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Assessment of the sustainable development status of districts and counties in the Yangtze River Delta urban agglomeration

Rui Huang[1,2*], Qing Huang[1], Prajal Pradhan[3], Yixuan Wang[1], Klaus Hubacek[3*]

(1. Key Laboratory of Virtual Geographic Environment, Ministry of Education, Nanjing Normal University, Nanjing 210023, Jiangsu, China;
2. Jiangsu Center for Collaborative Innovation in Geographical Information Resource Development and Application, Nanjing 210023, Jiangsu, China;
3. Integrated Research on Energy, Environment & Society, Energy and Sustainability Research Institute Groningen, University of Groningen, Netherlands)

Abstract: Assessing the sustainable development status at the subnational level is essential for accelerating the achievement of the Sustainable Development Goals (SDGs) during the second half of the 2030 Agenda. However, there are significant gaps in SDG assessment at the county scale and in comparative studies between different counties. In this study, the sustainable development status of counties at the administrative scale in the Yangtze River Delta urban agglomeration (YRDUA) was evaluated on the basis of localized SDG data. Our results revealed that from 2015–2021, the sustainable development status of districts and counties in the YRDUA gradually increased. Nevertheless, the distribution of the development status was uneven across these districts and counties. The sustainable development status of districts and counties in the eastern coastal region was greater than that in the western region. These differences were mainly due to a combination of interregional and intraregional variations. Compared with those in county-level cities and municipal districts, there were greater synergies among indicators in ordinary counties. This finding is related to the relatively balanced distribution of resources, relatively harmonized policy implementation and more consistent socioeconomic development needs in ordinary counties. However, the trade-offs among indicators in county-level cities were relatively notable, suggesting a need for comprehensive and systematic assessments when formulating policies. The governments of county-level cities should optimize resource allocation, enhance environmental regulation, and promote multigoal coordination. The scenario simulation results revealed that promoting sustainable development in ordinary counties, especially those in Anhui Province, could facilitate balanced achievement of the SDGs in the YRDUA. Therefore, support should focus more notably on ordinary counties in Anhui Province by increasing infrastructure construction, such as transportation, energy and communications, and promoting the equalization of public service resources to effectively enhance their sustainable development.
Keywords: Sustainable Development Goals; County level; Synergies and trade-offs

1 Introduction

The United Nations embraced the 2030 Agenda for Sustainable Development in 2015, which encompasses 17 Sustainable Development Goals (SDGs) and 169 targets. The 2030 Agenda aims to solve important global socioeconomic and environmental issues (Lu et al., 2015). China has attached considerable importance to sustainable development, elevating it to the level of a national strategy as early as 1996, and has comprehensively promoted implementation (Li et al., 2024). The Chinese government released its national plan for implementing the 2030 Agenda for Sustainable Development in 2016. In this plan, the 2030 Agenda is organically integrated with China's domestic medium- and long-term development plans, and it aims to promote the formulation of action roadmaps and annual plans by relevant departments in provinces, municipalities, and localities to implement various tasks. In 2018, National Sustainable Development Agenda Innovation Demonstration Zones were established in China. To date, 11 cities focusing on different sustainable development themes have been selected as demonstration zones. This program aims to demonstrate and fulfill a leading role in assessing the major social challenges of Chinese society in the new era, achieving development tasks in the new era, and providing Chinese experience for global sustainable development.

As the basic scale of national governance, districts and counties are directly related to the implementation of policies and the improvement in the quality of life of residents. Although significant progress has been achieved in SDG assessment at the national, provincial and municipal levels (Chen et al., 2021; Liu et al., 2023; Sarkodie, 2022), there is still a relative lack of assessments at the district and county scales. This gap may be due to difficulty in data acquisition, limited resources, and methodological inadequacies (Xiao et al., 2022). However, assessments at the district and county scales are crucial for full SDG implementation and the improvement in the well-being of residents (Jia et al., 2024; Li, 2024). Furthermore, the sustainable development status of districts and counties in large cities exhibits considerable disparities owing to differences in their geographic location, resource conditions, population density, infrastructure, public services, and management level. These differences can impede the sustained, stable, and healthy development of the urban economy (Dai et al., 2022). Therefore, conducting refined county-scale SDG assessments and cross-scale comparative studies is crucial for systematically guiding local governments during the second half of the implementation of the 2030 Agenda for Sustainable Development.

Selecting appropriate evaluation indicators and establishing a sound indicator system are essential to accelerate SDG achievement. While the United Nations has provided a unified quantitative evaluation system for global sustainable development measurement (Warchold et al., 2022), improving and updating primary data in many districts and counties remains impossible, making it difficult to directly apply the SDG global indicator framework in all areas (Cavalett and Cherubini, 2018). Therefore, constructing a localized SDG evaluation system and systematically assessing the development status of districts and counties are particularly urgent (Hu et al., 2023).

Moreover, the linear and nonlinear synergies and trade-offs among the SDGs provide opportunities and challenges for achieving them by 2030 (Pradhan et al., 2017; Warchold et al., 2020). Therefore, it is necessary to analyze synergies and trade-offs, clarify their intertwined and complex relationships, and propose suggestions to leverage them (Fu et al., 2024; Wu et al., 2022a). The synergies and trade-offs among the SDGs at the provincial and city scales in China have been analyzed to provide support for achieving comprehensive and balanced development of these goals (Cao et al., 2023; Xing et al., 2024). However, analyses of SDG synergies and trade-offs at the district and county levels are lacking, thus preventing local governments from effectively utilizing resources and synergistically achieving multiple goals.

In SDG assessment, the use of the scenario simulation method, which aims to explore the potential impacts of different development paths on the sustainable development level via the establishment of multiple possible future scenarios, could help policymakers better address the uncertainties in complex systems, optimize policy and strategic options, and promote sustainable development (Han et al., 2024). Given that the SDGs are expected to be realized in 2030, forecasting the SDG performance in districts and counties by 2030 could provide a clear development direction for lagging districts and counties, helping them implement targeted efforts within a limited period and bridging the gap with advanced districts and counties (Qi et al., 2024). However, to our knowledge, SDG performance forecasting at the district and county scales remains to be addressed.

The Yangtze River Delta urban agglomeration (YRDUA) is one of China's most active regions in terms of economic development and urbanization. However, the strain exerted by economic growth on regional natural resources and the environment is very high (Li et al., 2023). Moreover, the region exhibits significant economic and social differences, and sustainable development is challenging (Gan et al., 2024). Therefore, coordinating the relationships among inclusive economic growth, resource utilization, and ecological and environmental protection, enhancing interregional synergies and cooperation, and increasing sustainable development are urgent and critical issues in the YRDUA.

In summary, this study presents a refined county-scale SDG assessment with the YRDUA as the study area. The following research questions are addressed to inform local governments and accelerate SDG achievement in the YRDUA: What is the sustainable development level in the YRDUA at the district and county scales? What are the synergies and trade-offs among the SDG indicators at the fine-scale county level? What will the sustainable development level in the

YRDUA be in 2030 at the district and county scales? Addressing these issues can not only enrich SDG assessment research but also contribute significantly to the practical implementation of the SDGs by fostering balanced development across various administrative scales.

2 Materials and methods

2.1 Study area

Our study area encompasses 203 county-level units of 26 cities in the YRDUA, including 108 municipal districts, 43 county-level cities, and 52 ordinary counties (Fig. 1).

Districts and counties are the basic administrative scale in China, with relative autonomy and functional integrity in the long-term development and governance process (Qiao et al., 2023). Municipal districts, county-level cities, and ordinary counties all occur at the county level, yet they exhibit different administrative functions (Table 1). In terms of development orientation, municipal districts aim to optimize city management and facilitate the lives of their residents and usually comprise the urban areas of cities. County-level cities focus on promoting the development of modernized industries. In contrast, ordinary counties are more rural administrative divisions whose main function is managing rural settlements and affairs. In terms of the proportion of inhabitants, urban dwellers constitute a large proportion of the overall population of districts, whereas rural residents constitute a large proportion of the overall population of counties. In addition, only ordinary counties with a certain proportion of urban dwellers and a certain economic development level, where the nonagricultural economy dominates, can be upgraded to county-level cities.

Tab. 1 Differences at the county scale

Scale	Administrative significance

Municipal districts	County	Municipal districts typically leverage the resources of their host cities, benefiting from rapid economic development and industrial structures dominated by service and high-tech sectors. Public service facilities are well-developed, with concentrated resources in education, healthcare, transportation, and other areas, leading to a relatively high quality of life for residents. The planning of municipal districts is closely integrated with the overall urban development strategies of their host cities, prioritizing functional zoning and infrastructure advancement.
County-level cities	County	County-level cities demonstrate a more diversified economic structure, encompassing industrial foundations alongside service and agricultural sectors. Their economic development level is intermediate between municipal districts and ordinary counties. While public service facilities are relatively well-developed, they generally lack the concentration and sophistication seen in municipal districts. Resources such as education and healthcare are comparatively sufficient. The urban planning process for county-level cities operates with semi-autonomous governance, prioritizing urban expansion and functional upgrades while emphasizing coordinated urban-rural development.
Ordinary counties	County	Ordinary counties maintain an agriculture-dominated economy with comparatively underdeveloped industrial and service sectors. Characterized by lower economic development levels and homogeneous industrial structures, these regions face challenges in public service provision. Educational and medical resources remain scarce, resulting in residents' quality of life requiring substantial improvement. The developmental focus of ordinary counties centers on rural revitalization and agricultural modernization, coupled with coordinated enhancement of infrastructure and public service systems.

The YRDUA accounts for only 2.3% of the total land area of China, while its population and economy account for more than 12% and 20%, respectively, of the national totals (Jiang et al., 2023; Yin et al., 2023). However, the YRDUA faces complex challenges related to population, society, and environmental resources (Qiao et al., 2023), which impedes the full realization of sustainable development. The YRDUA exhibits obvious regional differences, with cities in the east, such as Shanghai, Wuxi, Hangzhou and Suzhou, demonstrating higher economic and social development levels but greater pressures on resources and the environment, whereas cities in the central and western parts mainly face shortcomings in economic and social development, which restricts the coordinated development of the region as a whole. Despite the abundance of innovation resources in select cities, the synergistic effect between areas has not yet been fully realized, thus affecting the overall innovation efficiency and industrial competitiveness of the region. Public service resources such as high-quality education and medical care are mainly concentrated in core urban areas, with a relative lack of resources in remote areas, leading to a notable gap in regional social welfare and affecting social fairness and cohesion. Moreover, the transregional mechanism for joint prevention and control of environmental pollution is still insufficient, leading to greater difficulty in environmental governance.

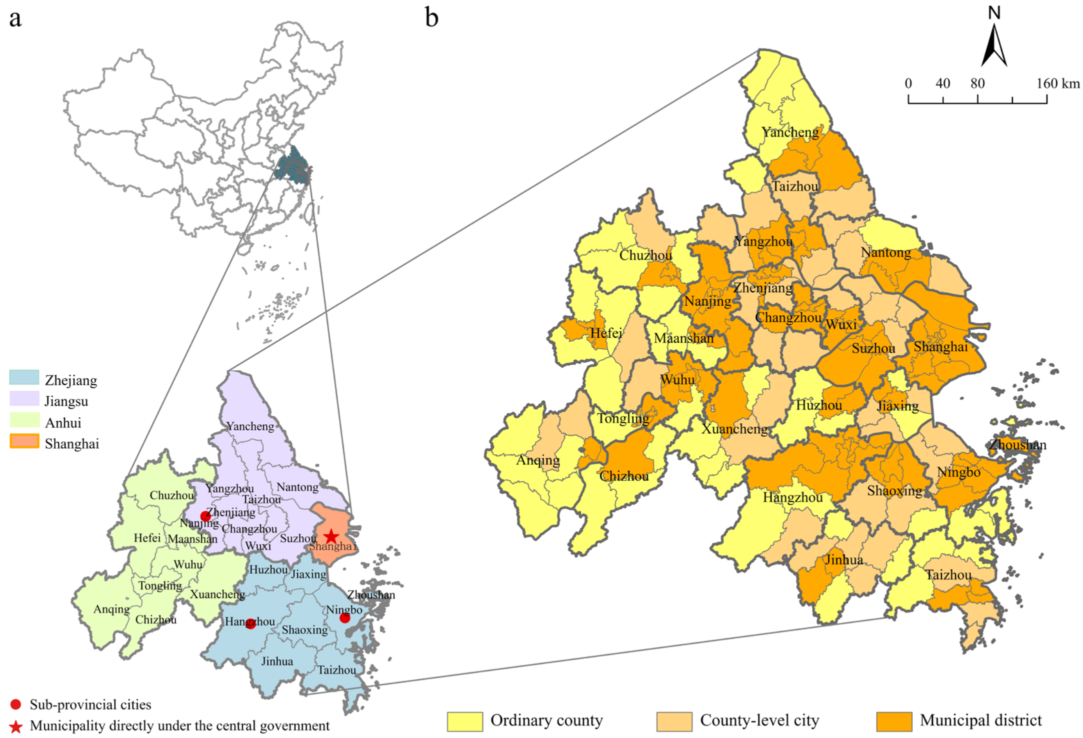

Fig. 1 Yangtze River Delta urban agglomeration (YRDUA). a. The upper panel shows the geographical location of the YRDUA in China. The lower panel shows the 26 cities included in Anhui Province, Zhejiang Province, Jiangsu Province, and Shanghai. Among them, Hangzhou, Ningbo, and Nanjing are subprovincial cities, and Shanghai is a municipality directly under the control of the central government. b. In terms of county units, the YRDUA includes 108 municipal districts, 43 county-level cities, and 52 ordinary counties.

2.2 Data description

Considering the data accessibility and accuracy, localized data from districts and counties in the YRDUA for 2015, 2017, 2019 and 2021 were used, and their correspondence to the indicators released by the Inter-Agency and Expert Group on Sustainable Development Goal Indicators (IAEG-SDGs) is detailed in Table 2. Socioeconomic and environmental data were obtained from the China County Statistical Yearbook, the statistical yearbooks of prefectural cities, the development bulletins of cities and districts and counties, and government work reports. Nighttime light satellite data were obtained from (Wu et al., 2022b), data on CO_2 emissions were obtained from the Emissions Database for Global Atmospheric Research (Oehri et al.) (Crippa et al., 2023; Oehri et al.), and net primary productivity (NPP) data were acquired from NASA.

Although the United Nations has provided a comprehensive system of indicators for sustainable development assessment, in practice, it is almost impossible to collect reliable economic, social and environmental data for all districts and counties in the YRDUA in all years. Therefore, this study is based on an analysis of indicator data collected to the best of our ability. These indicator data, although limited, still provide a suitable starting point for district- and county-scale sustainable development assessment. In the future, as more reliable data become available, they can be easily updated and refined from the existing base. This can contribute to a more comprehensive assessment of the sustainable development status of districts and counties in the YRDUA and provide a more systematic basis for policy formulation.

Tab. 2 Localized indicators; + and – denote positive and negative indicators, respectively.

Localized indicator	Correspondence to UN SDG indicators	Function
Nighttime light data	SDG1: 1.4.1	+
Proportion of the basic public service expenditure in the government expenditure (%)	SDG1: 1.a.2	+
Proportion of the education expenditure in the government expenditure (%)	SDG1: 1.a.2	+
Proportion of the social security and employment expenditure in the government expenditure (%)	SDG1: 1.a.2	+
Grain yield per square kilometer (tons/km^2)	SDG2: 2.3.1	+
Number of health technicians per thousand residents	SDG3: 3.c.1	+
Number of hospital beds per thousand residents	SDG3: 3.d.1	+
Carbon emissions per 1000 Yuan of the gross domestic product (GDP) (ton/1000 Yuan)	SDG7: 7.3.1	–
Per capita GDP (Yuan/person)	SDG8: 8.1.1	+
Urban per capita disposable income (Yuan)	SDG8: 8.1.1	+

Total retail sales of consumer goods (ten thousand Yuan)	SDG8: 8.1.1	+
Annual growth rate of the GDP (%)	SDG8: 8.2.1	+
Registered urban unemployment rate (%)	SDG8: 8.5.2	−
Proportion of the science and technology expenditure in the public financial expenditure (%)	SDG9: 9.5.1	+
Proportion of the output value of the secondary and tertiary industries (%)	SDG9: 9.b.1	−
Per capita disposable income ratio in urban and rural areas	SDG10: 10.1.1	−
Utilized foreign capital (ten thousand dollars)	SDG10: 10.b.1	+
Population density (persons/square kilometer)	SDG11: 11.3.1	−
Content of particulate matter with an aerodynamic diameter smaller than 2.5 microns (PM2.5) in air (microgram/cubic meter)	SDG11: 11.6.2	−
Proportion of days with a good air quality (%)	SDG11: 11.6.2	+
Green coverage rate in built-up areas (%)	SDG11: 11.7.1	+
Park green space area per capita (square meter/person)	SDG11: 11.7.1	+
Electricity consumption per 1000 Yuan of the GDP (kWh/1000 Yuan)	SDG12: 12.2.2	−
Annual mean net primary production (NPP) (0.1 g*c/m^2)	SDG15:15.1.1	+

2.3 Methods

2.3.1 Entropy weight method

The entropy weight method is particularly suitable for comprehensively evaluating multiple indicators and aims to synthesize multiple indicators into a single index for easy comparison and analysis. Therefore, we applied the entropy weight method to evaluate the sustainable development status of the districts and counties in the YRDUA. The entropy weight method is anchored in the principle of information entropy, which can be adopted to determine the weight of each indicator in multi-indicator decision analysis. The strength of the entropy weight method lies in its high objectivity, which reduces the impact of subjective factors on the results. Moreover, the calculation logistics are simple, clear, and easy to implement and apply. Therefore, the entropy weight method was adopted to assign weights of all indicators.

First, the raw data were processed to eliminate scale effects, thus ensuring that the data exhibited the same order of magnitude for easy comparison. Indicators can generally be differentiated into two categories, namely, positive and negative indicators, and they are tailored to the characteristics of different county units (Table 1). The data normalization steps are expressed in equations (1) and (2):

$$X_{ijt}^{*} = \frac{X_{ijt} - \min(X_{jt})}{\max(X_{jt}) - \min(X_{jt})} \quad (1)$$

$$X_{ijt}^{*} = \frac{\max(X_{jt}) - X_{ijt}}{\max(X_{jt}) - \min(X_{jt})} \quad (2)$$

where X_{ijt} denotes the raw data of indicator j in region i in year t, $\max(X_{jt})$ is the peak value of indicator j in year t, $\min(X_{jt})$ denotes the lowest value of indicator j in year t, and X_{ijt}^{*} is the standardized value.

The weight of each indicator for each evaluation object can be calculated on the basis of the standardized data as follows:

$$p_{ijt} = \frac{X_{ijt}^{*}}{\sum_{i=1}^{n}\sum_{t=1}^{m} X_{ijt}^{*}} \quad (3)$$

where m is the total count of years, n is the total count of districts and counties, and p_{ijt} is the proportion of each indicator.

The information entropy e_j of indicator j can be calculated via its proportion as follows:

$$e_j = -\frac{1}{\ln mn}\sum_{i=1}^{n}\sum_{t=1}^{m} p_{ijt} \quad (4)$$

In this study, the information entropy d_j was calculated as:

$$d_j = 1 - e_j \quad (5)$$

The weight w of each indicator was determined via equation (6):

$$w_j = \frac{d_j}{\sum_{j=1}^{n} d_j} \quad (6)$$

The sustainable development index (SDI) of each evaluation object can be calculated as follows:

$$S_{it} = \sum_{j=1}^{n}\left(w_j \times X_{ijt}^{*}\right) \quad (7)$$

where S_{it} is the sustainable development index of evaluation object j in year t.

2.3.2 Dagum Gini coefficient

The Dagum Gini coefficient was employed to quantify differences in the sustainable development status of county units across the YRDUA, which can accurately reflect the source of regional differences and efficiently address the issue of data overlap within samples (Dagum, 1997). The Dagum Gini coefficient can be calculated as follows:

$$G = \frac{\sum_{j=1}^{k}\sum_{h=1}^{k}\sum_{i=1}^{n_j}\sum_{r=1}^{n_h}|y_{ji}-y_{hr}|}{2n^2\bar{y}} \quad (8)$$

where G is the total Gini coefficient, n is the total number of county units in the YRDUA, $\bar{y}$ is the mean SDI value of each county unit, k is the total number of regions, n_j (n_h) is the total number of county units in region j (h), and y_{ji} (y_{hr}) is the SDI value of a given county unit in region j (h).

The overall Gini coefficient (G) can be divided into intraregional differences (G_w), interregional differences (G_{nb}) and hypervariable density (G_t). G, G_w, G_{nb} and G_t can be calculated as follows:

$$G = G_w + G_{nb} + G_t \quad (9)$$

$$G_w = \sum_{j=1}^{k} G_{jj} p_j s_j \quad (10)$$

$$\mathrm{G_{jj}} = \frac{\sum_{j=1}^{n_j}\sum_{r=1}^{n_h}|y_{ji}-y_{hr}|}{2n_j^2\overline{y_j}} \quad (11)$$

$$G_{nb} = \sum_{j=2}^{k}\sum_{h=1}^{j-1} G_{jh} D_{jh}\left(p_j s_h + p_h s_j\right) \quad (12)$$

$$G_{jh} = \frac{\sum_{i=1}^{n_j}\sum_{r=1}^{n_h}|y_{ji}-y_{hr}|}{n_j n_h(\overline{y_j}+\overline{y_h})} \quad (13)$$

$$G_t = \sum_{j=2}^{k}\sum_{h=1}^{j-1} G_{jh}(1-D_{jh})(p_j s_h + p_h s_j) \quad (14)$$

$$D_{jh} = \frac{d_{jh}-p_{jh}}{d_{jh}+p_{jh}} \quad (15)$$

$$d_{jh} = \int_0^{\infty} \mathrm{d}F_j\,(y) \int_0^{y} (y-x)\,\mathrm{d}F_h(x) \quad (16)$$

$$p_{jh} = \int_0^{\infty} \mathrm{d}F_h\,(y) \int_0^{y} (y-x)\,\mathrm{d}F_j(x) \quad (17)$$

where G_{jj} denotes the Gini coefficient of region j, G_{jh} denotes the Gini coefficient between regions j and h, p_j (p_h) is the proportion of the total number of county units in region j (h) to the total number of county units ($p_j = \frac{n_j}{n}$, j= 1, 2, …, k), s_j (s_h) is the proportion of the SDI value of region j (h) to the overall SDI value ($s_j = n_j\bar{y}_j/n\bar{y}$), D_{jh} is the relative influence of the SDI between regions j and h, and d_{jh} is the difference in SDI value between regions j and h.

2.3.3 Spearman's correlation coefficient

Drawing on existing studies (Pradhan et al., 2017; Warchold et al., 2020), the Spearman correlation coefficient was adopted to determine the correlation of each pair of indicators. First, correlation coefficients with P values lower than 0.05 were chosen to ensure the validity of the obtained synergistic and trade-off relationships. The correlations among the SDG indicators were then divided into categories, as summarized in Table 3.

Tab. 3 Five division categories

Spearman correlation coefficient	Category	Explanation
-1 ~ -0.5	Strong trade-off (ST)	There is significant conflict between the two indicators, with progress in one indicator impeding the realization of the other.
-0.5 ~ -0.3	Weak trade-off (WT)	There is moderate conflict between the two indicators, but the magnitude of the conflict is relatively small.
-0.3~0.3	Not classified (NC)	There are no obvious synergies or trade-offs between the two indicators and they may be independent.
0.3~0.5	Weak synergy (WS)	There is moderate synergy between the two indicators, and progress in one indicator may facilitate the achievement of the other.
0.5~1	Strong synergy (SS)	There is significant synergy between the two indicators, with progress in one indicator significantly contributing to the realization of the other.

2.3.4 Scenario simulation

Future SDI values of the districts and counties in the YRDUA were simulated under different shared socioeconomic pathways (SSPs). SSPs constitute a framework for capturing possible pathways for future socioeconomic development and are widely applied in climate change research and sustainable development analysis (O'Neill et al., 2017). There are five main SSP scenarios, of which SSP1 and SSP2 are the two core scenarios that are often employed to help policy makers, researchers and the public better understand the likely consequences of different development pathways. SSP1, referred to as the sustainability pathway, is the ideal scenario for achieving the SDGs. SSP2, also referred to as a middle-of-the-road scenario, refers to a moderate development scenario in which current trends continue. In this study, under the SSP2 scenario, the growth rates of the SDI values of ordinary counties, county-level cities and municipal districts from 2021–2030 matched the average growth rates from 2015–2021. Under the SSP1 scenario, from 2021–2030, the growth rate of the SDI values of ordinary counties will increase by 50% from the average growth rate over the 2015–2021 period, whereas county-level cities and municipal districts will maintain their respective average growth rates from 2015–2021. Under the SSP1+ scenario, from 2021–2030, the growth rate of the SDI values of ordinary counties in Anhui Province will double from the average growth rate over the 2015–2021 period, whereas the other ordinary counties, county-level cities and municipal districts will maintain their respective growth rates from the SSP1 scenario. The parameter settings for the different scenarios are listed in Table 4.

Tab. 4 Parameter description

	Object	Growth rate from 2021–2030
SSP2	Ordinary counties, county-level cities, municipal districts	Maintain the average growth rate from 2015–2021
SSP1	Ordinary counties	Increase by 50% from the average growth rate over the 2015–2021 period
	County-level cities, municipal districts	Maintain the average growth rate from 2015–2021
SSP1+	Ordinary counties in Anhui Province	Increase by 100% from the average growth rate over the 2015–2021 period
	Other ordinary counties, county-level cities, municipal districts	Maintain the average growth rate from 2015–2021

3 Results

3.1 Spatiotemporal patterns of the sustainable development index

While the natural breaks method can be used to automatically identify the optimal classification nodes on the basis of the natural distribution characteristics of the data and can accurately capture the intrinsic patterns within the data, to directly compare the differences in the sustainable development levels of various districts and counties during different periods, a consistent data classification standard must be employed to ensure data comparability across different periods. The SDI values of all districts and counties in the YRDUA gradually increased over time, and the mean value increased from 0.2 in 2015 to 0.27 in 2021 (Fig. 2). The changes in the SDI varied significantly across districts in Shanghai, ranging from 23.69% to 51.23%. Pudong New District (51.23%), Huangpu District (45.38%), and Putuo District (44.96%) in Shanghai exhibited considerable increases in their SDI values, thus securing the top three positions in terms of growth trajectory.

The SDI values of districts and counties in Jiangsu Province also exhibited varying changes, with change rates between 6.9% and 132.66%. The leaders were numerous county-level cities, such as Taixing, Dongtai, Xinghua, Jurong, Gaoyou, and Rugao, each demonstrating remarkable progress in their sustainable development efforts (50.9%~132.66%).

The range of variation in the SDI values of districts and counties in Zhejiang Province was even greater, with changes ranging from -9.51% to 86.71%. The growth rates of the SDI values of ordinary counties, such as Pujiang (86.71%), Sanmen (75.84%), Shengsi (73.93%), Xianju (72.13%), Deqing (70.38%), and Changxing (68.1%), were high, each demonstrating remarkable advancements in their sustainable development initiatives. In contrast, several municipal districts, such as Beilun (-9.51%), Zhenhai (-6.93%), Jiaojiang (-6.39%), Luqiao (5.82%) and Yinzhou (-

1.85%), exhibited considerable declines in their SDI values.

The SDI values of districts and counties in Anhui Province exhibited a similar situation. The SDI values of numerous ordinary counties substantially increased, and the leading ordinary counties were Feixi (144.7%) and Lujiang (98.75%). Conversely, numerous municipal districts, such as Tongguan (-23%), Baohe (-21.88%), and Yushan (-14.17%), experienced notable decreases in their SDI values.

There were considerable spatial differences in the SDI across the YRDUA, with high values in the southeast and low values in the northwest. Most districts and counties in Shanghai, Jiangsu Province, and Zhejiang Province exhibited relatively high sustainable development status levels. In contrast, the SDI values of most districts and counties in Anhui Province were low. In particular, Pudong New District in Shanghai has taken the lead due to its apparent advantages in terms of government interventions and policy support. Moreover, numerous districts in Hangzhou city and Ningbo city and county-level cities in Suzhou city demonstrated high SDI values.

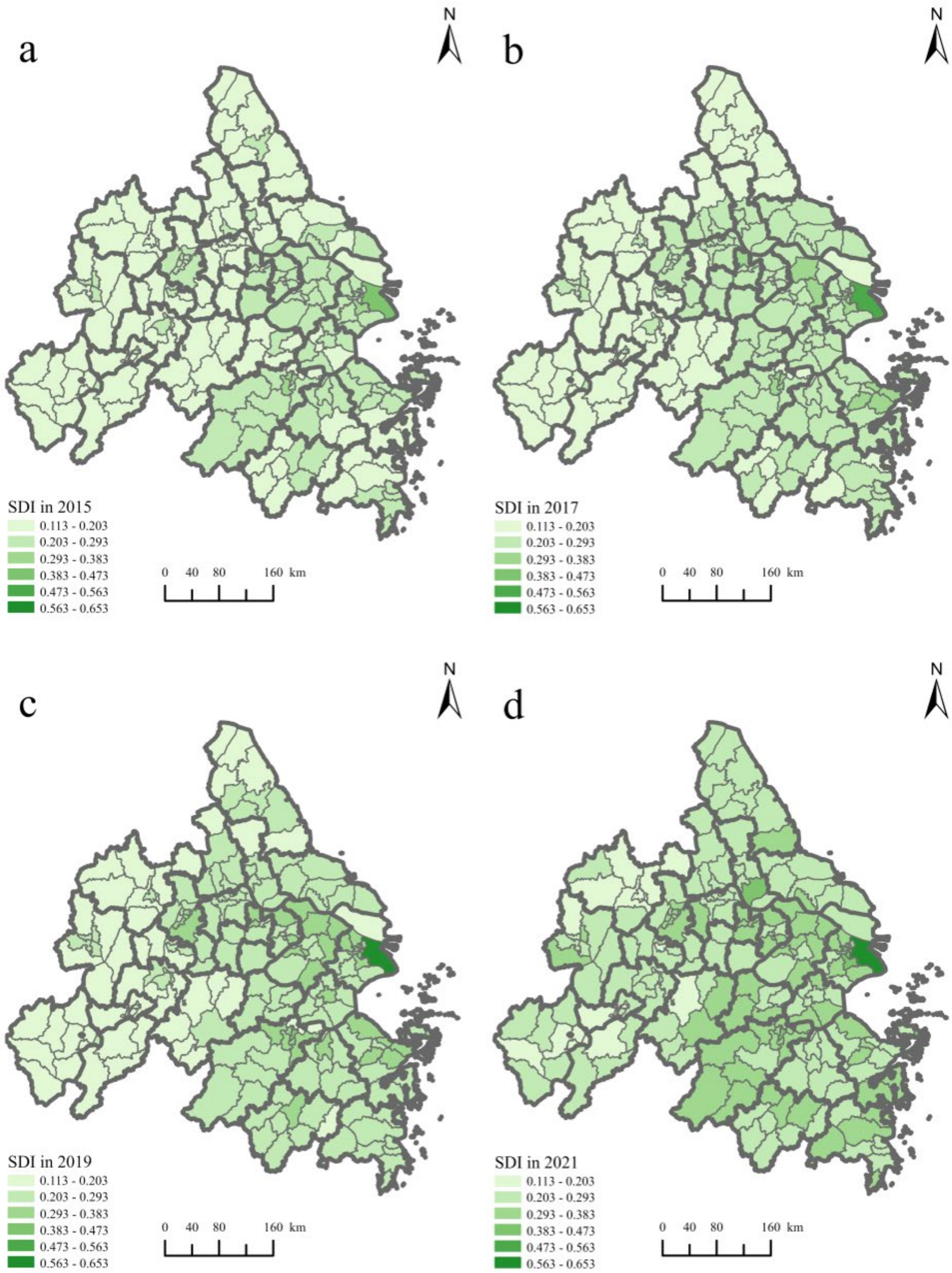

Fig. 2 Spatial distribution and temporal changes in the sustainable development status: a. Sustainable development index (SDI) in 2015; b. SDI in 2017; c. SDI in 2019; d. SDI in 2021.

3.2 Temporal variation in the sustainable development index

Although the sustainable development status of all districts and counties in the YRDUA showed a positive trend, SDI polarization gradually increased in 2021 (Fig. 3). The SDI distribution clearly indicated two clusters near high and low values, exhibiting a gourd shape. The range of the numerical values increased, and the gap between the highest and lowest values increased from 0.31 in 2015 to 0.49 in 2021. SDI polarization became highly notable in 2021, which may be related to the outbreak of COVID-19.

The SDI also varied considerably across different administrative units (Fig. 3b). The average SDI values of ordinary counties were the lowest. In regard to the data distribution, the SDI values of county-level cities and municipal districts were mainly concentrated at the median, whereas those of ordinary counties exhibited a gourd-shaped distribution. Moreover, ordinary counties exhibited greater dispersion in their SDI values than municipal districts and county-level cities did.

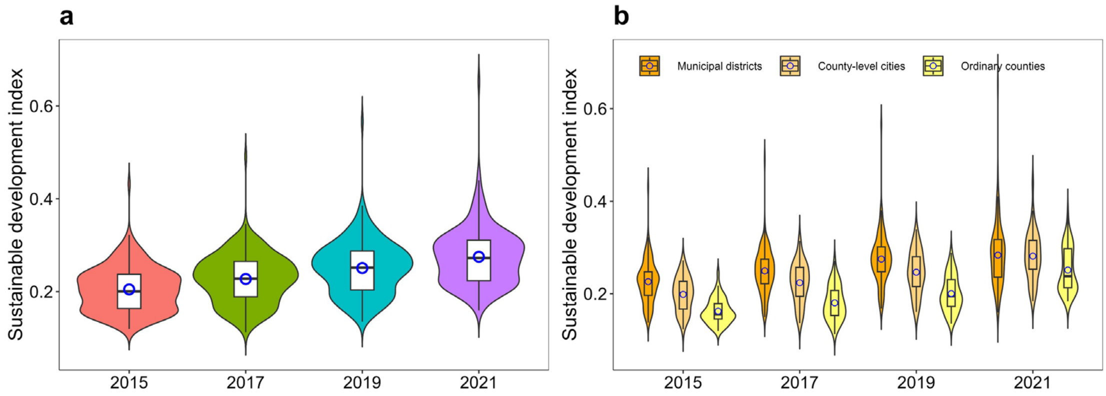

Fig. 3 Data distribution of the sustainable development index (SDI); the blue circle indicates the mean SDI value. a. Data distribution of the SDI in all counties. b. Comparison of the data distributions of the SDI across different administrative units.

3.3 Gini coefficient decomposition

The overall Gini coefficient value decreased from 0.13 in 2015 to 0.12 in 2021, which indicated that the difference in the SDI across all districts and counties gradually decreased during the study period (Fig. 4). The decomposition results for the disaggregated county units indicated that the contribution of interregional differences was the highest (49.16%~51.36%), followed by that of intraregional differences (34.11%~34.93%). In contrast, the contribution of hypervariable density ranged from only 13.71%~16.74% (Fig. 4b). This demonstrates that the difference in the SDI between municipal districts, county-level cities, and ordinary counties contributed considerably to the overall imbalance. In particular, the differences between municipal districts and ordinary counties were relatively large. However, they exhibited a decreasing trend (Fig. 4d). Regarding intraregional differences, the differences between ordinary counties varied dramatically. However, by 2021, this difference remained the smallest (Fig. 4c).

The decomposition results for the provinces indicated that the contribution of interregional differences was notably greater, with an average value of 61.69%, considerably outweighing the contributions of intraregional differences (20.39%) and hypervariable density (17.92%) (Fig. 4f). This suggests that SDI imbalance in the districts and counties within the YRDUA could be attributed primarily to the differences among provinces. In particular, the interregional differences in the SDI between Shanghai and Anhui were the greatest, followed by the interregional differences between Anhui and Zhejiang (Fig. 4h).

The decomposition results for cities at the different administrative levels demonstrated that the contributions of intra- and interregional differences were relatively large, with average values of 49.49% and 44.09%, respectively (Fig. 4j). Among them, the differences in the SDI across county units in the three subprovincial cities of Nanjing, Hangzhou, and Ningbo were the smallest (Fig. 4k). In terms of interregional differences, the differences between Shanghai (MdutCG in Fig. 4l) and other cities and between subprovincial cities and other cities were considerably greater than those between Shanghai and subprovincial cities.

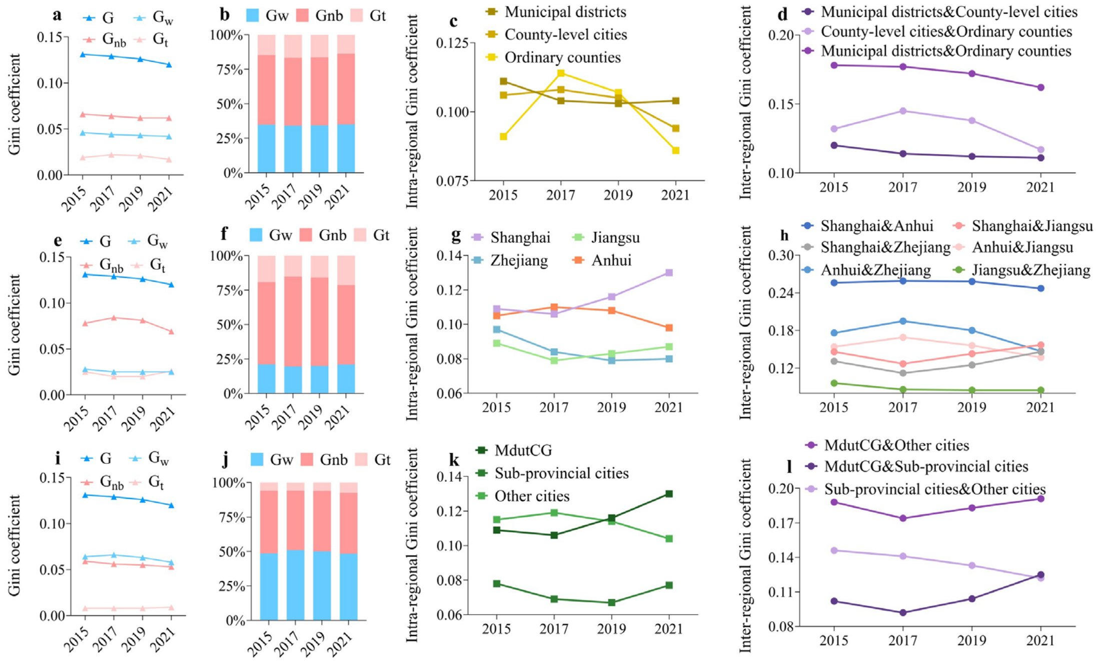

Fig. 4 Gini coefficient values of the sustainable development index (SDI). a, e, i: G denotes the total Gini coefficient, G_w denotes intraregional differences, G_{nb} denotes interregional differences, and G_t denotes hypervariable density. b, f, j: Contributions of G_w, G_{nb}, and G_t. c: Intraregional differences between municipal districts, county-level cities, and ordinary counties. g: Intraregional differences between Shanghai, Jiangsu, Zhejiang, and Anhui. k: Intraregional differences between municipalities directly under the control of the central government (MdutCG), subprovincial cities, and other cities. d: Interregional differences between municipal districts, county-level cities, and ordinary counties. h: Interregional differences among Shanghai, Jiangsu, Zhejiang, and Anhui. l: Interregional differences between MdutCG, subprovincial cities, and other cities.

3.4 Synergistic and trade-off effects at the refined county scale

Overall, the proportions of indicator pairs with strong and weak synergies for all counties in the YRDUA were 9.79% and 12.37%, respectively (Fig. 5). In contrast, the proportions of indicator pairs with strong and weak trade-offs were 4.12% and 3.09%, respectively. These findings highlight that there were more synergies than trade-offs among the localized indicators, providing a solid foundation for advancing SDG achievement in the YRDUA.

In terms of disaggregated county units, the proportion of strong and weak synergies among ordinary counties was greater than that among municipal districts and county-level cities. This finding indicates that ordinary counties exhibit greater leverage in the collaborative achievement of multiple SDGs. Moreover, the proportions of strong and weak trade-offs among county-level cities were 3.21% and 9.62% greater, respectively, than those among municipal districts and ordinary counties. Therefore, relevant managers of county-level cities should conduct comprehensive and systematic assessments when formulating policies to prevent adverse effects resulting from the implementation of ineffective policy components.

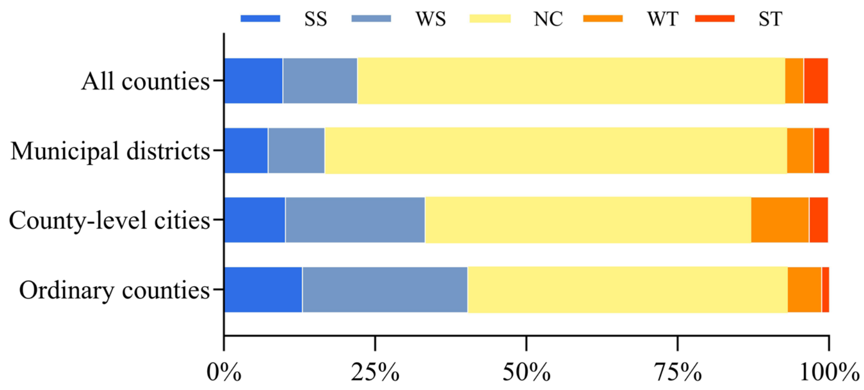

Fig. 5 Proportions of synergistic and trade-off effects for all counties and administrative units in the Yangtze River Delta urban agglomeration. SS denotes strong synergy among the localized Sustainable Development Goal indicators, WS denotes weak synergy among the indicators, ST denotes strong trade-offs among the indicators, WT denotes weak trade-offs among the indicators, and NC denotes not classified.

The correlation coefficient between each indicator pair in each county is calculated one by one, the number of counties with strong synergistic effect (strong trade-off effect) for each indicator pair is counted, and the indicator pair with the largest number of counties is identified as the typical indicator pair with synergistic effect (trade-off effect). This study analyzes the spatial distribution of typical indicator pairs, and the results are shown in Figure 6.

The left panel in Figure 6 shows the strong synergy between the number of health technicians per thousand residents and the green coverage rate in built-up areas. Both indicators reflect the performance of urban planning and public service. On the one hand, the number of health technicians per thousand residents is an important indicator for measuring the level of health care services in a region. When the level of healthcare services is high, the government usually pays more attention to urban planning and ecological services, including the green coverage rate in built-up areas. On the other hand, regions with high green coverage in built-up areas also tend to pay more attention to the provision and improvement of public service facilities, including medical service facilities. More than 85% of the counties in the YRDUA show strong synergistic effects, reflecting not only the overall improvement in urban planning and public service standards, but also the dual emphasis placed by local governments on healthcare and ecology in their development.

The right panel in Figure 6 shows the strong trade-off effect between carbon emissions per unit of GDP and green coverage in built-up areas. Approximately 40% of the counties in the YRDUA have a strong trade-off effect between these two indicators, mainly in Suzhou, Wuxi, Changzhou, Nanjing, Ningbo and Jinhua. The reason for the strong trade-off between carbon emissions per unit of GDP and greening coverage in built-up areas is mainly due to the tensions between economic development and ecological protection. Carbon emissions per unit of GDP is an important indicator for measuring the impact of economic activities on the environment, and lower carbon emissions per unit of GDP implies that carbon emissions can be controlled more effectively during the economic growth process. However, the increase in green coverage often requires the occupation of a certain amount of land in the city, which may compete with the land required for economic development. Especially in cities with limited land resources, it has become an important challenge to find a balance between economic development and ecological and environmental protection.

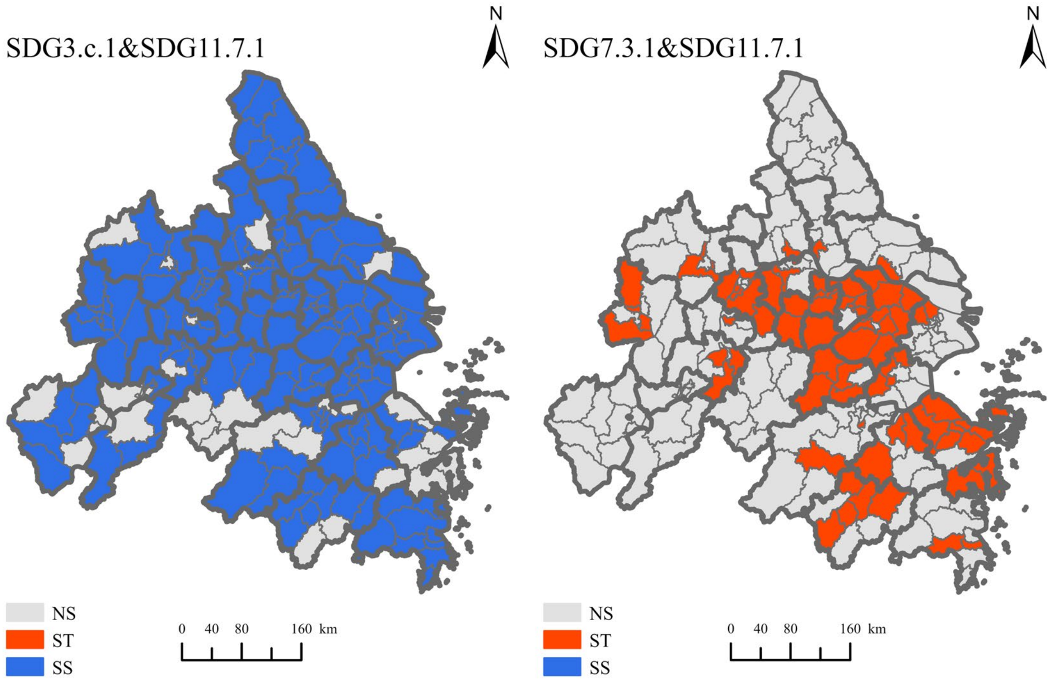

Fig. 6 Spatial distribution of strong synergistic and strong trade-off effects. SS denotes strong synergy. ST denotes strong trade-offs. NS denotes statistically non-significant. The left panel shows the strong synergy between the number of health technicians per thousand residents (SDG3.c.1) and the green coverage rate in built-up areas (SDG11.7.1). The right panel shows the strong trade-off effect between carbon emissions per unit of GDP (SDG7.3.1) and green coverage in built-up areas (SDG11.7.1).

3.5 Sustainable development index under future shared socioeconomic pathways

Under the SSP2 scenario, the sustainable development status in the YRDUA will increase, and the average SDI value will reach 0.37 in 2030 (Fig. 7). However, the total Gini coefficient value is 0.117. This suggests that if districts and counties sustain their current progress, the regional development imbalance will not be effectively mitigated. However, their sustainable development status will increase in the future. Under the SSP1 scenario, the average SDI value of the YRDUA will increase to 0.38 in 2030, and the total Gini coefficient value will decrease to 0.105. Under the SSP1+ scenario, the total Gini coefficient value decreases to 0.099. In particular, interregional differences under the SSP1+ scenario will decrease by 50% and 19.44% compared with those under the SSP2 and SSP1 scenarios, respectively, whereas interregional differences will decrease by up to

53.23% compared with that in 2021. Moreover, the SDI values in the western part of the YRDUA will dramatically increase (Fig. 7). This indicates that accelerating progress in the sustainable development of ordinary counties, especially those in Anhui Province, will greatly increase the overall sustainable development status of the YRDUA while notably mitigating the regional development imbalance.

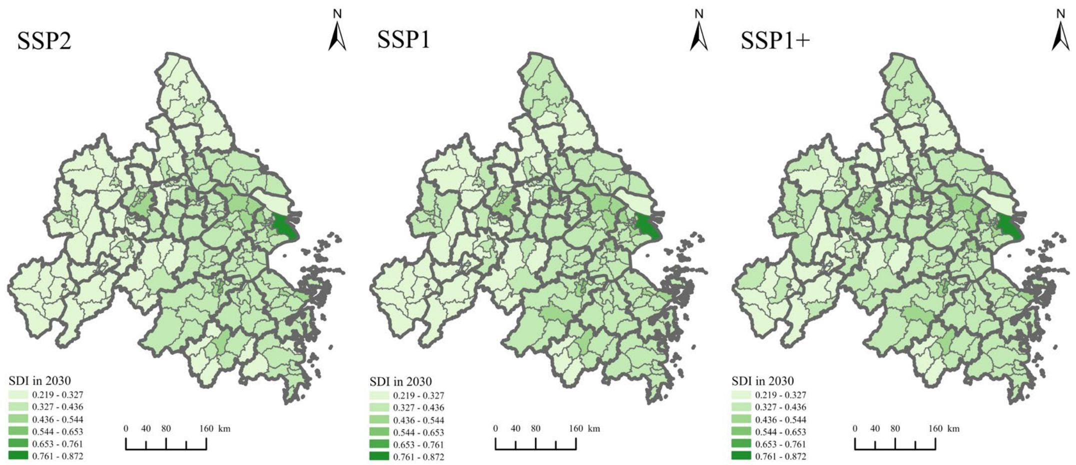

Fig. 7 Sustainable development status under the different shared socioeconomic pathways (SSPs). a. Sustainable development index (SDI) in 2030 under the SSP2 scenario; b. SDI in 2030 under the SSP1 scenario; c. SDI in 2030 under the SSP1+ scenario.

4 Discussion

4.1 Comparison with existing studies

4.1.1 Sustainable development index and its variation

The YRDUA is China's most economically competitive urban agglomeration and presents China's economy to the world. We investigated the sustainable development status of counties in the YRDUA at the microscopic scale on the basis of the United Nations 2030 SDG framework. We also measured the SDI values of municipal districts, county-level cities, and ordinary counties at different times. Owing to the refined granularity, the difference in the sustainable development status among municipal districts, county-level cities, and ordinary counties was further determined. Compared with the measurement of the sustainability index at the city scale (Dong et al., 2021; Ni et al., 2022; Yin et al., 2023), this study revealed a typical core–edge spatial structure within large cities, making it possible to better understand the remarkable heterogeneity in China's top urban agglomerations under a common global development vision and narrative system.

Our results indicated that the sustainable development status of the YRDUA continues to increase, which aligns with the results obtained by Yang et al. (Yang et al., 2023) and Zha et al. (Zha et al., 2022) on the basis of a high-quality development evaluation system. In 2017, the Chinese government articulated the notion of high-quality development, emphasizing the enhancement in the total factor productivity, prioritizing the integration of urban and rural areas, fostering coordinated regional growth, and advancing an inclusive economic development model. This highlights the alignment of China's pursuit of high-quality development with the SDGs of the United Nations.

However, there are large spatial differences across the YRDUA, and the northwestern region attained a lower score than that in the southeastern region. Differences in resource endowment, industrial labor division, population, capital investment, administrative scale, and administrative functions can cause significant spatial differences in sustainable development (Zhuang and Ye, 2023). The integrated development of the Yangtze River Delta is a significant national development strategy in China and the main engine of economic growth from high speed to high quality (Zhao et al., 2021). Accounting for less developed regions is an inherent requirement for establishing a just and inclusive sustainable development model and promoting high-quality development (Pan et al., 2023). Therefore, targeted measures are needed to increase the sustainable development status of lagging districts and counties and promote high-quality integrated development across the YRDUA (Mohammed et al., 2024).

4.1.2 Driving mechanisms for inter- and intraregional differences across scales

In this study, the Gini coefficient value at the county level decreased, reflecting the effect of YRD integration policies, such as the promotion of cross-county industrial collaboration parks (e.g., the G60 Science and Innovation Corridor) and measures to standardize basic public services (e.g., cross-provincial settlement of health insurance) (Guo et al., 2025). Interregional differences mainly stem from differences in administrative scales and policy preferences. Municipal districts in the YRD region usually exhibit higher high-tech industry agglomeration capacity and infrastructure investment (e.g., the Pudong New Area in Shanghai and Gulou District in Nanjing), whereas ordinary counties rely on agriculture or traditional manufacturing industries, leading to development gaps. For example, municipal districts attract high-tech firms through development zone policies, whereas ordinary counties are limited by land resources and environmental constraints, resulting in a core–periphery structure (Bi et al., 2024). Intraregional differences (e.g., differentiation among ordinary counties) may be related to resource endowments (e.g., location conditions and population density) and local governance capacity. For example, county-level cities close to central cities (e.g., Kunshan city, Suzhou) have achieved rapid growth by undertaking industrial transfers, whereas remote counties (e.g., counties in Lu'an city, Anhui Province) have fallen into path dependence due to transportation disadvantages. Moreover, the persistence of intraregional differences may suggest that local protectionism has not yet been completely eliminated (Li and Wei, 2010).

The findings of this study revealed that the contribution of the differences between provinces reached as high as 61.69%, which is greater than that in the Pearl River Delta (PRD). This occurs because PRD cities are located mainly in Guangdong Province, where provincial coordination costs are lower (Wang and Zhou, 2024). The interprovincial differences in the Beijing-Tianjin-Hebei region are due to the siphoning effect of Beijing, whereas the Yangtze River Delta region shows a pattern of multicenter competition (Yu et al., 2023). The significant differences in the sustainability status levels of Shanghai and Anhui reflect institutional barriers. Shanghai, as a municipality directly under the control of the central government, enjoys policy pilot privileges (e.g., the Free Trade Zone), whereas Anhui was included only in the YRD plan in 2016 and initially faced barriers to factor mobility. Notably, Shanghai's high-end service industry and Anhui's traditional manufacturing industry form a vertical division of labor. The low contribution of hypervariable density further suggests that the cross-provincial synergy mechanism is insufficient and that the interprovincial boundary effect remains significant (Wang et al., 2024b).

The differences between subprovincial cities (Nanjing, Hangzhou, and Ningbo) and other cities reflect the impact of China's urban hierarchy. Subprovincial cities possess provincial economic management authority to approve foreign investment projects and establish bonded zones, whereas prefectural cities must report to the provincial government, leading to differences in the efficiency of their policy response. For example, Ningbo has attracted multinational headquarters through its single-window trade facilitation reform, whereas prefecture-level cities (e.g., Huzhou) rely on slow upgrading by local firms (Rodríguez-Pose and Ezcurra, 2009). This is supported by the new economic geography theory stating that the administrative hierarchy reshapes the spatial structure by affecting transaction costs (Han et al., 2016). The institutional advantages of subprovincial cities render them policy highlands, while lower-level cities face market segmentation, creating negative feedback of administrative barriers–resource mismatch.

4.1.3 Synergy and trade-off effects

Conducting localized SDG assessments, systematically analyzing the opportunities and challenges during sustainable development in different areas, and clarifying the complex interrelationships between different indicators are essential steps in accelerating SDG achievement (Zhang et al., 2022). Our study results revealed more synergistic relationships than trade-offs among all counties in the YRDUA, which agrees with the results of Xing et al. (Xing et al., 2024). However, the synergies and trade-offs among the SDGs differed notably across different administrative scales. This finding indicates that sustainability assessments at the city scale can mask large differences between districts and counties. This further suggests that assessing synergies and trade-offs at the microscopic scale is necessary to facilitate sustainability transition toward the SDGs.

The results of this study demonstrated that, compared with those in county-level cities and municipal districts, there were greater synergies among the indicators in ordinary counties. However, the trade-offs among the indicators in county-level cities were relatively notable. This may occur because ordinary counties exhibit a relatively homogeneous economic structure, a more centralized distribution of resources, and less competition for resources among the different SDG indicators, thus making it easier to achieve synergies. Second, policy implementation in ordinary counties is relatively consistent, and local governments can coordinate the development of different fields more effectively to promote synergies among the SDG indicators. Third, the socioeconomic foundation of ordinary counties is relatively weak, but their development needs are relatively consistent, so it is easier to achieve synergies in fundamental sectors such as education, health and infrastructure.

In contrast, county-level cities usually exhibit a more developed industrial base and higher economic development levels, which may lead to resource overexploitation and increased environmental pressure, thus causing trade-offs between economic growth and environmental protection. Second, the allocation of limited resources, such as land and water resources, is more complex in county-level cities in the urbanization process, and there exists a competitive relationship between the different SDG indicators. Third, county-level cities must balance multiple targets, such as economic development, social welfare, and environmental protection, when formulating policies, which may result in trade-offs between the different targets. Therefore, in county-level cities, there is a need to optimize resource allocation, balance the relationship between economic development and environmental protection, and reduce resource waste. Second, the environmental regulation of industries and urban construction should be strengthened to promote green economic development and reduce environmental pressures. Third, an integrated policy framework should be formulated to coordinate the relationships between the different SDG targets and reduce conflicts between policy objectives. For example, Sustainable management of water and fertilizers not only effectively reduces the risk of land degradation and guarantees food security, but also generates considerable economic returns and provides stable employment opportunities (Mardani Najafabadi et al., 2023).

4.1.4 Scenario simulation results

This study revealed the differentiated effects of different development paths on regional sustainability and balance via a comparison of the trends in the SDI and Gini coefficient values in the YRDUA under the SSP2, SSP1 and SSP1+ scenarios. Although all three scenarios showed that the sustainable development status of the YRDUA will increase by 2030, there are significant differences in the driving mechanisms, policy assumptions and regional coordinated outcomes among these scenarios.

Under the SSP2 scenario, economic growth is still dominated by the traditional model, and resource allocation and technology diffusion do not effectively penetrate less developed counties (e.g., the western part of Anhui Province). This result is consistent with the criticism of inertia development in existing studies (Yang and Yang, 2020). This suggests that the market-driven Matthew effect may further solidify regional differences in the absence of proactive intervention (Wang et al., 2022). In contrast, under the SSP1 and SSP1+ scenarios, regional equity was significantly improved through policy design. The key mechanisms may be related to targeted resource redistribution (Luo and Wang, 2023), technology spillovers (Ma et al., 2023), and enhanced institutional synergies (Liu et al., 2017).

Notably, the SDI growth rate in Anhui's ordinary counties under the SSP1+ scenario was significantly higher than that in other districts and counties, suggesting that targeted inputs into weak regions can produce greater marginal benefits (Wang et al., 2024a). However, this also raises questions about the cost of policy implementation, as overreliance on external resource inputs may adversely affect the endogenous dynamics in less developed regions (Mrabet et al., 2025).

4.2 Policy implications

We propose the following measures to enhance the sustainable development of the YRDUA on the basis of our findings. The county units in the western part of the YRDUA should urgently aim to identify the shortcomings of their development efforts and implement measures to bridge the gaps between the leading districts and counties. The radiation effect and high network connectivity of municipal districts should be increased to exert a greater influence. Concurrently, the high economic and social development advantages of county-level cities should be fully harnessed. As such, the sustainable development status in currently lagging surrounding areas can be increased. This approach, in turn, can increase the overall sustainability of the YRDUA. Moreover, in lagging areas within the YRDUA, advanced technologies should be actively integrated and new drivers of productivity should be cultivated to increase their capacity for sustainable development.

Moreover, all counties of the YRDUA should prioritize indicators demonstrating strong synergistic effects as pivotal starting points (Pradhan et al., 2024). By focusing on increasing the performance of these indicators and leveraging synergies among the SDGs, their sustainable development status can be increased. Importantly, incorporating synergistic governance into performance appraisal systems is a forward-thinking strategy (Luo et al., 2024). This approach encourages local governments to prioritize and implement policies that yield the highest sustainable development outcomes. This can also help reduce the governance costs and financial constraints of local governments during the postpandemic period.

4.3 Limitations

In contrast to the pyramidal county–city–province–nation administrative model, the completeness and reliability of the SDG indicator data exhibit an inverted pyramid pattern due to the different statistical sources, and it is more challenging to obtain reliable statistical data at the district and county scales. The high mobility of people and production factors in the YRDUA, including intra- and interregional mobility components, mobility with other parts of China, and transnational mobility (Wiedmann and Allen, 2021; Zhang et al., 2024), increases the complexity and difficulty of obtaining district- and county-level data statistics. This dramatically impedes comprehensive sustainable development assessments at the fine-scale county level. However, districts and counties are the smallest units of sustainability policy implementation and are the areas where the lives of people are tangibly affected (Jin et al., 2024). Therefore, there is an urgent need to improve the statistics and disclosure of SDG-related indicators at the county scale.

Although scenario simulations can provide important reference data for policy design, a linear trend in SDG growth rates is assumed in current scenarios, which in reality may be constrained by nonlinear factors, such as the local governance capacity, multistakeholder interactions, extreme weather events and geoeconomic risks. A nonlinear integrated assessment model with multiscale spatial analysis is needed to more accurately capture the evolution of regional differences (Gu et al., 2021).

4.4 Future studies

In future studies, the following limitations of our study should be addressed. Owing to data availability limitations, the indicator data employed in this study do not exactly match the indicator list of the IAEG-SDGs. Moreover, the data were collected for only four nonconsecutive years. Big Earth data can be leveraged to enhance sustainability assessment. Second, spatiotemporal geographical models can be employed to analyze the spillover effect of sustainable development across counties in the YRDUA and, in turn, its effect on achieving several SDGs to provide more targeted policy recommendations for increasing the sustainable development status. Third, machine learning and integrated analytical models can be adopted to identify sustainable development patterns and anticipate future evolutionary trends, thus providing a more nuanced understanding of sustainable development dynamics in the YRDUA. For example, Human-earth coupled modeling can provide key elements contributing to sustainable development transformation, while helping us to gain a deeper insight into how some well-intentioned policies can yield undesirable consequences (Henderson and Loreau, 2023). Fourth, World-class urban agglomerations are increasingly dependent on external resource factors in the process of their development (Hu et al., 2025). There is a large amount of energy and air pollution embedded in interregional trade (Guarino et al., 2023). Therefore, in assessing the sustainability of the development of urban agglomerations, it is important to consider both internal and external resource and environmental pressures.

This study carried out a refined county-scale SDG assessment and a comparative analysis across different scales, establishing a good foundation for micro-scale sustainability assessment. In the future, with the deep integration of interdisciplinary knowledge and the continuous evolution of the methodological system, the understanding of the key elements affecting sustainability transformation and their interaction mechanisms will be further deepened (Jakeman et al., 2024).

5 Conclusions

We evaluated the sustainable development status of municipal districts, ordinary counties, and county-level cities in the YRDUA and analyzed the sources of regional differences. We further investigated the synergistic and trade-off effects between localized SDG indicators. Finally, the sustainable development status of different administrative units in 2030 was simulated under different SSP scenarios. Overall, the sustainable development status of counties in the YRDUA exhibited an increasing trend from 2015–2021, with the SDI values of ordinary counties, county-level cities, and municipal districts increasing at differing rates. The sustainable development status of county units in the YRDUA demonstrated obvious heterogeneity. The development level of counties in the western region was notably lower than that in the eastern coastal area. Intraregional and interregional differences collectively contributed to this uneven development pattern. The synergies among indicators in ordinary counties were greater than those observed in municipal districts and county-level cities. However, the trade-offs among indicators in county-level cities are a concern in the future, indicating that county-level cities should dedicate greater effort to formulating synergistic governance policies. Accelerating the sustainable development of ordinary counties, particularly those in Anhui Province, could significantly increase the overall sustainability of the YRDUA and substantially mitigate the regional development imbalance.

Acknowledgments

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