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Navigating Chinese cities to achieve sustainable development goals by 2030
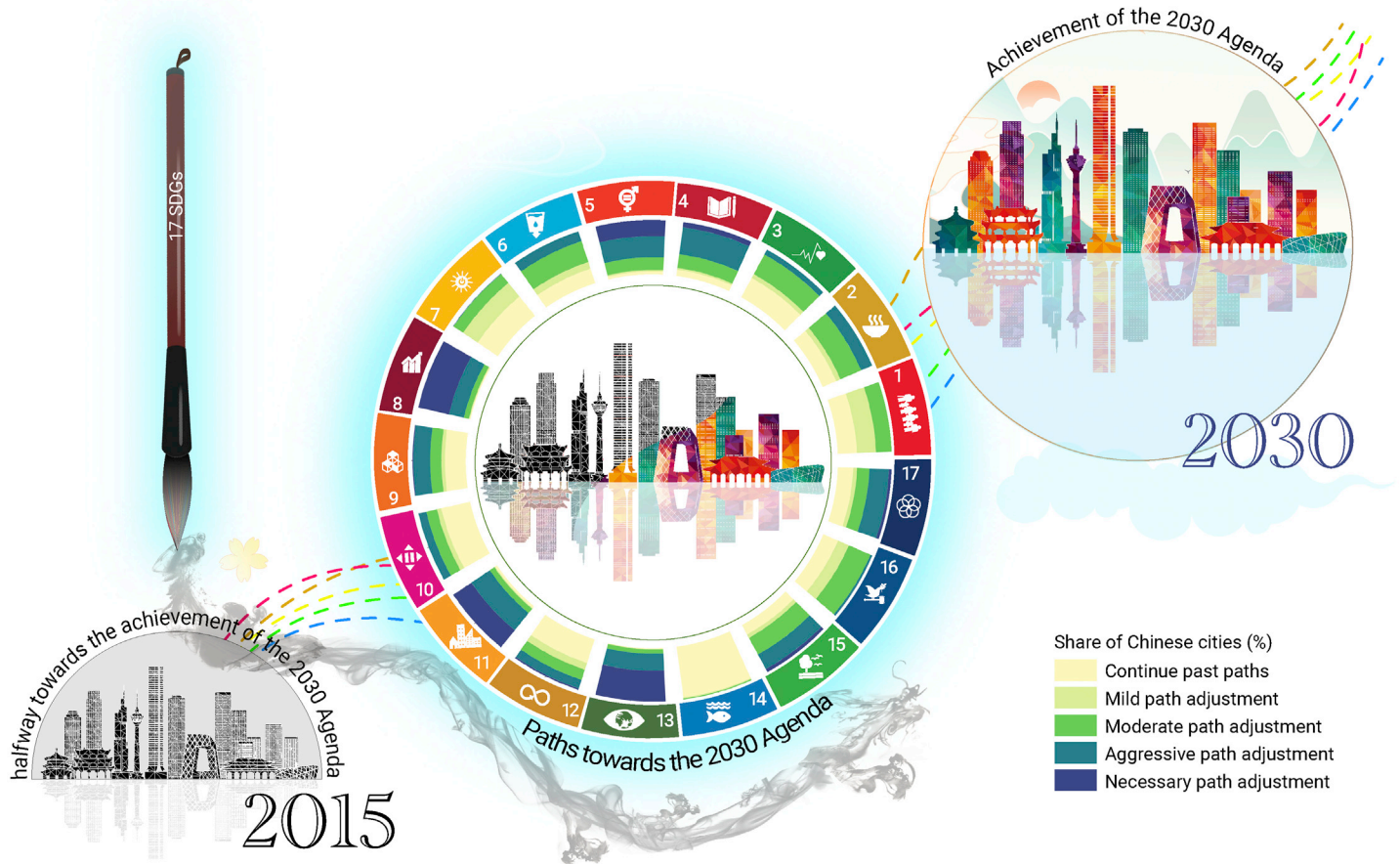
Huijuan Xiao,[1] Zhenci Xu,[2,3,*] Jingzheng Ren,[1,*] Ya Zhou,[4,7] Ruojue Lin,[1] Sheng Bao,[5] Long Zhang,[1] Shengfang Lu,[1] Carman K.M. Lee,[1] and Jianguo Liu[6]
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GRAPHICAL ABSTRACT

PUBLIC SUMMARY

- The first simulation of the performance of Chinese cities in 17 SDGs by 2030

- A scenario-based projection model is proposed to make simulation of SDGs

- Chinese cities can achieve an average of five SDGs by continuing past paths

- We present cost-effective integrated paths to promote the achievement of all SDGs

Navigating Chinese cities to achieve sustainable development goals by 2030

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Achieving the 17 United Nations sustainable development goals (SDGs) in China largely depends on the transition of cities toward sustainable development. However, significant knowledge gaps exist in evaluating the SDG index at the city scale and in understanding how to simulate pathways to achieve the 17 SDGs for Chinese cities by 2030. This study aimed to quantify the SDG index of 285 Chinese cities and developed a forecasting model to simulate the performance of each SDG in each city until 2030 using varied scenarios. The results indicated that although the SDG index in Chinese cities increased by 33.97% during 2005−2016, Chinese cities, which continued their past paths, achieved an average of only five SDGs by 2030. To promote the joint achievement of all SDGs, we designed different paths for all SDGs of each of the 285 cities and simulated their SDG index until 2030. Under the scenarios, 216 Chinese cities (75.79%) could achieve 9−13 more SDGs in 2030 and the overall SDG index can improve from 74.57 in 2030 to 97.49 (target score 100) by adopting more intensive path adjustment. We lastly determined a cost-effective path for each SDG of each city to promote joint achievement of all SDGs by 2030. The proposed simulation model and cost-effective path serve as a foundation for other countries to simulate SDG progress and develop pathways for achieving SDGs in the future.

INTRODUCTION

The 2030 Agenda that incorporated 17 sustainable development goals (SDGs) was implemented by all United Nations (UN) member states as a universal plan toward achieving sustainability.[1,2] Since the launch of the SDGs, numerous studies have investigated sustainability under the framework of the 2030 Agenda at the global, regional, and national levels.[1–4] While most goals specifically indicate the responsibility of national governments for the localization and implementation of SDGs, local governments such as cities are responsible for providing most of the needed progress.[5,6] The Sustainable Development Solutions Network estimated that 65% of SDG targets will not be fully reached without proper engagement of and coordination with cities.[7]

However, only several reports evaluated city-level SDG index (an aggregated score that is used to evaluate where each region stands with regard to achieving 17 SDGs) of some countries or regions.[7,8] For instance, European cities SDG Index and Dashboards Report evaluated the SDG index of 45 capital cities and large metropolitan areas in Europe in 2019 with 56 indicators.[7] As for China, Xu et al. (2020) constructed a provincial indicator system of SDGs and evaluated the SDG index of 31 provinces from 2000 to 2015 based on this system,[1] but did not present a city-level indicator system for China. The city-level indicator system of China is still missing and is more challenging to construct, because of a large number of cities, less data disclosure, and more frequent changes of administrative boundaries.

Additionally, most studies, including that by Xu et al. (2020), only evaluated the past progress of SDGs and did not answer whether the Chinese cities can achieve the 17 SDGs by 2030 or how paths can be simulated to achieve these goals by 2030.[1,2] Studies on the simulations of 17 SDGs and the SDG index up to 2030 under various scenarios are absent not only for China, but also for other member

states of the UN. The answers to the above-mentioned two questions are, thus, critical for policymakers to effectively allocate resources to vulnerable cities, formulate long-term integrated strategies, and underpin the achievement of the 2030 Agenda.[9]

To address these knowledge gaps, we first made a methodological contribution by proposing a scenario-based projection model to simulate the SDG index and 17 SDGs until 2030 with scenarios representing various improvement paths. The proposed projection model is not limited to a specific country and can be applied to other member states of the UN to predict SDGs under various scenarios. Then, we presented the first evaluation of the SDG index (scores 0–100) of Chinese cities over time and stimulated the SDG index and 17 SDGs up to 2030 based on our proposed scenario-based projection model. Our results revealed the extent to which different policy implementations of the 17 SDGs could direct the future sustainability outcomes of the cities. Finally, we determined a cost-effective path for each SDG of each city to enhance sustainability by 2030. Based on the available data, 285 Chinese cities were selected for analysis. A comprehensive, consistent, and comparable indicator system that is used to evaluate the SDG index of 285 Chinese cities is shown in Table S1.

RESULTS

Spatiotemporal performance of SDGs

The SDG index of the Chinese cities increased by 33.97% during 2005–2016, from 37.93 to 50.82 (target score 100) (Figure 1A), showing Chinese cities are halfway toward the achievement of the 2030 Agenda and significant further progress is required to finish the second half. Zhuhai (Guangdong province) showed the highest index (75.73) among the Chinese cities in 2016, followed by Beijing (73.12), Shenzhen (72.50, Guangdong province), Hangzhou (72.32, Zhejiang province), and Xiamen (70.39, Fujian province) (Figure 1B). The top 10 cities with the highest SDG index were non-resource-based cities, while among the 10 cities with the worst index, eight were resource-based cities, that is, Lvliang (39.05, Shanxi province), Linfen (39.34, Shanxi province), Xinzhou (39.78, Shanxi province), Shuozhou (39.78, Shanxi province), Yulin (40.39, Shaanxi province), Handan (40.76, Hebei province), Zhangjiakou (40.87, Hebei province), and Liupanshui (41.96, Guizhou province) (Figure 1C). Resource-based cities also showed an increase in their SDG index from 35.19 in 2005 to 47.75 in 2016 (Figure 1A), but their index was generally 5.15 (10.78%) lower than that of non-resource-based cities (52.90) (Figure 1A).

Simulation of the SDG index up to 2030

To observe the changes in the trajectory of the SDGs under different scenarios, we simulated the SDG index from 2017 to 2030 based on five scenarios (continue past paths, mild path adjustment, moderate path adjustment, aggressive path adjustment, and necessary path adjustment). If Chinese cities continue the past paths, the highest SDG index in 2030 could be 95.54 and 133 Chinese cities could score in the range of 70–80 (Figure 2A; Scenario 1). The sustainability patterns across the Chinese cities could change significantly under different scenarios. The number of Chinese cities scoring in the range of 80–85, 85–95, and 95–100 under mild, moderate, and aggressive path adjustments are 98, 238, and 252, respectively (Figures 2B–2D; Scenarios 2–4).
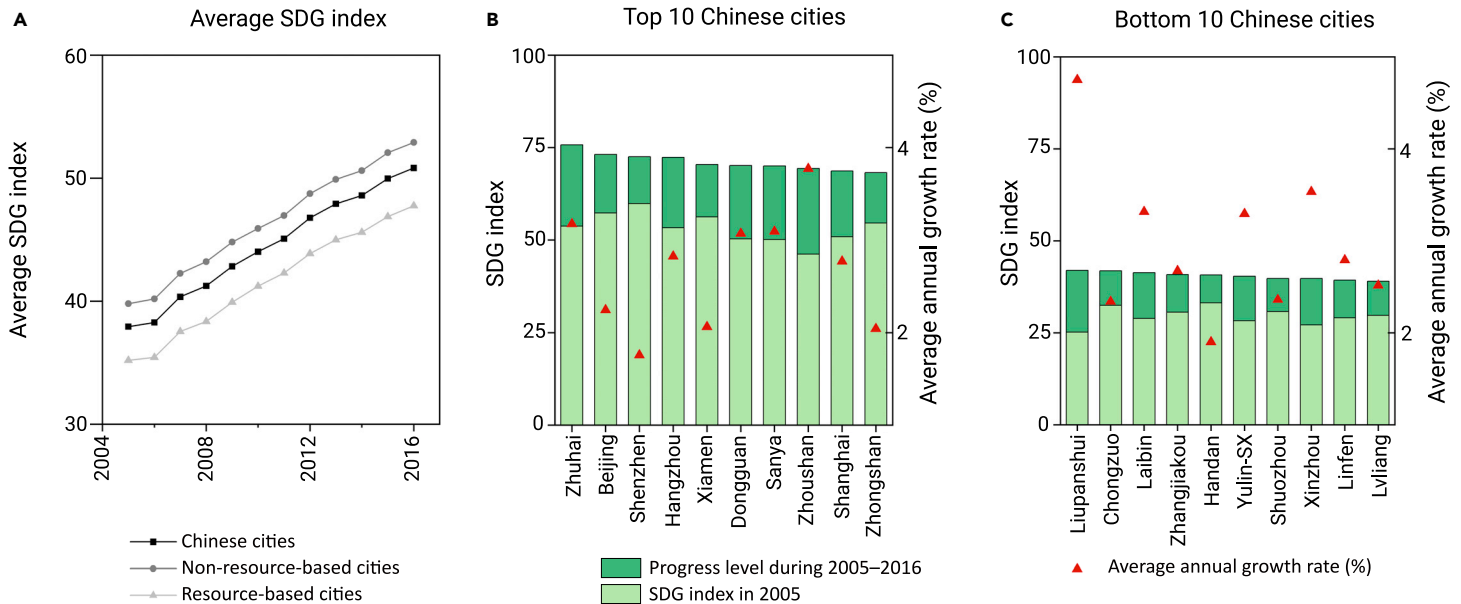
Figure 1. SDG index of the Chinese cities in 2005–2016 (A) Average SDG index of 285 Chinese cities during 2005–2016. (B and C) The top/bottom 10 Chinese cities in the SDG index in 2016. The stacked bar chart in (B) and (C) indicates the SDG index (left *y* axis), while the triangle indicates the average annual growth rate from 2005 to 2016 (right *y* axis). The bottom section of the stacked bar in (B) and (C) indicates the SDG index in 2005, while the top section shows the progress level during 2005–2016.

Simulation of the 17 SDGs up to 2030

As shown in Figure 3, although all 17 goals exhibited a promising increase during 2005–2016, the performance of some was still low and the gap to achieve these goals was large. SDG 8 (Decent work and economic growth), SDG 9 (Industry, innovation, and infrastructure), and SDG 15 (Life on land), with a score of 36.17, 30.63, and 36.39, respectively, had the lowest scores for the Chinese cities in 2016 (Figure 3). Continuing the past paths could improve the performance of these three SDGs to 48.17, 69.62, and 65.85 in 2030, respectively (Figures 3H, 3I, and 3O; Scenario 1), with 23 (8.07%), 124 (43.51%), and 72 (25.26%) Chinese cities scoring 100 before 2030, respectively (Figure 4; Scenario 1). If the Chinese cities
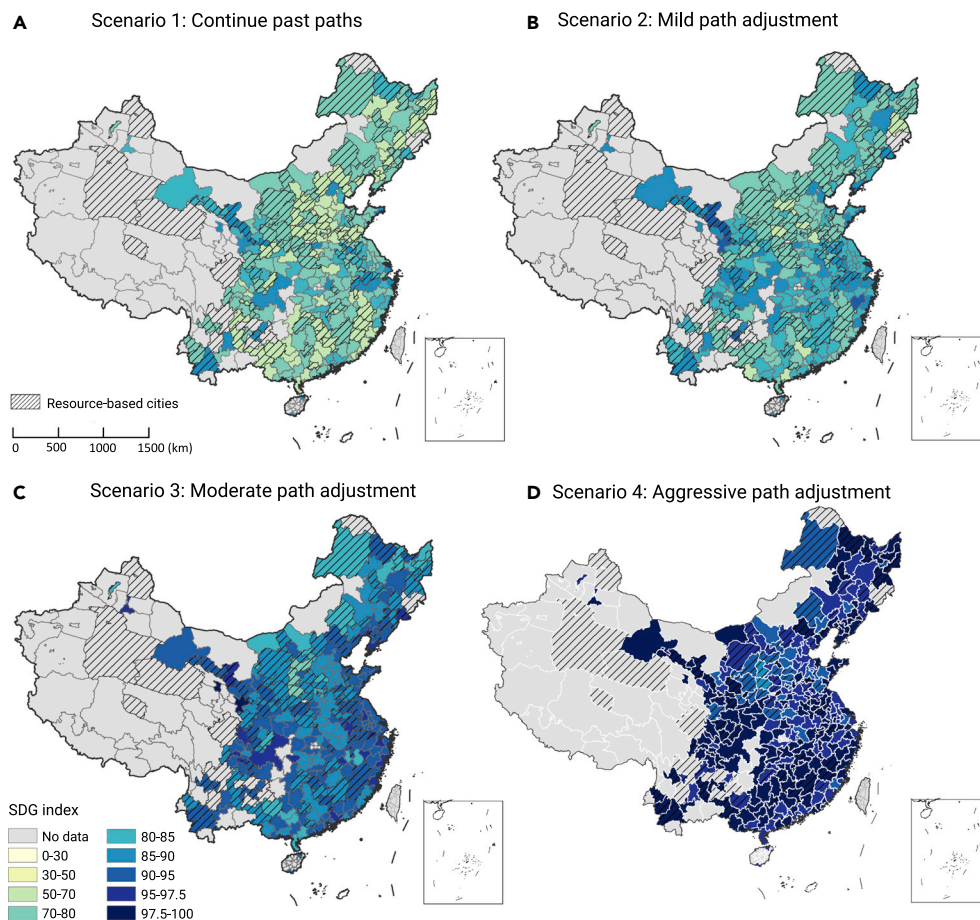

Figure 2. Simulation of the SDG index of the Chinese cities in 2030 (A–D) SDG index under scenario 1 (A), scenario 2 (B), scenario 3 (C), and scenario 4 (D). As the SDG index under scenario 5 (necessary path adjustment) in 2030 is equal to 100 for all cities, the SDG index under this scenario was not demonstrated here.

adopted a further intensive path adjustment, such as a moderate path adjustment, the average scores of SDG 8 (Decent work and economic growth), SDG 9 (Industry, innovation, and infrastructure), and SDG 15 (Life on land) could increase to 51.04, 75.30, and 73.78, respectively, in 2030 (Figures 3H, 3I, and 3O; Scenario 3). Under the aggressive path adjustment, the average scores of the three SDGs could further improve to 88.86, 99.80, and 98.29, respectively (Figures 3H, 3I, and 3O; Scenario 4).

Cost-effective integrated paths of the 17 SDGs

As shown in Figure 2A, if the cities continued with their past paths, it will be difficult for them to achieve the 2030 Agenda, and substantial challenges would exist to address all SDGs by 2030. On an average, Chinese cities could achieve five goals (31.03%) before 2030 by continuing the past paths (Dataset S1, Scenario 1). Based on the improvement paths of other cities, if cities adopted more intensive path adjustment, including a mild path adjustment (Scenario 2), moderate path adjustment (Scenario 3), or aggressive path adjustment (Scenario 4) (Dataset S1), 11
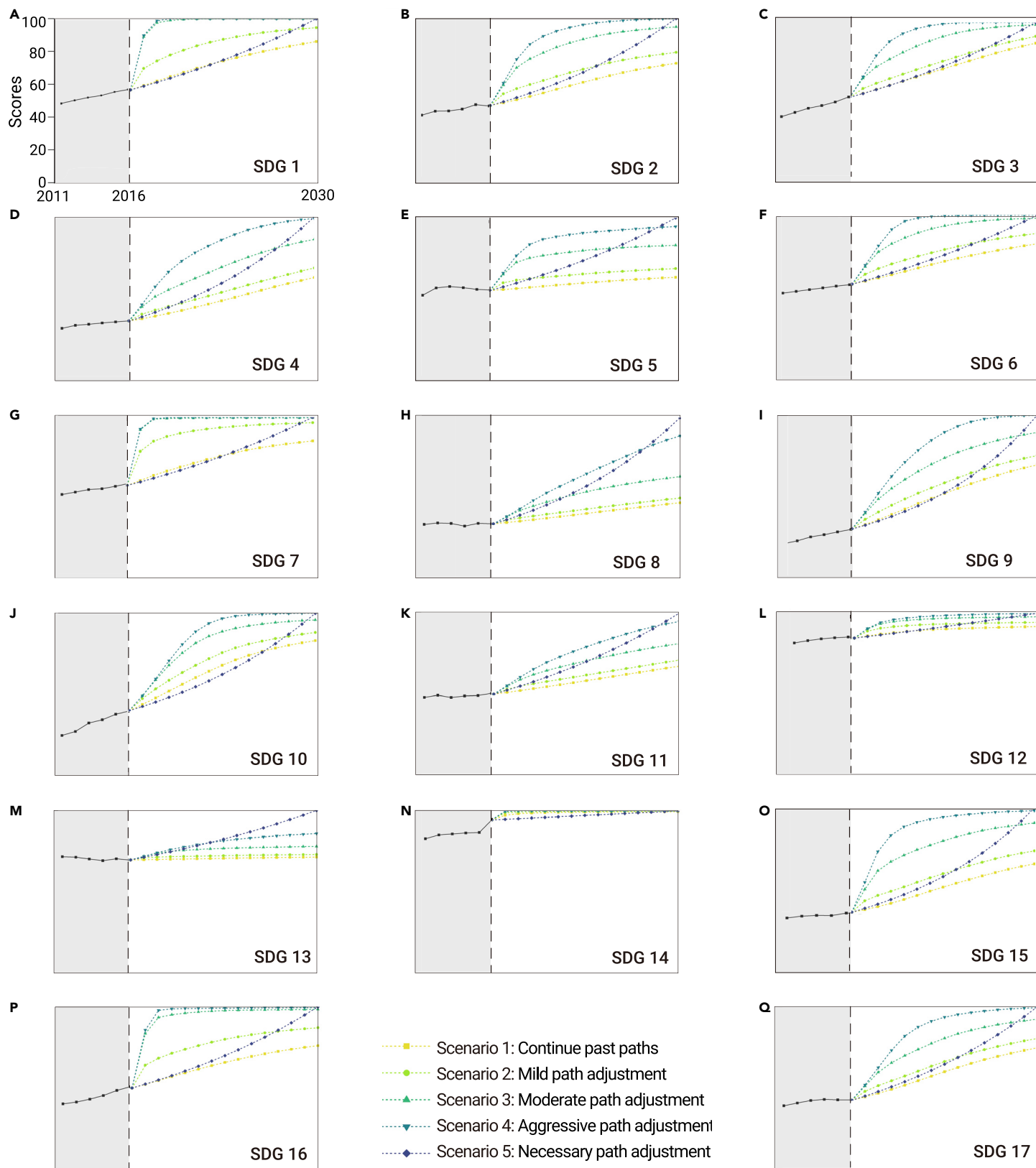
Figure 3. Performance of the 17 SDGs during 2011−2016 and the scenario-based projections of the Chinese cities up to 2030 (A−Q) The 17 graphs correspond to 17 SDGs. The performance of 285 Chinese cities during 2011−2016 are on the left side of each graph, while the simulations of the Chinese cities for 2030 are on the right side. The horizontal and vertical axes of 17 graphs are all the same.

more goals on an average (67.88%) could be achieved (Dataset S1). Two hundred sixteen Chinese cities (75.79%) can achieve 9−13 more goals by shifting to Scenarios 2, 3, and 4 (Dataset S1). On an average, the SDG index of the Chinese cities could improve from 74.57 in 2030 following the existing paths (Figure 2A; Scenario 1) to 80.38, 90.59, and 97.49 after mild, mod-

erate, and aggressive path adjustments, respectively (Figure 2D; Scenarios 2, 3, and 4). To ensure that all goals of a city collectively score 100 points by 2030 and to avoid excessive efforts, we further designed a cost-effective path based on the specific context of each goal (Figure 5; Dataset S1). Considering Zhuhai (Guangdong province), with the best SDG index in

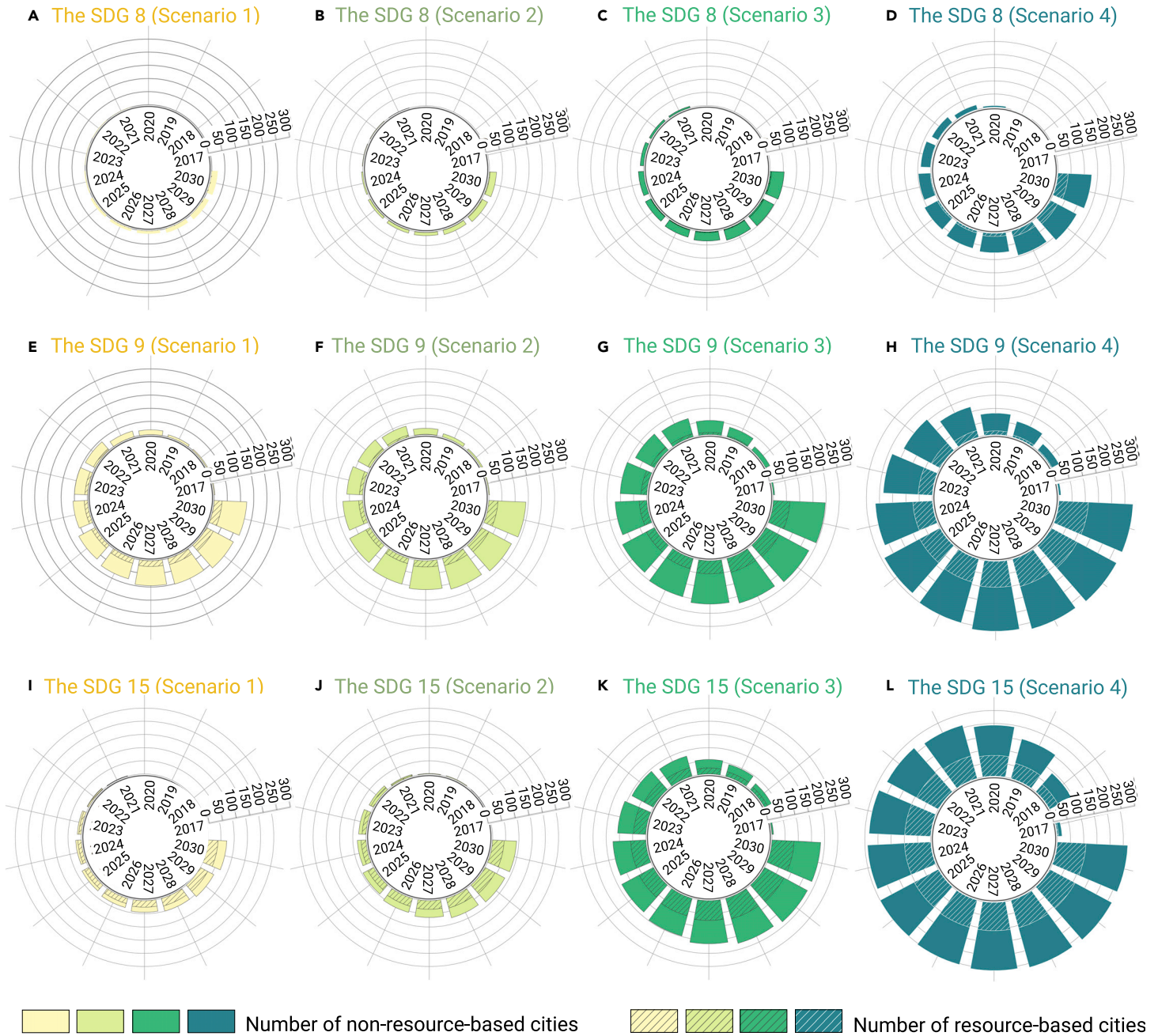**A** The SDG 8 (Scenario 1) **B** The SDG 8 (Scenario 2) **C** The SDG 8 (Scenario 3) **D** The SDG 8 (Scenario 4)

E The SDG 9 (Scenario 1) **F** The SDG 9 (Scenario 2) **G** The SDG 9 (Scenario 3) **H** The SDG 9 (Scenario 4)

I The SDG 15 (Scenario 1) **J** The SDG 15 (Scenario 2) **K** The SDG 15 (Scenario 3) **L** The SDG 15 (Scenario 4)

Number of non-resource-based cities   Number of resource-based cities

Figure 4. Number of Chinese cities scoring 100 under various scenarios during 2017−2030 (A−L) Number of Chinese cities with scores of 100 regarding SDG 8 (A−D), SDG 9 (E−H), and SDG 15 (I−L) under four scenarios. As the performance of each SDG under scenario 5 in 2030 is equal to a score of 100 for all cities, the situation under this scenario was not demonstrated here. The bottom part of the radial stacked bar represents the number of resource-based cities, while the upper part indicates the number of non-resource-based cities.

2016, as an example (Figure 1B), the cost-effective integrated scenarios of Zhuhai were the combination of Scenarios 1, 3, 1, 1, 5, 1, 1, 1, 1, 1, 1, 4, 4, 1, 4, 1, and 1 corresponding with the 17 goals (Figure 5). Twelve goals (SDGs 1, 3, 4, 6, 7, 8, 9, 10, 11, 14, 16, and 17) of Zhuhai could be achieved by continuing the past path (Figure 5; Scenario 1).

The integrated paths of 285 Chinese cities shown in Figure 5 are summarized in Figure 6. On an average, 34.18% of the Chinese cities could achieve one SDG by 2030 if the past improvement paths were maintained (Figure 6A; Scenario 1). Among the 17 SDGs, SDG 14 (96.23%), SDG 10 (58.95%), SDG 12 (50.88%), SDG 7 (48.42%), and SDG 9 (43.51%) (Figure 6A; Scenario 1) had the greatest contribution under Scenario 1. This finding suggests that a relatively large number of Chinese cities can achieve these five goals directly without changing their past paths. In contrast, the proportion of Chinese cities that could achieve the desired goals by continuing the past paths was relatively low for SDG 4 (15.09%), SDG 11 (11.93%), SDG 5 (9.82%), SDG 13 (8.42%), and SDG 8 (9.07%) (Figure 6A; Scenario 1).

DISCUSSION

The SDG index and simulation results were evaluated, and the results provided a scientific reference not only for China, but also for other UN member states to investigate the SDG index at the city level, facilitate the city transformation toward sustainability, and underpin the achievement of the 2030 Agenda. Achieving the 2030 Agenda is challenging for Chinese cities because it requires a holistic achievement of all goals rather than biased selection of some goals.[10] We observed that substantial challenges remain for the Chinese cities to jointly achieve all SDGs by 2030. Specifically, by continuing the past paths, an average of five goals could be achieved for Chinese cities before 2030. The challenge of joint achievement can be interpreted as unbalanced development across the 17 SDGs, some overly ambitious targets,[11] and pervasive trade-offs across economic growth, social inclusion, and environmental protection.[11–13] Achieving the 2030 Agenda is challenging not only for Chinese cities, but also for some other cities around the world.[7,8] For instance, as mentioned in the 2019 US Cities Sustainable Development Report, 66 of the 105 most populous US cities are less than

Rank	City / SDG	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	Zhuhai																	
2	Beijing																	
3	Shenzhen																	
4	Hangzhou																	
5	Xiamen																	
6	Dongguan																	
7	Sanya																	
8	Zhoushan																	
9	Shanghai																	
10	Zhongshan																	
...	...																	
276	Liupanshui																	
277	Chongzuo																	
278	Laibin																	
279	Zhangjiakou																	
280	Handan																	
281	Yulin-SX																	
282	Shuozhou																	
283	Xinzhou																	
284	Linfen																	
285	Lvliang																	

Scenario 1 — Continue past paths
Scenario 2 — Mild path adjustment
Scenario 3 — Moderate path adjustment
Scenario 4 — Aggressive path adjustment
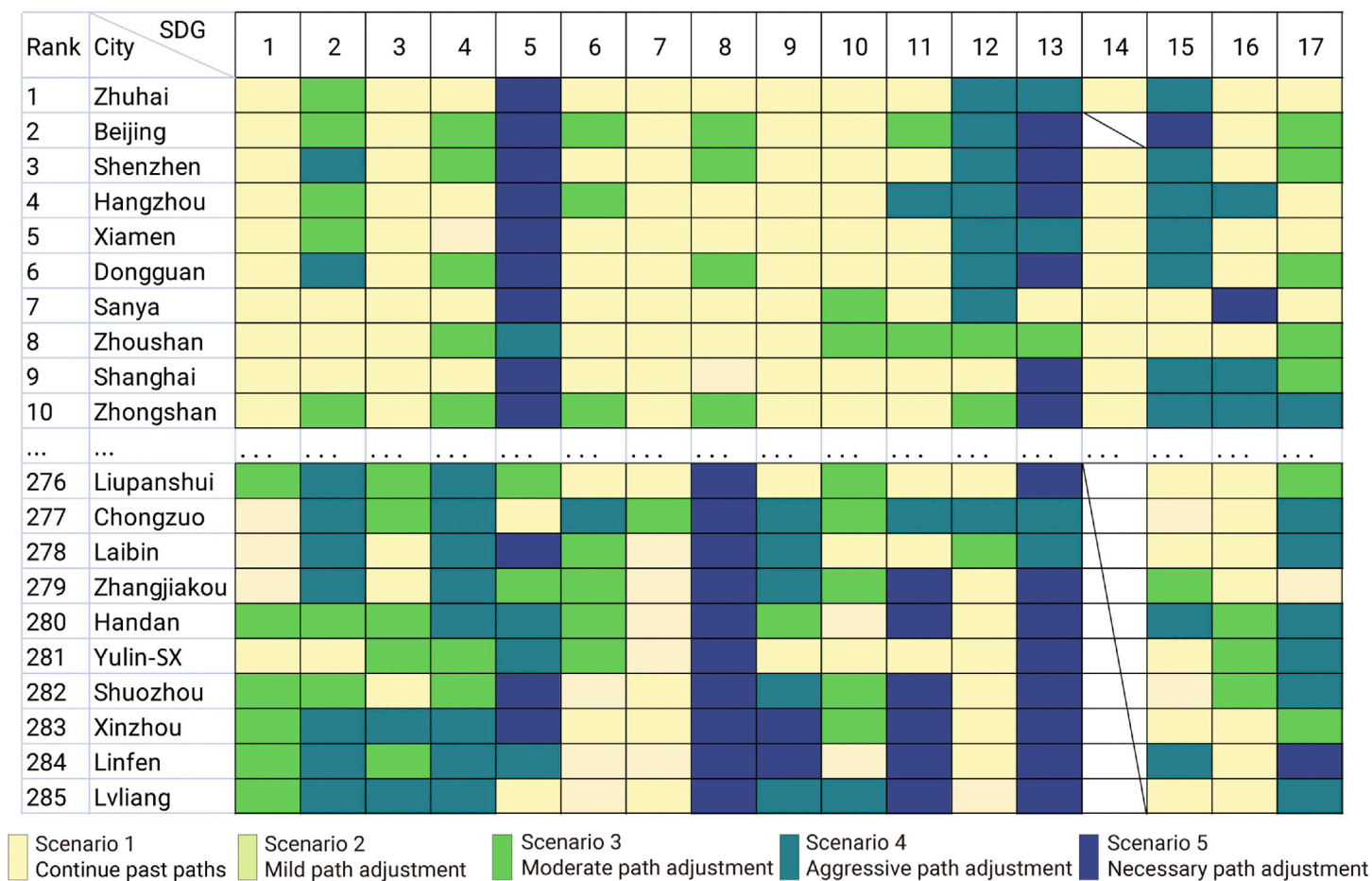Scenario 5 — Necessary path adjustment

Figure 5. Cost-effective improvement paths for the top 10 and bottom 10 Chinese cities Cities are arranged according to their ranks of SDG index in 2016. Five scenarios could be selected for each SDG. We determined one scenario, which was the most cost-effective, for each SDG of each city.

one-half way to achieving these SDGs (the SDG index was <50).[8] As the best performing European city, Oslo still had 25.2% of the way toward the achievement of the 2030 Agenda (the SDG index was 74.8 in 2019).[7] Future research can focus on evaluating long time series subnational SDG index of other countries with consistent indicators and make comparisons with them regarding development levels and change rates.[14]

Policymakers could include greater feasibility in achieving SDGs (eg, having the time frame extended), and at the same time, adopt more powerful and effective strategies to advance the SDG progress. On the one hand, the strategies should consider metacoupling—human-nature interactions within cities as well as between cities and other places nearby and faraway.[15,16] For example, advancing SDG progress in Chinese cities should avoid or minimize negative spillover impacts, such as excessive resource exploitation and environmental pollution, on adjacent and distant rural areas that provide many essential resources.[17–19] In contrast, local policymakers could adopt further intensive path adjustment, which is specific to each SDG, to facilitate the improvement of the SDG index. To adjust paths toward achieving SDGs, different driving factors (eg, population size, economic growth, industry structure, and transparency of governance) specific to each SDG should be considered and integrated since these internal and external factors generally work together to promote the path adjustment.[17]

The "leave no one behind" principle proposed by the UN highlighted that the 2030 Agenda should reduce inequalities and vulnerabilities. Chinese policymakers should closely monitor laggards, that is, resource-based cities. To improve the SDG index of resource-based cities, upgrading industry and diversifying economic structure can be regarded as crucial strategies to broaden development channels and should be implemented in advance of resource depletion.[20] Second, improving institutional quality is an important factor that can help to decrease the negative effects of resource use in resource-based cities (eg, increasing governance transparency).[21,22] Governance transparency is the government's obligation to share information with citizens, such as the proactive disclosure of how officials conduct public business and spend taxpayers'

money.[23] As for non-resource-based cities, many of them are supported by importing energy resources and raw materials from resource-based cities located nearby, so consumption-oriented policies may allow cities with a high SDG index to subsidize the development pressure of resource-based cities.

In the future, we should focus on the following two issues. First, current city-level indicator systems still cannot comprehensively reflect the progress of SDGs, mainly because of data limitations. We call for international institutions and bureaus of statistics to increase investments in SDG data and monitoring systems based on Table S9, which presents the major data gap of Chinese cities. Second, the coronavirus disease that began in late 2019 and the trade war between the US and China that began in 2018 had significant impacts on many SDGs of China and may continue to have impacts until 2030.[24,25] The ongoing Russia-Ukraine war also has cascading effects on food, energy, biodiversity, climate, and many other dimensions of SDGs around the world.[26] Future work will need to explore how these factors affect the achievement of the 2030 Agenda and how to strengthen systemic resilience to cope with various shocks.

METHODS

Sample cities and city categorization

We selected 285 Chinese cities for analysis based on the available data, including four direct-administered municipalities (Beijing, Chongqing, Shanghai, and Tianjin) and 281 prefecture-level cities (Table S2). In terms of sustainable development, resource-based cities face more challenges than others since heavy reliance on resource exploiting and processing activities could give rise to many economic, social, and environmental problems.[27–31] For decades, resource-based cities are regarded as significant strategic bases of energy resources and raw materials in China, which promoted the establishment of an independent and complete industrial system of China and drive national economic and social progress.[23,32] Monitoring SDG progress of resource-based cities is of great importance for China to improve a country's overall sustainability (Table S10), and is also of global interest since unsustainable development of these cities has also been recognized worldwide.[32–35] Therefore, this study classified 285 Chinese cities into two categories, that is 170 non-resource-based cities and

A Chinese cities

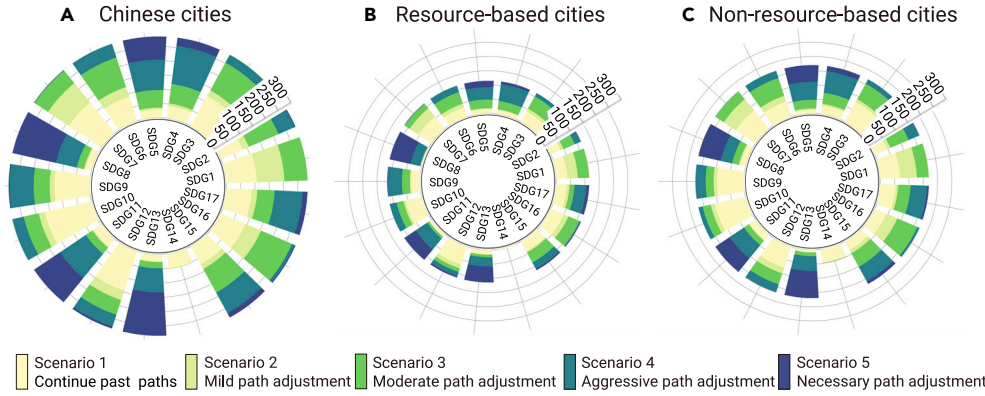**B** Resource-based cities

C Non-resource-based cities

Figure 6. Number of cities under the cost-effective scenario for each SDG (A–C) The total number of Chinese cities (A), resource-based cities (B), and non-resource-based cities (C) under the cost-effective scenario for each SDG. The figures shown in (A) are the summation of those in (B) and (C).

Scenario 1 Continue past paths	Scenario 2 Mild path adjustment	Scenario 3 Moderate path adjustment	Scenario 4 Aggressive path adjustment	Scenario 5 Necessary path adjustment

115 resource-based cities based on Sustainable Development Plan for Resource-based Cities in China (2013–2020) issued by the State Council (Table S2).

Evaluation of the SDG index

There are 17 SDGs with several targets under each goal, adding up to 169 targets and 231 unique indicators in the global indicator framework. Our indicators were selected mainly based on the official list of global SDG indicators proposed by the UN, and supported by the study about SDGs evaluation of Chinese provinces and countries,[1,2] and reports from international institutions.[36,37] The study includes as many indicators with as robust data as possible from these sources. In cases where these indicators had data limitation problems, we chose alternative indicators based on the circumstance of Chinese cities and our understanding of targets shown in UN's official list of global SDG indicators. In general, 61 indicators can be used to evaluate SDG index and their data sources are shown in Table S1. Four interrelated steps for evaluating the SDG index of Chinese cities are shown in supplemental information, which are consistent with our previous study.[1]

Scenario-based projections of 17 SDGs

We developed a scenario-based projection model to forecast the scores of each goal as well as the SDG index for each city under various scenarios, that is, an adjacency-based iteration forecasting model. The theoretical basis of this model is that a city can follow its past path or facilitate the progress of the SDG index by learning from others' paths, and it is easier for it to learn the improvement path from another city with similar situations in economic, social, and environmental development.[38,39] Based on the various similarity degree of development across cities, a city can adopt various paths by learning from each other to facilitate the progress, and then the SDG outcomes will be different.[39] Here, we define the adjacency-based iteration forecasting model as a scenario analysis tool to forecast the trend of a decision-making unit (DMU) in the next period based on its adjacent DMUs (similar DMUs in sustainability, geography, economy, or other characteristics) and this process will iterate until a specific period. The advantage of this model is that it is not limited to a specific country but can be applied to other nations to simulate SDGs progress (or even other research fields) based on different scenarios. The steps for the proposed model are as follows.

Step 1: Estimate the past annual growth rate. The past average annual growth rate from period t_0 to t of SDG j of city l (g_{lj}^t) can be obtained, as follows:

$$g_{lj}^t = \left(\frac{Y_{lj}^t}{Y_{lj}^{t_0}}\right)^{\frac{1}{t-t_0}} - 1, \qquad \text{(Equation 1)}$$

where Y_{lj}^t and $Y_{lj}^{t_0}$ is the score of SDG j for city l in period t and t_0, respectively. Since the study period of this study is from 2005 to 2016, we set $t_0 = 2005$ and $t = 2016$.

Step 2: Construct the matrix of distance in sustainability. The distance in sustainability indicates the similarity degree of sustainability between two cities. A shorter distance means greater similarity. We used a symmetric 285×285 matrix (D) with the diagonal elements equaling 0 to represent the distance in sustainability across 285 Chinese cities in period t, as follows:

$$D^t = [d_{il}^t]_{M \times M} = \begin{bmatrix} 0 & d_{12}^t & \cdots & d_{1M}^t \\ d_{21}^t & 0 & \cdots & d_{2M}^t \\ \vdots & \vdots & 0 & \vdots \\ d_{M1}^t & d_{M2}^t & \cdots & 0 \end{bmatrix}, \quad i \text{ and } l = 1,2,3,...M, \qquad \text{(Equation 2)}$$

where d_{il}^t indicates distance regarding sustainability between city i and city l in period t. M is the total number of cities (285). In this study, $d_{il}^t = \sum_{j=1}^{N} w_j \left| Y_{ij}^t - Y_{lj}^t \right|$, which is based on

Manhattan distance. w_j indicates the weight of SDG j. In this study, all SDGs were weighted equally and $\sum_{j=1}^{N} w_j = 1$. N refers to the number of SDGs that can be used to measure the similarity between two cities. Since coastal cities have 17 SDGs and non-coastal cities have 16 SDGs (excluding SDG 14: Life below water), we only measured the distance of the sustainability of 16 SDGs if the city pair do not have the same number of SDGs, and thus set $N = \min(N_i, N_l)$. In other words, only the paired-up cities are both coastal cities, $N = 17$, or else, $N = 16$. In this study, d_{il}^t is in the range of [0, 100]. The smaller the d_{il}^t, the greater similarity in sustainability between city i and city l in period t.

Step 3: Determine the future growth rate in the next period based on an adjacent city.

$$g_{ij}^{t+1} \in \left[\min_{1 \leq l \leq M} \left(g_{lj}^t | d_{il}^t \leq \alpha \right), \max_{1 \leq l \leq M} \left(g_{lj}^t | d_{il}^t \leq \alpha \right) \right], \qquad \text{(Equation 3)}$$

where g_{ij}^{t+1} indicates the growth rate regarding SDG j of city i for the next period. g_{ij}^{t+1} is ranging from $\min_{1 \leq l \leq M} \left(g_{lj}^t | d_{il}^t \leq \alpha \right)$ to $\max_{1 \leq l \leq M} \left(g_{lj}^t | d_{il}^t \leq \alpha \right)$. There are 285 cities (including itself) that can be treated as adjacent cities for city i and we set a threshold (α) to screen out cities with a relatively large difference in sustainability. α is in the range of 0–100, which is the key parameter to designing different scenarios. For example, $\alpha = 0$ means only the city with the same sustainability in all SDGs can be treated as an adjacent city, and at least one city (itself) can be regarded as an adjacent city for city i. $\alpha = 100$ means that all cities can be treated as adjacent cities for city i, even if they are diametrically different in sustainability. Then, we chose the maximum of the average annual growth rate regarding SDG j within the adjacent city list for city i, that is $g_{ij}^{t+1} = \max_{1 \leq l \leq M} (g_{lj}^t | d_{il}^t \leq \alpha)$. This setting indicates, in the next period, that city i will learn from the growth path of the most fast-growing city with similar sustainable development in economy, society, and environment. If g_{ij}^{t+1} is negative, we keep the scores the SDG j of city i constant.[39]

Step 4: Simulate the scores of an SDG of a city in the next period.

$$Y_{ij}^{t+1}\left(g_{ij}^{t+1}, Y_{ij}^t\right) = Y_{ij}^t \times \left(1 + g_{ij}^{t+1}\right) \qquad \text{(Equation 4)}$$

Y_{ij}^{t+1} and Y_{ij}^t, respectively, indicate the scores of the SDG j of city i in period $t+1$ and t. For cities whose SDGs would reach 100 before 2030, the score of the SDG j would remain constant at 100 since then. The SDG index is the weighted average of the scores of all SDGs in the period $t+1$.

Step 5: Iterate from step 1 to step 4 up to 2030. After obtaining the simulation of the SDG j for city i in the period $t+1$ (Y_{ij}^{t+1}), the similarity degree of sustainability between city i and others has changed, so we need to find another fast-growing city with similar sustainable development in economy, society, and environment. Therefore, to obtain the scores of an SDG of a city in period $t+2$, we repeated steps 1–4 again by replacing t with $t+1$. Then, the scores of an SDG of a city in period $t+2$ can be obtained as follows:

$$Y_{ij}^{t+2}\left(g_{ij}^{t+2}, Y_{ij}^{t+1}\right) = Y_{ij}^{t+1} \times \left(1 + g_{ij}^{t+2}\right). \qquad \text{(Equation 5)}$$

There will be 14 iterations for simulation an SDG of a city since the simulation period is from 2017 to 2030. After this, we could obtain the simulated value of each SDG for each city from 2017 to 2030, and their overall SDG index.

It is more straightforward for a city to learn from the fast-growing paths of cities with similar sustainability in economy, society, and environment. Therefore, we designed scenarios 1, 2, 3, and 4 to simulate the scores of each SDG and the SDG index for Chinese cities from 2017 to 2030, representing learning from each other city's growth path.

(1) Scenario 1 (Continue past paths): The existing trends in the past years will continue until 2030 ($\alpha = 0$).
(2) Scenario 2 (Mild path adjustment): Learning from the path of the most fast-growing city with a mild difference in sustainability (on average less than a 10-point difference) ($\alpha = 10$).

(3) Scenario 3 (Moderate path adjustment): Learning from the path of the most fast-growing city with a moderate difference in sustainability (on average less than a 20-point difference) ($\alpha = 20$).

(4) Scenario 4 (Aggressive path adjustment): Learning from the path of the most fast-growing city with a significant difference in sustainability (on average less than a 30-point difference) ($\alpha = 30$).

(5) Scenario 5 (Necessary path adjustment): The necessary average annual growth rate to ensure an SDG score of 100 in 2030.[39]

For cities whose SDG cannot score 100 by 2030 under scenarios 1, 2, 3, and 4, we further designed scenario 5, which indicates that the achievement of the SDG of these cities should explore new growth paths instead of following its or other cities' existing paths.

Cost-effective integrated paths of 17 SDGs

We determined a cost-effective path for each SDG of each city, and then combined the path choices of all SDGs into a cost-effective integrated path for each city. There are five scenario choices for each SDG, that is, continue past paths, mild path adjustment, moderate path adjustment, aggressive path adjustment, and necessary path adjustment. Scenario 1 costs the least, followed by scenarios 2, 3, 4, and 5. We determined the most cost-effective scenario for an SDG of a city as follows: if an SDG can score 100 by 2030 under scenario 1, this SDG will be designed to continue its own trend. In contrast, this SDG will adopt a more intensive scenario, starting from a mild path adjustment, followed by moderate path adjustment and then aggressive path adjustment. If this SDG still cannot score 100 by 2030 even with aggressive path adjustment, we chose the necessary path adjustment that is scenario 5. By doing the above steps, all SDGs of a city can score 100 by 2030.

Resource availability

Lead contact. Further information about data and methods should be directed to and will be fulfilled by the lead contact, Zhenci Xu (xuzhenci@hku.hk).

Materials availability. This study did not generate unique materials.

Data availability. The SDG index of 285 Chinese cities during 2005–2016 can be found in the file of supplemental tables.

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AUTHOR CONTRIBUTIONS

H.X.: data curation, formal analysis, methodology, original draft. Z.X.: conceptualization, supervision, review and editing. J.R.: conceptualization, supervision, resources. Y.Z.: formal analysis, review and editing. R.L.: data curation, formal analysis. S.B.: methodology, software. L.Z.: formal analysis, review and editing. S.L: review and editing. C.K.M.L.: review and editing. J.L.: formal analysis, review and editing.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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