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Regional Disparities in China's Sustainable Development Under Different Classification Systems

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Abstract: Unbalanced regional development remains a major obstacle to sustainable development. In recent years, China has experienced slower GDP growth, shifting population trends, rural revitalization, and nationwide poverty reduction. It is unclear if China's core pattern of uneven regional development has changed as a result. This study analyzes county-level data from 2010 to 2020 using five regional categories: poverty-stricken vs. non-poverty-stricken counties, urban-dominant vs. rural-dominant areas, population growth vs. population decline, GDP growth vs. decline, and Eastern, Central, Western, and Northeast China regions. Using the Sustainable Development Index and Theil Index, we calculated 21 county-level sustainability indicators to measure regional gaps across economy, environment, and social services. Results show that as of 2020, the overall sustainable development in China steadily improved. While the disparity between poverty- and non-poverty-stricken counties has largely narrowed, disparities between urban-rural-dominant areas and between Eastern and Western China remain the main challenges. Differences linked to population or GDP changes were not significant. However, many Northeast China regions pose sustainability concerns due to simultaneous population and GDP decline.

Key words: sustainable development; SDGs; urban-rural difference; Theil Index; Northeast China regions

1 Introduction

The concept of sustainability as policy began with the United Nations' (UN) Brundtland Commission report, "Our Common Future" (WCED, 1987; Clark and Wu, 2016). In 2015, the UN launched the 2030 Agenda for Sustainable Development, which set 17 Sustainable Development Goals (SDGs) that were agreed to by 193 countries. Significant work has been done toward achieving these 17 SDGs (Xu et al., 2020). Following the promulgation of the 2030 Agenda, China created its own National Program to guide its sustainable development through its current economic, environmental, and social challenges. From 2000 to 2015, China's overall progress on the SDGs improved; however, progress varied greatly across provinces (Xu et al., 2020).

Since China's "reform and opening up" in 1978 (Lu et al., 2019), the Chinese economy saw rapid growth for over 30 years. By 2010, however, 165.7 million people still lived in extreme poverty, mostly in remote, harsh mountainous or highland plateau areas where escaping poverty was difficult. To tackle this issue, the Chinese government began a targeted poverty program in 2013 based on a 10-year plan (2011–2020) (Guo et al., 2022). In 2014, the National Rural Revitalization Administration focused its support on 832 counties that were especially poor. By 2021, China declared it had ended extreme poverty nationwide by improving sustainability and reducing inequality (Pan et al., 2024).

Furthermore, the gap between urban and rural development was a major challenge for China's continued sustainability. Recent policies, such as rural revitalization, have helped reduce this urban–rural divide. However, this inte-

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gration still faces a huge negative impact of path dependence due to historical reasons (Yang, 2016). In addition, other than studies on China's economic differences, research comparing urban and rural sustainability is limited. A notable gap also exists in relation to the disparities in educational resources between cities and the countryside. This human capital gap has worsened following digitalization, as human resources tend to concentrate in cities (Sun et al., 2023). Differences in electricity use also clearly highlight the rural–urban divide in relation to economic development, urbanization, and income (Song et al., 2022). Some experts point to this "great inequality" as reflecting how global economic inequality leads to environmental inequality. In 2015, for example, the richest 10% of the world's population caused 34% of global carbon emissions, while the poorest 50% caused only 15% (Rammelt et al., 2022), which suggests that inequalities in energy, food, water, and infrastructure illustrate the true depth of sustainability gaps between regions or groups.

China's population growth has slowed since 2022 and may start declining, partly because rural-to-urban migration has caused population losses in many rural areas (Wang, 2023). In this study, "population change areas" were defined to compare regions with growing and shrinking populations from 2010 to 2020 to identify how this change has affected per-person sustainability.

Tracking economic sustainability is tied to population changes. Many Chinese cities relying on natural resources now face severe pollution, resource depletion, and loss of skilled workers. Hence, these cities experience both economic decline and population losses, threatening their sustainability (Wang, 2022). China's complex topography and landforms in its Eastern, Central, Western, and Northeast regions also cause different changes in their industrial and economic qualities (Jiang and Han, 2023). In particular, the Northeast and Western regions are the main areas of China where poor counties are losing people to urban migration.

While China has made considerable progress in its regional sustainability between 2010 and 2020, uneven regional development remains a major hurdle. While focusing on rural revitalization and poverty reduction recently, China has also experienced new challenges, such as slower GDP growth and a turning point in its population growth. It is unclear if China's main sustainability challenges—such as the urban-rural gap, differences between poverty- and non-poverty-stricken counties, and the East-Central-West economic imbalance—have changed. We also need to identify which areas will need the most attention in the future (Jiang et al., 2022). This paper uses five regional classification systems to examine the changes in economic, environmental, and social sustainability at the county level from 2010 to 2020. By calculating the disparity and Theil indices within these systems, we can analyze the differences in economies, environments, and social services to identify key regional sustainability challenges and how they have changed over time.

2 Research methods

2.1 Regional classification methods

This paper established five regional classification systems, including "poverty-stricken counties" and "non-poverty-stricken counties", "urban-dominant areas" and "rural-dominant areas", "population growth areas" and "population decline areas", "GDP growth areas" and "GDP decline areas" and "Eastern-Central-Western-Northeast regions" (using Eastern China regions as the benchmark, comparing Eastern China regions with Central China regions, Eastern China regions with Western China regions, and Eastern China regions with Northeast China regions) (Figure 1 a-e). The specific criteria for classification are as follows: 1) Poverty-stricken counties and non-poverty-stricken counties: The classification is based on official data from China. A total of 832 poverty-stricken counties are listed by the National Rural Revitalization Administration, while all other counties and cities are categorized as non-poverty-stricken in this study. 2) Urban-dominant areas and rural-dominant areas: Based on previous studies, this paper first extracts the number of people engaged in farming, forestry, animal husbandry, sideline production, and fishery in each county and district according to the data of the seventh population census and calculates their proportion to the total population. Then, counties and regions with a ratio lower than the national average and a population density higher than 500 people per square kilometer are classified as urban-dominant areas, and the remaining areas are classified as rural-dominant areas(Wang, 2018). 3) Population growth areas and population decline areas: In this study, areas where the population in 2020 exceeds that in 2010 are designated as population growth areas; conversely, those where the population in 2020 is lower than that in 2010 are considered to be population decline areas. 4) GDP growth areas and GDP decline areas: This paper categorizes areas with a higher GDP in 2020 than in 2010 as experiencing GDP growth, and those with a lower GDP in 2020 as experiencing GDP decline. 5) Eastern-Central-Western-Northeast regions: Following the official classification of China, this paper divides Beijing, Tianjin, Hebei Province, Shandong Province, Jiangsu Province, Shanghai, Zhejiang Province, Fujian Province, Guangdong Province, and Hainan Province into Eastern China regions. Shanxi, Henan, Hubei, Hunan, Anhui and Jiangxi provinces are categorized as Central China regions. Inner Mongolia Autonomous Prefecture, Shaanxi Province, Sichuan Province, Chongqing, Yunnan Province, Gansu Province, Qinghai Province, Guizhou Province, Ningxia Hui Autonomous Prefecture, Xinjiang Uygur Autonomous Prefecture, Tibet Autonomous.

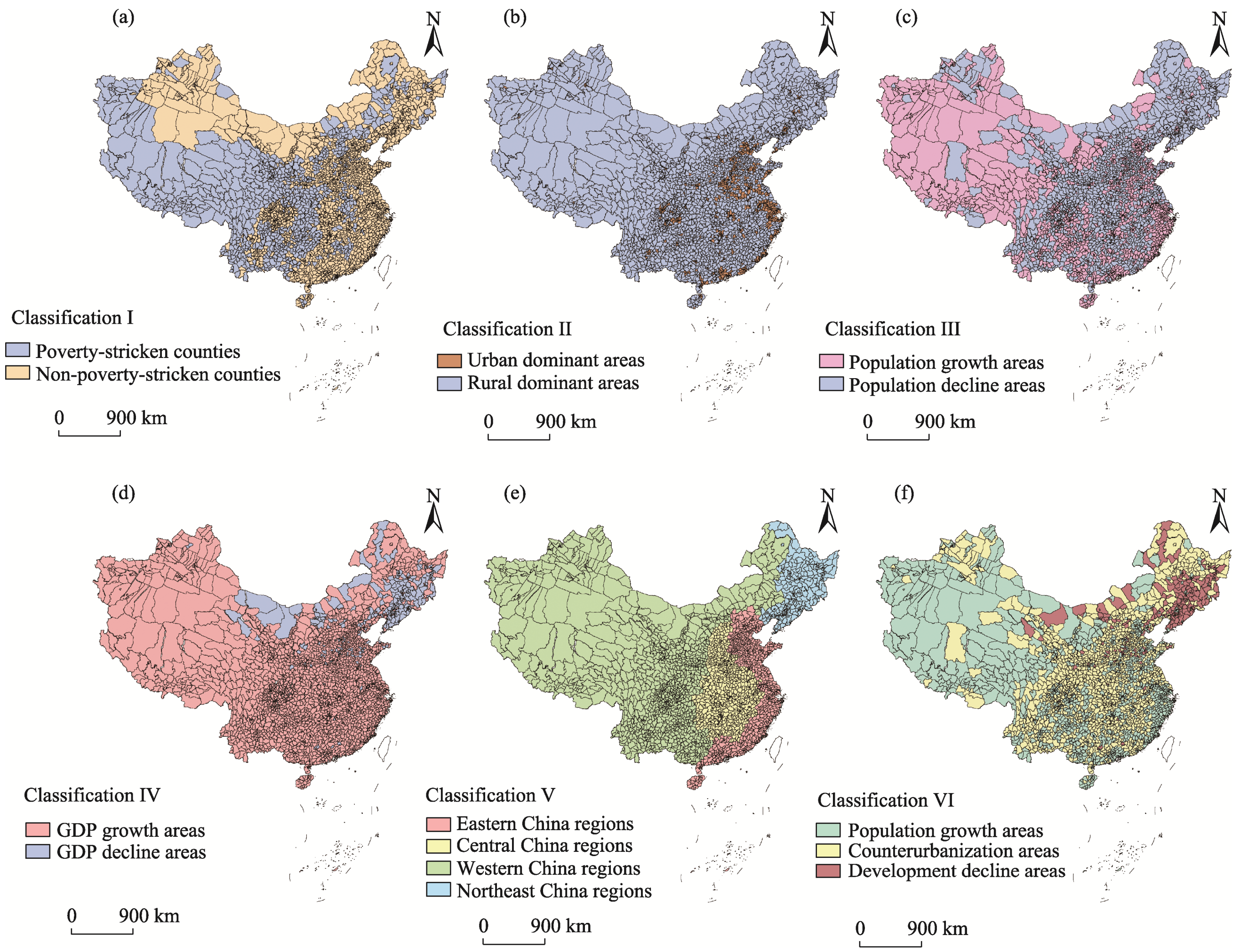

Figure 1 First five main different regional classification systems and a final system subdivision for population decline areas. (a) "poverty-stricken counties" and "non-poverty-stricken counties"; (b)"urban-dominant areas" and "rural-dominant areas"; (c)"population growth areas" and "population decline areas"; (d)"GDP growth areas" and "GDP decline areas"; (e)"Eastern-Central-Western-Northeast regions"; (f)"population growth areas", "counterurbanization areas" and "development decline areas". Among them, "counterurbanization areas" and "development decline areas" are subclasses of "population decline areas"

Note: Data for Hong Kong SAR, Macao SAR, and Taiwan Province are not included in this study.

Prefecture and Guangxi Zhuang Autonomous Prefecture are classified under Western China regions. Heilongjiang Province, Jilin Province, Liaoning Province are included in Northeast China regions.

2.2 Sustainability indicators

Based on the United Nations Sustainable Development Goals (UN-SDGs) index system, 21 indicators were selected to reflect sustainability changes across different regions in China from 2010 to 2020. These indicators are categorized into three dimensions: economy, environment, and social services. Specifically, the economic dimension encompasses indicators such as "GDP" and "GDP per capita" representing SDG1, and "Percentage of households using purified tap water" for SDG6, and "Proportion of areas with electricity" for SDG7. Although the "population" indicator does not fall under the economic category, it is closely associated with "GDP per capita" and thus is discussed alongside other economic metrics. Environmental indicators include "atmospheric particulate matter ($PM_{2.5}$ emissions)", "CO_2 emissions per capita" (data available for 2010 and 2017) for SDG13, "ammonia nitrogen in surface water" for SDG14, and "net primary production of terrestrial ecosystem (NPP)" for SDG15. The social dimension is further divided into educational and medical components. The educational component represents SDG4 and includes indicators such as "number of primary educational buildings and facilities", "number of higher educational buildings and facilities", "number of vocational educational buildings and facilities", "number of teachers in primary education", "number of teachers in middle education", " number of teachers in vocational education" and " number of teachers in higher education ". The medical

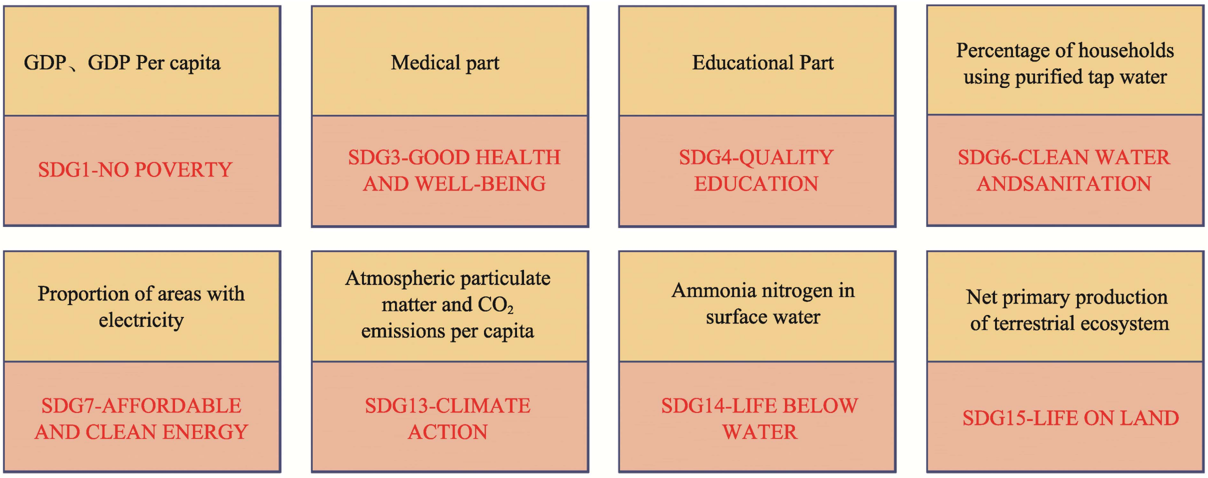

Figure 2 Selected sustainable development indicators representing each SDGs

component represents SDG3 and includes indicators like "number of rural clinics and anti- epidemic stations", "number of drug stores", "number of general hospital buildings and facilities", "number of medical beds" and "life expectancy."

The sustainability scores of each indicator were normalized using Equations (1) and (2) as cited in the reference (Zhao et al., 2022). Negative indicators include atmospheric particulate matter, ammonia nitrogen in surface water, and CO_2 emissions per capita. All other indicators are positive and are calculated using Equation (2). The calculation of all indicators is performed at the county level. Subsequently, the indicator scores associated with a particular sustainability indicator for each county were averaged to obtain the total score for that specific sustainability indicator:

$$S_{ij} = \frac{\max(x_i) - x_{ij}}{\max(x_i) - \min(x_i)} \quad (1)$$

$$S_{ij} = \frac{x_{ij} - \min(x_i)}{\max(x_i) - \min(x_i)} \quad (2)$$

where S_{ij} represents the sustainability score of indicator i in year j; X_{ij} denotes the original value of indicator i in year j. Furthermore, max(X_i) and min(X_i) stand for the upper and lower bounds of the best and worst performance associated with indicator i, respectively (Xu et al., 2020). The upper bound signifies the optimal performance in achieving sustainability, while the lower bound indicates suboptimal performance. The value of S_{ij} ranges from 0 to 1, with values approaching 1 indicating that the county is closer to sustainable development.

2.3 Disparity Indicators

Theil index was applied to construct the inter-regional disparity index. Specifically, we employed the Theil-L index of the first-order Theil index to calculate the inter-regional difference (TBR), and obtained an indicator that can demonstrate China's inter-regional disparity under different regional classifications by incorporating population as a weight (Conceição and Ferreira, 2000). The specific calculation method is outlined as follows:

$$TBR_{ij} = TBR_i + TBR_j = \sum_i \left(\frac{N_i}{N}\right) \log\left(\frac{N_i / N}{Y_i / Y}\right) + \sum_j \left(\frac{N_j}{N}\right) \log\left(\frac{N_j / N}{Y_j / Y}\right)$$

where TBR_{ij} represents the inter-regional Theil index, which is calculated by combining TBR_i and TBR_j. This index is used to assess the inequality disparity between regions classified as i and j. TBR_i measures the contribution of classification i regions to the inter-regional inequality disparity, while TBR_j measures the contribution of classification j regions. N_i denotes the population of classification i region; Y_i indicates the sustainability measure value of classification i region. Similarly, N_j represents the population of classification j region; Y_j signifies the sustainability measure value of classification j region. N is the total population of both classification i and j regions, while Y represents their combined sustainability measure value. The value of TBR_{ij} ranges from 0 to 1. A smaller TBR_{ij} value indicates a smaller inequality disparity between classified region i and classified region j.

The GAP index was introduced to measure China's inter-regional disparity under different regional classifications from the perspective of mean value (Pan et al., 2024). The specific methods are as follows:

$$GAP_{ij} = \frac{mean(Y_i) - mean(Y_j)}{mean(Y)}$$

where GAP_{ij} represents the disparity score between classified regions i and j, which measures the inequality disparity in the mean of the sustainability measure between the two. The values *mean* (Y_i) and *mean* (Y_j) indicate the average sustainability measure of regions classified by i and j, respectively, while *mean* (Y) refers to the overall average sustainability measure for both regions. The denominator is set to the mean value of the total sustainability measurement of both regions in order to facilitate a more comprehensive comparison of disparity scores across different regional classifications.

Since the dimensions of the results calculated by the two methods are different for the TBR index and GAP index, this paper does not compare their specific values. Instead, we focus on their change trends.

2.4 Data records

Statistics: The GDP data for 2010 and 2020 were sourced from the statistical communiques on national economic and social development issued by various regions, reported at current prices. In cases where a region's GDP data for a given year is unavailable, the preceding or following year's data was used to fill in the gap. The inflation rate data over the period from 2010 to 2020, obtained from the National Bureau of Statistics of China, indicates an overall increase of 128.9%. To facilitate comparison, the 2020 GDP figures have been adjusted to constant prices using 2010 as the base year. Population data were derived from the Sixth and Seventh National Census Bulletins. Per capita GDP was calculated based on the GDP and population data. Data on the proportion of tap water supply and electricity supply were obtained from the China Statistical Yearbook and the Rural Poverty Monitoring Report. The list of impoverished counties was provided by the National Rural Revitalization Administration (Table 1).

Point of Interest data: The amounts of buildings and facilities for primary education, vocational education, higher education, rural clinics and anti-epidemic stations, drug stores, and general hospitals were calculated from the Points of Interest database obtained from the Resource and Environment Science and Data Center. The raw data consist of point-like maps displaying the name, type, and location of various facilities and buildings. The number of teachers in primary education, secondary education, vocational education and higher education is sourced from the China City Statistical Yearbook. The number of medical beds is obtained from the China Statistical Yearbook (Township). County-level population life expectancy is downscaled from the provincial population life expectancy based on GDP disparity (Gong et al., 2020), with data sourced from the National Census Bulletin. The total count of each type of building or facility in each county was aggregated using the spatial link function of ArcGIS 10.8 (ESRI Inc.), with the count in each county then divided by its population to obtain a per million persons figure (Table 1).

Environmental monitoring data: The environmental monitoring data includes atmospheric particulate matter, CO_2 emissions, and the amount of ammonia nitrogen in surface water. The information on atmospheric particulate matter is derived from the Tracking Air Pollution in China database (Xiao et al., 2021a, 2021b, 2022c). These original national-scale raster data (ug m^{-3}) have a spatial resolution of 1 km. Averages for counties in 2010 and 2020 were calculated using ArcGIS 10.8 (ESRI Inc.). County-level CO_2 emissions are sourced from the Carbon Emission Accounts & Datasets (CEADs) database (Chen et al., 2020; Xian and Chen, 2022; Chen and Bian, 2023). The original data represent total annual CO_2 emissions at the county level from 1997 to 2017. For this study, we specifically selected emission data for 2010 and 2017 to analyze changes during the poverty eradication program (Le Quéré et al., 2021). To calculate per capita CO_2 emissions, we divided the total CO_2 emissions of each county by its corresponding population totals. Data on ammonia nitrogen content in surface water were collected from weekly water quality reports of key sections in major river basins across China (Pan et al., 2024). This raw dataset provides information on ammoniacal nitrogen content in surface waters as well as the geographical coordinates of the monitoring sites. In 2010, there were a total of 100 monitoring sites, while in 2020 this number rose to 162 sites. Using the cokriging interpolation method within ArcGIS 10.8 (ESRI Inc.), data from these monitoring sites were interpolated into pixel maps with a resolution of 1 km. In addition, average values for counties in both time periods were then calculated based on these derived maps (Table 1).

Remote sensing data: Net primary production data for terrestrial ecosystems were acquired from the Moderate Resolution Imaging Spectroradiometer (MOD17A3). The original data consists of pixel-level information with a resolution of 500 m, and the average values for counties in 2010 and 2020 have been calculated (Table 1).

3 Research results

3.1 Overall changes of sustainable development indicators in China

From 2010 to 2020, the county-level Sustainable Development Goals in China demonstrated an overall increasing trend (Tables 2 & 3).

Utilizing 2010 GDP as the base period and comparing constant-price 2020 GDP against current-price 2010 GDP, the analysis reveals a steady upward trajectory in overall GDP development. Most classified regions exhibited average GDP growth approximating a doubling over the decade, while GDP decline areas and Northeast China regions registered negative average growth (–4.43 billion yuan and –0.60 billion yuan per decade, respectively). Concurrently, China's overall population trend showed positive but decelerating growth. High GDP and population clusters predominantly occurred in non-poverty-stricken counties, urban-dominant areas, population growth areas, GDP growth areas, and Eastern China regions. Conversely, poverty-stricken counties, rural-dominant areas, population decline areas, GDP decline areas, and Northeast China regions demonstrated varying population declines, with the most significant reductions observed in population decline areas (–51800 people per county per decade), GDP decline areas (–44700 people per county per decade), and Northeast China regions (–53000 people per county per decade). Regarding per capita GDP, most regions approached a doubling; Northeast China regions showed a comparatively modest increase (0.318 yuan per county per decade), while GDP decline areas experienced the largest decrease (–0.855 million yuan per county per decade). Electricity accessibility improvements were modest, achieving near-universal coverage (≈98% to 100% by 2020) across all regions. In contrast, purified tap water access displayed significant disparities: non-poverty- stricken counties, urban-dominant areas, GDP decline areas, Eastern China regions, and Northeast China regions exceeded 90% coverage by 2020; rural-dominant areas, population change areas, GDP growth areas, and Central China regions surpassed 80%; Western China regions remained lowest at 75.44%, with poverty-stricken

Table 1 Data source

Indicators		Metrics and unit	Data source
Economical	Housing	Gross Domestic Product (hundred million yuan)	Statistical bulletins of national economic and social development of all regions (https://www.stats.gov.cn/)
		Population (ten thousand people)	National Census Bulletin (https://www.stats.gov.cn/)
		Gross Domestic Product per capita (ten thousand yuan)	By calculation
		Consumer Price Index (%)	National Bureau of Statistics
		Proportion of areas with electricity (%)	China's statistical yearbooks and rural poverty monitoring reports (www.stats.gov.cn)
		Percentage of households using purified tap water (%)	China's statistical yearbooks and rural poverty monitoring reports (www.stats.gov.cn)
Ecological & Environmental	Ecological resources	Net primary production of the terrestrial ecosystem (g C m^{-2})	The Moderate Resolution Imaging Spectroradiometer (MOD17A3) (https://modis.gsfc.nasa.gov/)
	Clean air	Atmospheric particulate matter ($PM_{2.5}$, μg m^{-3})	Tracking Air Pollution in China database (http://tapdata.org.cn)
	Clean surface water	Ammonia nitrogen in surface water (NH_3-N, mg L)	weekly reports on water quality in key sections of China's major river basins (http://www.cnemc.cn/sssj/szzdjczb)
	Climate change	CO_2 emission per capita (t CO_2 per capita)	Carbon Emission Accounts & Datasets (CEADs) database (https://www.ceads.net)
Social service	Education	Primary educational buildings and facilities (Amounts per million persons)	The Resource and Environment Science and Data Center (https://www.resdc.cn/)
		Vocational educational buildings and facilities (Amounts per million persons)	The Resource and Environment Science and Data Center (https://www.resdc.cn/)
		Higher educational buildings and facilities (Amounts per million persons)	The Resource and Environment Science and Data Center (https://www.resdc.cn/)
		Number of teachers in primary education (Amounts per million persons)	China City Statistical Yearbook (https://www.stats.gov.cn/)
		Number of teachers in middle education (Amounts per million persons)	China City Statistical Yearbook (https://www.stats.gov.cn/)
		Number of teachers in vocational education (Amounts per million persons)	China City Statistical Yearbook (https://www.stats.gov.cn/)
		Number of teachers in higher educational institutions (Amounts per million persons)	China City Statistical Yearbook (https://www.stats.gov.cn/)
	Health	Rural clinics and anti-epidemic stations (Amounts per million persons)	The Resource and Environment Science and Data Center (https://www.resdc.cn/)
		Drug stores (Amounts per million persons)	The Resource and Environment Science and Data Center (https://www.resdc.cn/)
		General hospital buildings and facilities (Amounts per million persons)	The Resource and Environment Science and Data Center (https://www.resdc.cn/)
		Number of medical beds (Amounts per million persons)	China Statistical Yearbook (township) (https://www.stats.gov.cn/)
		Life expectancy (ages)	National Census Bulletin (https://www.stats.gov.cn/)
Other		list of poverty-stricken counties	https://nrra.gov.cn/

Table 2 Indicators related to economic, ecological, and environmental aspects of sustainability and disparity, and their performance

Indicators		Economical					Ecological & Environmental			
		Housing					Ecological resources	Clean air	Clean surface water	Climate change
Metrics and unit		Gross Domestic Product (hundred million yuan)	Population (ten thousand people)	Gross Domestic Product per capita (ten thousand yuan)	Proportion of areas with electricity (%)	Percentage of households using purified tap water (%)	Net primary production of the terrestrial ecosystem (g C m^{-2})	Atmospheric particulate matter ($PM_{2.5}$, μg m^{-3})	Ammonia nitrogen in surface water (NH3-N, mg L)	CO_2 emissions per capita (t CO_2 per capita)
Poverty-stricken counties	Average value in 2010	38.66	32.09	1.294	97.97	34.27	506.6	40.63	1.159	3.889
	Average value in 2020	82.15	30.44	2.965	100.0	58.57	544.5	22.89	0.126	5.811
Non-poverty-stricken counties	Average value in 2010	190.2	52.47	3.576	100.0	71.50	420.5	58.84	1.168	8.308
	Average value in 2020	338.1	55.82	5.679	100.0	96.90	458.7	30.10	0.177	9.721
Urban-dominant areas	Average value in 2010	303.8	66.15	4.328	99.98	70.63	334.2	70.22	1.251	7.306
	Average value in 2020	572.9	77.77	7.019	100.0	96.26	366.7	34.08	0.195	7.132
Rural-dominant areas	Average value in 2010	85.07	38.95	2.363	99.19	56.78	488.6	47.09	1.133	6.923
	Average value in 2020	144.0	37.09	4.065	100.0	81.65	528.9	25.65	0.150	9.154
Population growth areas	Average value in 2010	189.4	49.15	3.548	99.21	63.17	427.7	54.12	1.041	7.657
	Average value in 2020	369.1	59.41	5.625	100.0	87.60	461.8	27.66	0.158	8.186
Population decline areas	Average value in 2010	109.3	44.31	2.371	99.58	58.50	460.7	53.03	1.271	6.499
	Average value in 2020	174.2	39.13	4.264	100.0	84.13	502.3	28.28	0.166	8.934
GDP growth areas	Average value in 2010	140.8	47.04	2.703	99.35	59.64	456.3	53.45	1.160	6.336
	Average value in 2020	275.3	49.60	4.979	100.0	84.69	494.6	27.74	0.161	7.637
GDP decline areas	Average value in 2010	194.8	41.62	4.874	99.95	70.10	343.7	54.25	1.221	13.63
	Average value in 2020	150.5	37.15	4.019	100.0	95.51	380.6	30.49	0.176	17.67
Eastern China regions	Average value in 2010	283.7	64.46	3.929	99.99	69.52	435.1	63.66	1.137	7.084
	Average value in 2020	502.7	70.83	6.286	100.0	94.37	472.5	30.16	0.194	7.287
Central China regions	Average value in 2010	114.2	50.26	2.418	99.81	60.23	434.3	66.25	1.383	5.960
	Average value in 2020	233.0	50.29	4.814	100.0	88.02	470.0	33.63	0.194	7.045
Western China regions	Average value in 2010	73.61	33.10	2.473	98.61	52.65	480.1	41.11	1.163	7.251
	Average value in 2020	150.6	34.90	4.342	100.0	75.44	521.0	23.43	0.115	9.884
Northeast China regions	Average value in 2010	129.5	40.24	3.045	99.92	68.34	368.9	42.30	0.712	8.577
	Average value in 2020	123.5	34.94	3.363	100.0	96.18	396.6	25.77	0.181	11.00
Counterurbanization areas	Average value in 2010	89.67	43.88	2.058	99.52	56.55	480.0	52.74	1.286	5.742
	Average value in 2020	165.1	39.07	4.287	100.0	82.22	522.8	27.95	0.165	7.877
Development decline areas	Average value in 2010	179.6	42.02	4.057	99.93	69.75	362.5	53.01	1.183	11.30
	Average value in 2020	135.9	34.80	3.661	100.0	95.16	398.5	29.71	0.178	15.69

Note: Four significant digits are reserved.

counties exhibiting minimal penetration at 58.57%.

Regarding ecological conditions, China's net primary production (NPP) of terrestrial ecosystems exhibited an increasing trend across all classified regions, averaging a gain of 37.16 g C m^{-2} $decade^{-1}$. Concurrently, regional averages for atmospheric particulate matter ($PM_{2.5}$) concentration and ammonia nitrogen levels in surface water demonstrated consistent declines, decreasing by 25.23 μg m^{-3} $decade^{-1}$ and 0.995 mg L^{-1} $decade^{-1}$, respectively. These trajectories indicate favorable progress toward sustainability for the corresponding SDGs (SDG15, SDG11, and SDG14). However, per capita CO_2 emissions showed a concerning upward trend across all regions, increasing by an average of 1.898 t $decade^{-1}$. This rise signifies a deterioration in sustainability for this metric (SDG13). Despite this challenge, the overall environmental sustainability profile remains positive.

Educational metrics reveal relatively equitable per capita primary education infrastructure distribution across China,

Table 3 Indicators related to social service aspects of sustainability and disparity and their performance

Indicators		Social service											
		Education							Health				
Metrics and unit		Number of primary educational buildings and facilities (Amounts per million persons)	Number of vocational educational buildings and facilities (Amounts per million persons)	Number of higher educational buildings and facilities (Amounts per million persons)	Number of teachers in primary education (Amounts per million persons)	Number of teachers in middle education (Amounts per million persons)	Number of teachers in vocational education (Amounts per million persons)	Number of teachers in higher educational institutions (Amounts per million persons)	Number of rural clinics and anti-epidemic stations (Amounts per million persons)	Number of drug stores (Amounts per million persons)	Number of general hospital buildings and facilities (Amounts per million persons)	Number of medical beds (Amounts per million persons)	Life expectancy (ages)
Poverty-stricken counties	Average value in 2010	103.3	9.778	3.559	2918	2238	183.8	105.4	46.46	49.79	48.79	2541	71.49
	Average value in 2020	197.3	7.821	2.498	4264	3740	136.1	125.9	310.6	546.9	102.7	5671	74.91
Non-poverty-stricken counties	Average value in 2010	165.9	32.55	12.93	4448	4057	652.0	1114	71.74	152.6	58.71	2226	74.72
	Average value in 2020	256.3	14.61	25.00	4327	4405	448.9	1323	379.6	959.1	187.7	3789	77.55
Urban-dominant areas	Average value in 2010	119.2	34.25	15.24	2744	2552	589.9	1376	76.27	181.5	39.45	1003	75.47
	Average value in 2020	192.9	14.57	42.01	2832	2872	459.0	1883	268.8	824.4	182.0	1649	78.55
Rural-dominant areas	Average value in 2010	46.52	5.794	1.662	1434	1297	130.4	104.3	13.12	27.77	16.26	961.1	73.12
	Average value in 2020	87.84	3.685	2.696	1735	1680	108.8	147.2	125.5	280.1	46.96	1965	76.10
Population growth areas	Average value in 2010	169.9	35.68	15.23	4075	3603	686.4	1297	95.25	171.4	61.35	2156	73.91
	Average value in 2020	237.4	14.45	28.27	3904	3681	436.4	1491	337.2	870.3	174.1	3531	77.04
Population decline areas	Average value in 2010	129.5	17.85	6.002	3947	3476	374.1	422.9	38.65	82.34	51.50	2455	73.66
	Average value in 2020	240.9	11.12	10.31	4660	4670	291.1	546.5	379.2	814.9	154.2	5019	76.56
GDP growth areas	Average value in 2010	148.2	26.29	10.43	4006	3516	520.4	846.1	66.39	124.8	55.99	2285	73.62
	Average value in 2020	237.2	12.81	19.23	4343	4184	354.4	1002	352.6	812.8	159.9	4390	76.73
GDP decline areas	Average value in 2010	146.3	23.30	8.328	3999	3703	485.6	603.1	47.25	107.0	56.22	2637	75.27
	Average value in 2020	259.5	11.05	11.89	4036	4534	388.4	753.7	429.8	1102	195.3	3848	77.29
Eastern China regions	Average value in 2010	197.0	32.99	13.98	4289	4015	653.2	1057	86.12	183.9	54.51	1848	75.76
	Average value in 2020	282.7	18.27	28.52	4784	4361	540.2	1292	385.4	970.4	190.6	3417	78.50
Central China regions	Average value in 2010	137.5	27.10	9.004	4951	4308	644.9	981.9	49.81	106.7	54.55	2122	73.91
	Average value in 2020	254.1	10.42	17.43	4798	5066	387.6	1080	369.0	770.5	156.5	4666	76.93
Western China regions	Average value in 2010	119.7	17.72	7.522	3131	2581	323.4	227.8	57.81	79.85	56.50	2776	71.80
	Average value in 2020	192.6	10.13	11.30	3782	3431	414.6	623.9	328.3	684.6	126.7	5119	75.20
Northeast China regions	Average value in 2010	146.5	35.30	13.21	4224	3905	560.7	1057	66.68	160.6	59.90	2318	75.69
	Average value in 2020	262.2	12.45	21.06	3831	4695	381.5	1202	385.9	1248	243.6	3009	77.85
Counterurbanization areas	Average value in 2010	127.7	17.08	5.464	3976	3481	362.2	395.2	38.04	79.38	51.11	2409	73.33
	Average value in 2020	237.8	11.12	9.668	4744	4692	285.3	528.1	371.2	770.4	146.6	5157	76.40
Development decline areas	Average value in 2010	138.1	19.70	6.978	3848	3469	428.3	453.6	38.04	90.41	52.57	2762	75.42
	Average value in 2020	260.6	10.15	7.955	4206	4594	325.4	512.8	434.6	1087	188.8	4268	77.35

Note: Four significant digits are reserved.

with consistent expansion of facilities nationwide. While per capita secondary education teaching resources demonstrate growth in all regions except urban-dominant areas, primary education teacher distribution exhibits pronounced regional disparities. Vocational and higher education resources display significant geographical imbalances, concentrated predominantly in non-poverty-stricken counties, urban-dominant areas, population growth regions, GDP growth areas, and Eastern/Central China regions. Notably, vocational education infrastructure and instructional personnel show unsustainable trajectories across all classified regions, with universal declining trends. Conversely, higher education infrastructure demonstrates declining sustainability only in poverty-stricken countries, while higher education teaching personnel exhibit positive growth trajectories across all demographic classifications.

Medical sector trends contrast with educational patterns, demonstrating consistent per capita increases in rural clinics, epidemic prevention stations, pharmacies, and general hospital facilities across all regions, accompanied by corresponding sustainability indicator improvements. While basic medical resources exhibit relatively equitable distribution, advanced healthcare infrastructure remains disproportionately concentrated in urban-dominant areas and Eastern China regions. Notably, the Northeast China regions maintain comparatively robust medical resources across all tiers despite significant population outmigration. Sustainability metrics for per capita hospital beds and life expectancy show positive trajectories universally, with poverty-stricken counties, rural-dominant areas, population-decline regions, and Central/Western China regions displaying the highest bed availability—a pattern coinciding with sustained population loss and ongoing governmental medical investment. Life expectancy patterns mirror economic development gradients, registering the highest values in non-poverty-stricken counties, urban- dominant zones, economically dynamic areas, and Eastern China regions, consistent with GDP's established influence on longevity metrics.

3.2 Regional changes of sustainable development indicators in China

Significant disparities persist between poverty-stricken and non-poverty-stricken counties, with 2020 average GDP and per capita GDP differentials reaching 25.595 billion yuan and 27140 yuan, respectively. However, foundational service gaps in housing, environment, primary education, and basic healthcare have narrowed substantially within poverty- stricken counties. Notably, medical bed availability approaches parity (poverty-stricken counties have 1882 more medical beds per million persons than non-poverty-stricken counties), indicating that social infrastructure no longer constrains sustainable development in these regions. Nevertheless, advanced service disparities remain pronounced: higher education institutions show a tenfold differential (2.498 vs. 25 per million persons); higher education faculty demonstrate an order-of-magnitude gap (125.9 vs. 1,324 per million persons); and general hospital access reflects significant inequality (102.7 vs. 187.7 facilities per million persons) as documented in Tables 2 and 3.

Urban-dominant and rural-dominant areas exhibit a substantial 2020 GDP disparity (428.9 billion yuan), markedly exceeding the poverty classification gap yet demonstrating comparatively limited differences in housing and environmental indicators, with purified tap water access slightly favoring urban zones. Rural-dominant areas outperform urban counterparts in environmental sustainability metrics, though exhibit higher per capita CO_2 emissions. While primary education and healthcare disparities persist, vocational education indicators show notable convergence: per capita secondary/vocational education facilities and teaching personnel gaps decreased significantly between 2010 and 2020, partially compensating for widening differentials in primary education buildings (72.68 to 105.06 per million persons), higher education facilities (13.58 to 39.31 per million persons), and higher education faculty (1272 to 1736 per million persons). Counterintuitively, as of 2020, medical bed availability was significantly higher in rural-dominant areas, surpassing that in urban-dominant areas by 316 beds per million persons, potentially reflecting urban resource dilution due to population density. Nevertheless, urban zones maintain absolute advantages in advanced services: general hospital infrastructure disparity remains substantial (182 vs. 46.96 facilities per million persons), indicating persistent tertiary service inequalities (Tables 2 & 3).

Minimal disparities exist between population growth and decline areas across environmental and social services. Population decline regions demonstrate superior performance in primary education, healthcare, and medical bed availability, while growth areas maintain clear advantages in higher and vocational education. Conversely, GDP decline areas exhibit decreasing populations alongside significantly lower net primary productivity (NPP) and higher education resources compared to GDP growth areas, while registering higher per capita CO_2 emissions and advanced medical service availability. This divergence indicates the absence of a deterministic linkage between demographic contraction and economic decline.

Integrating GDP distribution patterns with population dynamics reveals two distinct decline typologies (Figure 1f): counterurbanization areas (population loss with GDP growth, prevalent in metropolitan cores) and development decline areas (synchronous population-economic contraction, concentrated in Northeast China regions and Inner Mongolia Region). The latter exhibits stark environmental disadvantages: By 2020, counterurbanization areas recorded higher NPP (822.8 g C m^{-2}) and lower per capita CO_2 emissions (7.877 tons) compared to development decline areas (NPP: 398.5 g C m^{-2}; CO_2: 15.69 t), reflecting Northeast

China's dual challenges of economic stagnation and industrial environmental burdens. Nevertheless, development decline areas maintain near- parity in per capita primary/vocational education resources and exceed counterurbanization areas in vocational teaching personnel (325.4 vs. 285.3 per million persons). Medical infrastructure advantages further highlight Northeast China's historical investment legacy, with development decline areas surpassing counterurbanization counterparts across most healthcare metrics (Tables 2 and 3).

Eastern China regions lead in socioeconomic indicators with sustained population growth, yet rank suboptimally environmentally: second in NPP (472.5 g C m^{-2}) and per capita CO_2 emissions (7.287 t), third in $PM_{2.5}$ (30.16 μg m^{-3}) and surface water ammonia nitrogen (0.194 mg L^{-1}). Central and Western China regions show modest GDP/population growth but divergent environmental performance: Western China regions lead in NPP (521.0 g C m^{-2}) and lower $PM_{2.5}$ (23.43 μg m^{-3}), though elevated CO_2 emissions (9.884 tons) reflect heavy industry relocation. Both regions trail Eastern China regions significantly in advanced education and medical services, despite higher per capita bed availability—a likely consequence of outmigration reducing local demand while straining destination resources. Northeast China regions manifest the most acute challenges: average county GDP declined by 0.6 billion yuan and population by 53000 over the decade. Environmental metrics rank consistently low (NPP: 396.6 g C m^{-2}, fourth; CO_2: 11 tons, fourth), though retained institutional capacity sustains social service advantages over Central/Western China regions, preserving foundational elements for regional revitalization.

3.3 Changes of various sustainable development disparity indicators in China

This study employs an equally weighted composite methodology, summing individual sustainability indicators to derive sector-specific disparity indices. The economic housing disparity index integrates "electrification coverage" and "purified tap water access," representing the sum of their respective GAP and TBR indices. Environmental disparity encompasses the aggregated GAP and TBR indices for net primary productivity (NPP), $PM_{2.5}$ concentration, surface water ammonia nitrogen, and per capita CO_2 emissions. Social services disparity comprises fourteen indicators: primary/vocational/higher education facilities, primary/secondary/vocational/higher education teachers, rural clinics, epidemic prevention stations, pharmacies, general hospitals, medical bed availability, and life expectancy-each contributing their GAP and TBR indices. The comprehensive disparity index synthesizes these economic, environmental, and social sector indices through additive aggregation.

From 2010-2020, comprehensive GAP and TBR indices exhibited largely parallel trajectories across most regional classifications, indicating narrowing disparities. Notable exceptions include widening gaps in GDP-variant areas and Eastern-Northeast China regions comparisons. Absolute disparities proved most pronounced between poverty/non-poverty counties, urban-rural-dominant areas, and Eastern/Western China regions, with urban-rural divergence representing the most substantial imbalance (Figure 3a). Conversely, minimal absolute disparities characterized population-variant areas, GDP-variant areas, and Eastern-Central China regions comparisons.

The disparity index representing the areas of housing, environment, and social services: In the 10 years from 2010 to 2020, in terms of housing in the economic field, the absolute disparity between poverty-stricken counties and non-poverty-stricken counties, urban-dominant areas and rural-dominant areas, and Eastern and Western China regions is large. However, the overall disparity shows a downward trend, and this trend is consistent across most classified regions. Only in population change areas do the GAP index and TBR index show opposite trends. In the environmental field, the change trends of these two disparity indexes in some classified regions are similar; however, the GAP index and TBR index for poverty-stricken counties versus non-poverty-stricken counties as well as GDP changing areas contradict each other when comparing Eastern with Western China regions or Eastern with Northeast China regions. In social fields, while both types of disparity indicators exhibit similar change trends overall—alongside significant absolute disparities between poverty-stricken counties versus non-poverty-stricken ones as well as urban versus rural-dominant areas—the narrowing gap among social indicators within these first three categories is noteworthy. Conversely, only the disparity between Eastern China regions and Northeast China regions continues to grow (Figure 3 b-d).

Respective disparity indicators between counterurbanization/development decline areas and population growth regions reveal distinct trajectories over the decade. Counterurbanization areas demonstrate converging sustainability trends with population growth regions across housing, environmental, and social service dimensions, evidenced by significantly narrowing composite disparity indices. Conversely, while development decline areas exhibit divergent economic-housing and environmental disparity trends versus growth regions, these discrepancies remain statistically negligible due to minimal absolute values and consequently marginal impact on composite indices. However, development decline areas display persistent divergence in social services, driving progressively widening comprehensive disparity indices relative to growth regions. This pattern indicates fundamentally diverging sustainable development pathways between development decline and population growth areas (Figure 4).

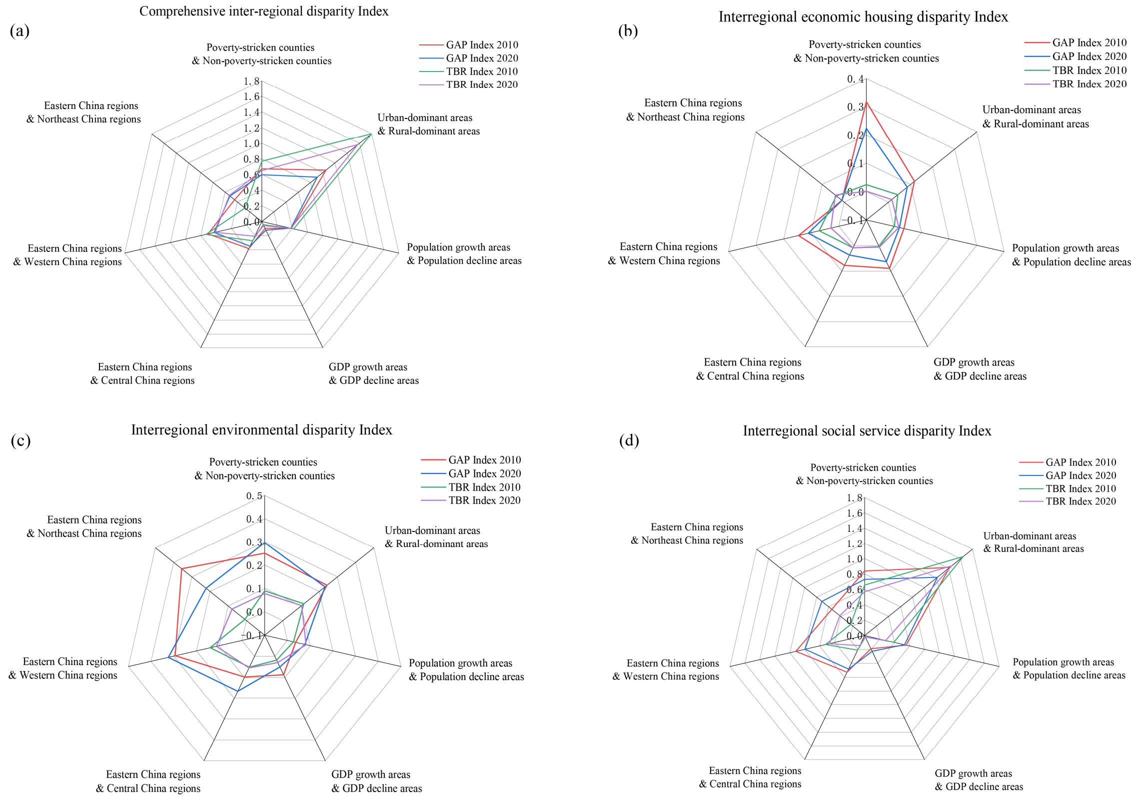

Figure 3 Disparity index at the national scale by comprehensive inter-regional, economic, environmental and social service categories. Among the four classifications (a) Comprehensive inter-regional disparity index; (b) Interregional economic disparity Index; (c) Interregional environmental disparity Index; (d) Interregional social service disparity Index

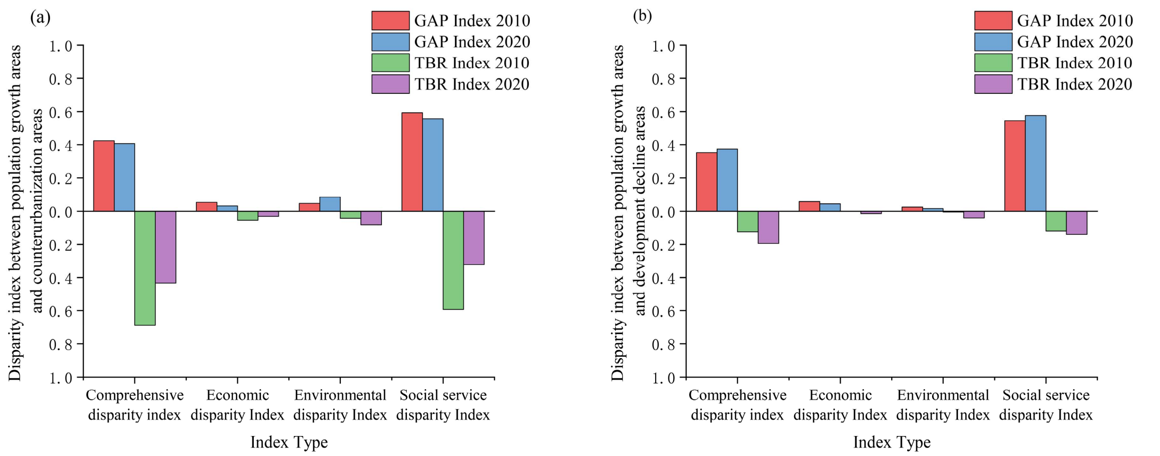

Figure 4 Disparity index between counterurbanization areas and development decline areas on a national scale. Among the two systems (a) is the disparity index between population growth areas and counterurbanization areas; and (b) is the disparity index between population growth areas and development decline areas

4 Discussion and conclusions

4.1 The regional disparities in China's sustainabledevelopment have undergone structural changes

As of 2020, substantial GDP and per-capita GDP disparities persisted between poverty-stricken and non-poverty-stricken counties (reflecting gaps in SDG1 [end poverty]), while differences in housing security have narrowed significantly (Tables 2 & 3). China's comprehensive initiatives to alleviate poverty have effectively resolved the tensions between SDG6 (water security) and SDG7 (energy access). Environmental and social service gaps have shown notable convergence, with environmental disparities reduced substantially and differences in primary education and health care controlled, which indicate the near satisfaction of SDGs 3, 4, 13, 14, and 15 in these regions. Therefore, developmental inequality no longer constitutes China's primary sustainability challenge, demonstrating the efficacy of targeted strategies to eradicate poverty.

Despite their incremental narrowing over the past decade, urban–rural disparities remain China's most consequential challenge in regional development. Fundamental obstacles for sustainable development persist in this domain, despite the increasing spatial ambiguity between urban and rural zones. This artificial urban-rural dichotomy is increasingly inadequate for contemporary analyses. Crucially, China's economic, environmental, and social service disparities, which are manifested across all eight aforementioned SDGs, exceed poverty-related differentials, becoming the predominant constraint on national sustainable development, which necessitates targeted policy interventions beyond the current frameworks.

East-West regional disparities present another critical challenge, with Western China continuing to lag significantly across all eight SDG indicators. Despite substantial investments through the Western Development Strategy yielding notable provincial economic growth since 2000, these gains remain predominantly externally financed. Western China's endogenous development capacity is still underdeveloped compared with Eastern China's globally integrated economy. Therefore, Western China regions urgently require the cultivation of distinctive industries, the development of internal economic circulation, and enhanced connectivity with South and Central Asian and European markets to leverage their geographical advantages and build sustainable competitiveness.

Tables 2 and 3 show that the sustainability differentials between Northeast China regions and other regions are particularly acute. The high spatial overlap between population decline, GDP decline, and the Northeast regions compounds these sustainability deficits. The widening SDG performance gap over the past decade in Northeast China regions reflects the systematic developmental challenges in this region. Achieving regional revitalization demands substantial national resource allocation to counter this expanding sustainability divide.

4.2 Contradictions in disparity indicators

The divergent trajectories between the GAP and TBR indices emerge across several sustainability indicators, including economic sector metrics (e.g., purified tap water access), environmental parameters (e.g., atmospheric particulate matter, surface water ammonia nitrogen), and social service provisions (e.g., per-capita medical beds, life expectancy, teacher availability). These contradictions manifest when an indicator's GAP index declines while its TBR index rises, or vice versa. Such discrepancies stem from fundamental methodological differences: the GAP index measures deviation from interregional means, while the TBR index incorporates population-weighted distribution structures, thereby capturing demographic influences on disparity measurements.

As an illustrative case, consider atmospheric particulate matter with a diameter of 2.5 μm ($PM_{2.5}$) in urban-rural-dominant areas. Urban populations increased from 39.59% in 2010 to 44.72% in 2020; however, their $PM_{2.5}$ contribution declined from 36.53% to 33.89%. Conversely, rural populations decreased from 60.41% to 55.28% while their $PM_{2.5}$ share increased from 63.47% to 66.11%. Crucially, urban-dominant areas demonstrated greater efficiency improvements while generating 2.64% less $PM_{2.5}$ share amid 5.13% population growth and rural-dominant areas produced 2.64% more emissions despite their 5.13% population decline. Consequently, the TBR indices reflect the widening urban-rural disparity due to amplified positive urban contributions and intensified negative rural contributions.

Parallel absolute reductions in $PM_{2.5}$ occurred nationwide: that is, urban concentrations decreased from 70.22 to 34.08 μg m^{-3}, rural concentrations decreased from 47.09 to 25.65 μg m^{-3}, and national averages decreased from 53.53 to 28.00 μg m^{-3}. Correspondingly, the $PM_{2.5}$ GAP Index declined from 0.432 to 0.301 from 2010 to 2020, which demonstrates the capacity of the GAP Index to track aggregate environmental improvements while obscuring the population distribution effects captured by the TBR Index.

Notwithstanding such sectoral contradictions, Figure 3 confirms that these discrepancies exert limited influence on composite disparity indices. Both comprehensive and sectoral disparity metrics retain analytical validity for assessing sustainable development across regional classifications, as index convergence ultimately outweighs methodological divergences in final determinations.

4.3 Research limitations and future prospects

First, the indicator selection methodology prioritized data accessibility over a comprehensive representation of SDG dynamics. Critical considerations were overlooked, including: 1) Whether these 20 indicators could adequately capture the target SDG dimensions; 2) Potential inter-indicator contradictions; and 3) Synergistic or antagonistic interactions between indicators. Furthermore, trend analyses for 2010–2020 remain descriptive rather than explanatory, lacking both a causal interrogation of the observed patterns and predictive modeling of future trajectories. These methodological limitations warrant systematic investigation in future research.

Second, divergent trajectories in the GAP-TBR indices emerge selectively rather than universally. Notable concordance persists in urban–rural contexts (e.g., CO_2 emissions, educational infrastructure) and GDP-variant regions (e.g., net primary productivity, medical bed availability). Three principal factors govern index alignment: 1) Data completeness, which is particularly critical for medical/educational indicators; 2) Demographic weighting in TBR calculations that amplify population distribution effects; and 3)The mathematical sensitivity of the logarithmic transformation inherent to TBR computation, where parameter variations yield disproportionate changes in outcomes.

Third, China's regional heterogeneity manifests complex urbanization patterns, such as counterurbanization in developed megacities compared with population outflows in declining economies. Consequently, zones showing population and GDP decline demonstrate limited spatial overlap, with approximately 63.7% cooccurrence. This investigation preliminarily establishes differences in the SDG indicators between counterurbanization areas and those with declining development in depopulating regions, but does not examine their underlying structural determinants. Future work must establish the causal relationships between regional economic restructuring and sustainability metric variations.

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不同分类体系下中国可持续发展的区域差异

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摘　要：区域发展不均衡是阻碍可持续发展的重要因素，中国近年来在乡村振兴和全面脱贫的同时遭遇 GDP 增速放缓、人口增长出现拐点等，在此形势下中国区域发展不均衡的主要结构是否发生变化仍不清楚。本研究在县域水平下，构建五种区域分类体系，包括贫困与非贫困、城市主导区与乡村主导区、人口增长区与下降区、GDP 增长区与下降区和东部-中部-西部-东北部。利用可持续发展指标、泰尔指数等计算了 2010 至 2020 年县域尺度的经济、环境、社会三大类别共 21 项可持续性发展及区域差异的变化。结果表明：截至 2020 年，中国整体的可持续发展态势稳步上升，贫困县与非贫困县之间的可持续发展差异基本得到解决，但城市主导区与乡村主导区，东部与西部之间的差距依然是中国可持续发展所面临的主要矛盾，另外中国的人口变化区和 GDP 变化区的区域发展差异虽并未占主要，但东北大部分地区同时作为人口下降区和 GDP 下降区，其可持续发展态势也不容忽视。

关键词：可持续发展；SDGs；城乡差异；Theil 指数；东北地区