 0.0392 | 0.0201 | 66.13 | 33.87 |
| 2016 | 0.0421 | 0.0298 | 0.0123 | 70.71 | 29.29 |
| 2017 | 0.0340 | 0.0221 | 0.0119 | 65.13 | 34.90 |
| 2018 | 0.0298 | 0.0186 | 0.0113 | 62.20 | 37.80 |
| 2019 | 0.0269 | 0.0222 | 0.0047 | 82.58 | 17.38 |
| 2020 | 0.0281 | 0.0232 | 0.0048 | 82.82 | 17.15 |
| 2021 | 0.0290 | 0.0210 | 0.0080 | 72.31 | 27.69 |

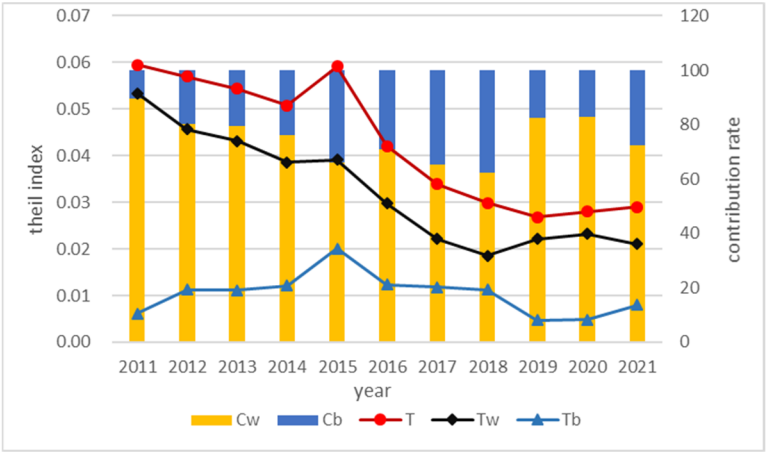


**Fig. 3.** Total Theil index and decomposition

## 5.2 The Within-Group Disparities and Evolution of the Eight Economic Zones

As shown in Table 5 and Figure 4, Zone 2 (Northern China) consistently shows the highest Theil index and contribution rate, indicating the largest within-group disparities in GDE within that zone, mainly due to provincial disparities in industrial structure and development levels (Beijing ranking high, Hebei and Tianjin lagging). Zones 4 (Southern Coastal), 5 (Middle Yellow River), and 7 (Southwest) show decreasing within-group disparities over time. Zone 8 (Northwest) has large fluctuations due to provinces like Qinghai and Xinjiang. Zones 3 (Eastern) and 6 (Middle Yangtze River) reveal significant increases in within-group disparities, largely due to lagging provinces within these zones (e.g., Anhui).

**Table 5.** Theil Index of green development level and its contribution rate of eight economic zones

| | zone1 | zone2 | zone3 | zone4 | zone5 | zone6 | zone7 | zone8 |
|---|---|---|---|---|---|---|---|---|
| 2011 | 0.0349 | 0.1407 | 0.0134 | 0.0460 | 0.0528 | 0.0141 | 0.0347 | 0.0585 |
| | (6.71) | (36.50) | (1.99) | (8.40) | (11.32) | (2.63) | (9.99) | (12.14) |
| 2012 | 0.0225 | 0.1396 | 0.0098 | 0.0458 | 0.0537 | 0.0168 | 0.0200 | 0.0257 |
| | (4.52) | (38.58) | (1.68) | (8.92) | (12.81) | (3.47) | (6.06) | (4.22) |
| 2013 | 0.0050 | 0.1302 | 0.0029 | 0.0596 | 0.0657 | 0.0131 | 0.0239 | 0.0105 |
| | (1.03) | (36.31) | (.47) | (13.21) | (15.87) | (2.87) | (7.96) | (1.88) |
| 2014 | 0.0062 | 0.1257 | 0.0050 | 0.0439 | 0.0329 | 0.0160 | 0.0221 | 0.0384 |
| | (1.47) | (37.57) | (.91) | (8.65) | (8.28) | (4.07) | (8.22) | (6.97) |
| 2015 | 0.0060 | 0.1304 | 0.0047 | 0.0369 | 0.0550 | 0.0170 | 0.0157 | 0.0491 |
| | (1.35) | (29.56) | (.67) | (6.54) | (11.99) | (3.61) | (5.33) | (7.14) |
| 2016 | 0.0097 | 0.0993 | 0.0074 | 0.0138 | 0.0536 | 0.0263 | 0.0079 | 0.0261 |
| | (2.98) | (28.72) | (1.60) | (3.48) | (15.73) | (8.41) | (3.66) | (6.16) |
| 2017 | 0.0054 | 0.0549 | 0.0125 | 0.0206 | 0.0300 | 0.0232 | 0.0079 | 0.0308 |
| | (2.00) | (18.88) | (3.38) | (6.76) | (11.80) | (8.91) | (4.45) | (8.97) |
| 2018 | 0.0004 | 0.0472 | 0.0111 | 0.0084 | 0.0303 | 0.0215 | 0.0091 | 0.0208 |
| | (.18) | (18.83) | (3.39) | (2.75) | (15.47) | (8.84) | (5.28) | (7.49) |
| 2019 | 0.0025 | 0.0769 | 0.0263 | 0.0003 | 0.0192 | 0.0162 | 0.0044 | 0.0430 |
| | (1.01) | (32.02) | (9.95) | (.12) | (9.52) | (7.65) | (3.02) | (19.29) |
| 2020 | 0.0032 | 0.0886 | 0.0223 | 0.0001 | 0.0165 | 0.0175 | 0.0015 | 0.0501 |
| | (1.25) | (35.02) | (7.75) | (.03) | (7.64) | (8.22) | (.97) | (21.92) |
| 2021 | 0.0070 | 0.0730 | 0.0322 | 0.0117 | 0.0003 | 0.0231 | 0.0059 | 0.0259 |
| | (2.48) | (31.12) | (11.72) | (4.10) | (.16) | (10.28) | (3.67) | (8.81) |

Note: Data in brackets indicates contribution rate (%)

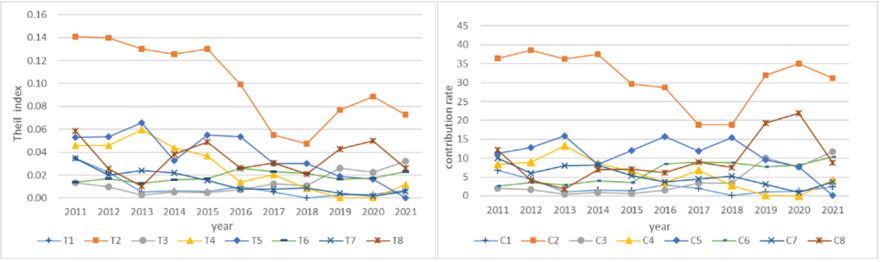


**Fig. 4.** Theil Index of green development level and its contribution rate of eight economic zones

## 6 Conclusions and Policy Implications

GDE in the eight economic zones generally increased during the study period, with spatial disparities presenting a decreasing "central > eastern > western" gradient.

The total disparity decline is attributed to increased government attention and policy incentives fostering more balanced green development.

Within-group disparities contribute more to total disparity than between-group differences.

Policy suggestions at the national level include improving the policy framework, increasing financial support for green industries and technology R&D, promoting innovation, and enhancing international cooperation.

At the economic zone level, recommendations include strengthening regional collaboration, leveraging regional advantages to develop characteristic green industries, establishing green economic belts and ecological demonstration zones, and building mechanisms for coordinated green development across regions.

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