Spatiotemporal evolution of sustainable development of China’s provinces: a modelling approach

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ABSTRACT

Three sustainable development sub-indicators were established along with 49 indicators of sustainable development at the provincial level. We collected data for the key years of 2010, 2015, and 2018 and evaluated the sustainable development level of 31 provinces in China by using the best and worst value improved equal-weight TOPSIS method. With spatial autocorrelation and hotspot analysis, the spatial characteristics of the sustainable development level were studied. Grey correlation analysis and the offset degree index were also used to find out which indicators should be of most concern to improve the level of sustainable development. The results showed the following. (1) The level of sustainable development of China’s provinces is increasing, but there is a decrease from east to west. (2) In terms of sustainable development, the gap between the four major economic regions is narrowing. (3) The overall sustainable development level is highly consistent with the mainstream green development and the human development index, indicating that exploiting the driving force behind developing and improving the quality of development is the key to China’s sustainable development strategy. (4) Different measures should be taken to promote the realization of Sustainable Development Goals in different areas.

Introduction

The 2030 Agenda for Sustainable Development (United Nations 2015) consists of 17 sustainable development goals (SDGs), 169 sub-goals, and 232 indicators, adopted by all UN member states in 2015, are milestone actions that follow on from the UN millennium development goals (MDGs). To implement this important global political agenda, the UN Statistical Commission created the Interagency and Expert Group on SDG Indicators (IAEG-SDGs) to update the SDG global measurement system dynamically. They divided the indicators into different tiers: Tier I (the indicator is conceptually clear and has an internationally established methodology, standards are available, and data are regularly produced by at least 50% of countries and for 50% of the population in every region where the indicator is relevant), Tier II (the indicator is conceptually clear, has an internationally established methodology, and standards are available but countries do not regularly produce data), and Tier III (no internationally established methodology or standards are yet available for the indicator, but a methodology is being or standards are being (or will be) developed or tested). (As of the 51st session of the UN Statistical Commission, the global indicator framework contains no Tier III indicators.) Due to differences in statistical systems and data availability (United Nations 2017), the UN’s Global SDG Index Framework does not monitor and evaluate SDGs in specific countries, especially at the local level. Accordingly, across the globe, it is common to build localized SDG index systems according to national conditions. Some cities have conducted local explorations at the city-level based on these localized SDGs. In general, the coherence of the policies in the 2030 Agenda for Sustainable Development and the future political agenda for sustainable development will benefit from increased efforts to develop indicators and supporting data in line with the principle of sustainability and from progress in sustainability science and governance (Luca Cosciencie and Mortensen et al. 2019). Quantifying goals can help measure progress in tracking SDG, and indicators will be the basis for monitoring SDG (Sarvajayakesavalu, 2015). After considering the need to localize urban SDGs, the International Institute of Environment and Development has pointed out that the priority is to determine, which indicators are needed locally; meanwhile, national statistics need to integrate these indicators and consider how to improve the current data collection system.

Following the release of the 2030 Agenda for Sustainable Development, scientists, and relevant research institutions have been committed to linking...
previous research with SDGs, actively establishing SDG-oriented localization indicators suitable for specific countries or regions, and monitoring and analyzing the implementation of SDGs. Based on statistical data for more than 200 economies, the World Bank has measured and visualized selected indicators for the 17 SDG targets. Since 2016, the Sustainable Development Solutions Network (SDSN) has published a global SDG Index and Dashboards Report every year (SDSN, Bertelsmann Foundation, 2016–2020). It includes calculated values of the SDG index for each country using a uniform global scale and gives each country a global ranking. The reports point out the challenges each country faces in achieving the SDGs. Since 2018, the SDSN has continuously released the SDG Index and Dashboards Report for specific regions, countries, and cities (SDSN, 2017–2019) to guide governments in more effectively formulating strategic actions in line with the SDGs. Tomislav (2018) introduced the origin, development process, and current situation of sustainable development theory based on a global perspective, focusing on the core results of the 2030 Agenda for Sustainable Development in terms of economics, society, and resources. Several scholars also evaluated the sustainable development of certain regions or certain types of countries based on the SDGs, including Guijarro and Poyatos (2018) for European Union countries, Sadeka, Mohamad, and Sarkar (2018) for southeast Asian countries, Gonzalez-Cabezas, Zaror, and Herrera (2019) for South American countries, Asongu (2018) for sub-Saharan African countries, Cuenca-Garcia, Sanchez, and Navarro-Pabsdorf (2019) for the least developed countries, and Huan et al. (2021) for 15 countries that are part of the Belt and Road Initiative. Currently, multiple cities are developing systems to provide relevant local data. Brazil, for example, has created an urban sector to illustrate how much its performance concerning the SDGs depends on local governments. Several cities have also explored SDG localization at the urban level. For example, the ONE NYC:2050: Building a Strong and Just City (United Nations Development Program (United Nations Development Solutions Network, Bertelsmann Foundation 2019) plan integrates SDGs into urban planning and consists of eight goals and thirty initiatives that constitute a strategy to prepare New York City for the future. Scholars have also studied the localization theory of urban SDGs and evaluated sustainable urban development based on SDGs. Giles-Corti, Lowe, and Arundel (2020) examined the extent to which SDGs will help cities evaluate their efforts toward achieving sustainable development, integrated the SDGs with the action framework for urban indicators designated by UN-HABITAT (UN Habitat, 2017). They suggested a more comprehensive approach should be adopted to formulate benchmarks, monitor and evaluate policies, and evaluate spatial inequality to build sustainable cities. Kochand Krellenberg(2018) accounted for the specific role of cities in promoting sustainable development, focused on the relationship between the national and local levels, and analyzed how Germany adopted different measures to link SDGs with city-level sustainability.

China attaches great importance to the 2030 Agenda for Sustainable Development. The Chinese Ministry of Foreign Affairs has led the establishment of an inter-ministerial coordination mechanism consisting of 43 governmental departments. China is also the first country in the world to establish a national program for implementing the 2030 Agenda for Sustainable Development; this program organically combines the 2030 Agenda for Sustainable Development with China’s medium- and long-term development plans. Domestic scholars and major research institutions have also actively promoted SDG localization research and measured and monitored each SDG. “Index construction and progress evaluation report of SDGs in China 2018” established a preliminary index system consisting of 163 indicators for China’s localized, sustainable development (Chinese Academy of Environmental Planning, World Wide Fund for Nature 2018). Zhenci et al. (2020) developed and tested a systematic approach for assessing spatiotemporal progress toward the SDGs, quantifying progress toward 17 SDGs at the national and provincial levels in China. Wang, Yonglong, and Guizhen et al. (2020) built a localized, sustainable development indicator system for the SDGs, evaluated the sustainable development level of each province in China in 2016, and constructed a provincial sustainable development indicator board. “The evaluation of the sustainable development of China report” (China Center for International Economic Exchanges 2018; 2019) established an evaluation index system for sustainable urban development. It comprises economic development, social livelihood, resources and environment, consumption and emission, and environmental governance. This report includes an exploratory evaluation of the sustainable development level of 100 major cities in China. Weishuang et al. (2020) developed the T21 China 2050 model, studied China’s long-term challenges and opportunities for sustainable development, and adopted the terms “balance,” “narrow,” and “base” to test possible policy interventions in six areas where China’s sustainable development is facing particular challenges. These authors also pointed out that various policy measures can explore China’s sustainable development prospects in the future. National Basic Geographic Information Center (2018) carried out localization of sustainable development at the county level, issued “Deqing’s Progress Report on Implementing the 2030 Agenda for Sustainable Development 2017” (National Basic Geographic Information Center 2018), constructed 102 indicators.
Based on the SDGs, and performed qualitative and quantitative evaluations of the sustainable development level of Deqing County. Liu, Bai, Chen (2019) successfully constructed an SDG localization index system by adopting four localization models based on previous studies. They applied this to a quantitative evaluation of the progress toward achieving SDG15 in Deqing County. Xue and Weng (2017) objectively analyzed the most urgent challenges currently facing China in achieving the 17 SDGs and proposed strategies and action plans for participating in realizing the UN post-2015 development agenda based on China’s national conditions.

However, some problems remain with these studies evaluating sustainable development at the national and local levels. First, there is no systematic method for localizing the SDG, and there is no specific classification and benchmarking index. This leads to the performance of the economic and social dimensions at the national and local levels being unclear, and the short time spans used for the evaluation of sustainable development at the local level lead to the changes in the level of sustainable development not being well reflected in the results. In addition, some experts (2020) pointed out that the goals of eradicating poverty, protecting the environment, and improving well-being by 2030 are largely off-track. Adjusting the SDGs in the current global environment will not be easy; however, these experts have also pointed out that achieving the SDGs will require changing actions. In this context, it is extremely urgent to objectively show the regional characteristics of China’s progress toward achieving the SDGs and carrying out scientific diagnosis and data support for the problems that exist about achieving high-quality development at and below the national level. Therefore, this study assessed sustainable development at the provincial level was made, the SDGs were localized at the provincial level on the basis of domestic and foreign localization experience, an SDG index system applicable to the provincial level was established, and index data were collected for the 31 provinces, autonomous regions, and municipalities in China for 2010 (the tenth anniversary of the adoption of the MDGs at the Millennium Summit, which was also the key year for the implementation of the MDGs (Zhao 2010; Wang, Yang, and Wang et al. 2016) (the base year for the implementation of the UN sustainable development agenda and the endpoint of the UN MDGs), and 2018 (the key year for the implementation of the SDGs and the latest year for which data are available). The optimal value and the worst value improved equal-weight technique for order of preference by similarity to ideal solution (TOPSIS) are used to evaluate the level of sustainable development. On this basis, the spatiotemporal characteristics of the level of sustainable development at the provincial level in China are analyzed, the main obstacles to the realization of the SDGs in different provinces and regions in China are identified, and policy suggestions for further progress toward the realization of the SDGs are proposed.

**Materials and methods**

**SDG localization method and localization index selection at the provincial level**

**SDG localization**

For consistency with other studies on SDG localization progress across the world, we retained the indicators proposed by IAEG–SDGs for which China has reliable data sources in this study. For those indicators we could not use directly, we used existing domestic target indicators, such as the “Evaluation Index System of Innovation Ability of National Sustainable Development Experimental Zone,” the “Evaluation Target System of Ecological Civilization Construction,” the “Annual Statistical Index of Sustainable Development Experimental Zone,” the “Green Development Index System,” and the current local assessment system. We also considered the indicators that are to be assessed clearly according to China’s medium- and long-term special development plans, such as the National Nutrition Plan (2017–2030) and the outline of the “Healthy China 2030” plan. We also referred to the “Progress report on China’s implementation of the 2030 sustainable development agenda” and the “China SDGs Index Construction and Progress Evaluation Report” released by the state institutions and fully considered the internal driving forces and external needs of provincial development. The IAEG–SDG indicators were transformed into expressions to assess the domestic situation. The relevant indicators with clear assessment requirements that were also in line with the sub-goals of SDG162 were added to build an SDG localization index system that conformed to China’s national conditions and was suitable for the provincial level. Figure 1 shows the process used for constructing this index system.

**Method to establish a classification index**

According to the basic principles of sustainable development, the ultimate goal of sustainable development is to achieve the sustainable development of human beings based on the premise that the balance of the Earth’s ecosystems is maintained. That is, the goal is the sustainable utilization of resources and the environment. The core of maintaining sustainable development is the sustainability of the driving forces of social and economic development. Therefore, in this study, we aimed to make a change from the traditional methods for evaluating sustainable social development, sustainable economic development, and sustainable...
environmental development and from the classification of the three “cake” layers of the economy, society, and biosphere proposed by the Stockholm Disaster Relief Center (Philippidis, Shutes, and Robert et al. 2020). Therefore, to give full consideration to mature international sustainable development evaluation indexes, to establish classification indexes based on (A) human welfare, (B) resources and the environment, and (C) development power, and to consider the needs of sustainable development at the provincial level, these three major aspects were divided into 10 sustainable development pillars. Figure 2 shows the classification indexes and pillars.

Localization index selection and data sources
According to the method used for localization of the SDGs and based on the classification indexes, a provincial sustainable development index system was constructed. This consisted of three aspects: human well-being, resources and environment, and development power. In turn, these three aspects included living standards, social stability, infrastructure, natural resources, pollution discharge, environmental governance, ecological construction, economic vitality, and human resources. As a result, the provincial sustainable development index system conformed to the context of the SDGs. Table 1 shows the full list of indicators. There are 18 indicators related to human welfare, 15 indicators related to the status of resources and environment, and 16 indicators related to developing power. Of these, 23 indicators were derived directly from the SDG indicators or by making simple changes to them and 26 indicators were altered based on the context of the SDGs and according to China’s national conditions and assessment needs. Table 1 shows the specific components of the different indicators and the optimal (“opt”) and worst values.

The data used were mainly obtained from various statistical yearbooks for all levels, statistical bulletins on national economic and social development, and on the status of the environment. Some of the index data were also obtained from research results available on platforms such as the China Economic and Social Big Data Research Platform and the China Carbon Emission Database, and from academic papers. Indicators such as the contribution rate of scientific and technological progress and the ecological environment index, for which continuous data were not available but which are highly consistent with the SDG, were retained but were evaluated only for years for which data were available.

Construction of a sustainable development index
The TOPSIS method quantifies a ranking by comparing the relative distance between each measured object and the best and worst schemes. The method has the
advantages of involving simple calculations, being strongly adaptable, and producing reasonable results (Yuan, Zeng, and Chen 2019). The core concept of the SDGs is not to let anyone fall behind. Therefore, in this study, the equal-weight method was adopted. Thus, all the SDG indicators received equal attention. This method also had the advantages of rationality and objectivity (SDSN, Bertelsmann Foundation, 2016). “If it can’t be measured, it can’t be managed.” In this study, the three major aspects shown above and the overall sustainable development levels for 2010, 2015, and 2018 were evaluated using the equal-weight TOPSIS method. This meant that the measurements and evaluations were more objective, accurate, and credible. According to the relevant literature and data characteristics, provinces with scores of 0–20.00 were defined as provinces with a low sustainable development level; provinces with scores of 20.00–40.00, 40.00–60.00, 60.00–80.00, and 80.00–100.00 were defined as provinces with a lower, medium, higher, and high sustainable development levels, respectively.

Based on the normalized original data matrix, this method gave equal-weight to each index and determined the best and worst schemes (expressed by the best and worst vectors, respectively) in the finite scheme using the cosine method. The distances between each evaluated object and the best and worst schemes were then calculated to obtain the relative proximity between each evaluated object and the best scheme. This was the basis for evaluation quality. This method can be divided into the following steps.

1. Standardize the index data. Refer to the five-step decision tree method of the optimal value and the worst value in the SDSN dashboard report to determine the optimal value and the worst value of each indicator (SDSN, Bertelsmann Foundation, 2016). A linear transformation of the variables within the range of [0, 1] is carried out using the following formula:

\[
Y_{ij} = \frac{X_{ij} - \text{wor}(X_{ij}, \ldots, X_{nj})}{\text{opt}(X_{ij}, \ldots, X_{nj}) - \text{wor}(X_{ij}, \ldots, X_{nj})}
\]

where \(i\) represents the year, \(j\) represents the sustainable development index, \(X_{ij}\) and \(Y_{ij}\) represent the original and standardized sustainable development index values, respectively, and \(\text{opt}(X_{ij})\) and \(\text{wor}(X_{ij})\) denote the optimal and worst values of \(X_{ij}\) respectively. Following this calculation, the values of all the indicators were arranged in ascending order, with higher values indicating that the SDGs were closer to being achieved. For example, if a city scored 0.5 on a particular index, it had implemented the SDG to a degree equivalent to half of its optimal value;
Table 1. Provincial-level index system based on the SDGs.

| SDG     | Code  | Component             | Field                          | Unit           | Normalization |
|---------|-------|-----------------------|-------------------------------|----------------|---------------|
| SDG1   | A10   | Living standards      | A %                           | SB, opt = 0, worst = 100 |
| SDG1   | A12   | Living standards      | A %                           | LB, opt = 100, worst = 0 |
| SDG2   | C20   | Economic vitality     | C 10,000 yuan per person      | LB, opt = 10, worst = 0 |
| SDG3   | A20   | Social stability      | A per 1,000 persons           | LB, opt = 12, worst = 0 |
| SDG3   | A21   | Social stability      | A per 1,000 persons           | LB, opt = 8, worst = 0 |
| SDG3   | A23   | Social stability      | A per 10,000 persons          | SB, opt = 0, worst = 1.5 |
| SDG3   | A25   | Social stability      | A per 10,000 persons          | SB, opt = 0, worst = 30 |
| SDG3   | A26   | Social stability      | A per 10,000 persons          | SB, opt = 0, worst = 304.94 |
| SDG4   | C30   | Human resources       | C %                           | LB, opt = 100, worst = 0 |
| SDG4   | C31   | Human resources       | C years                       | LB, opt = 16, worst = 0 |
| SDG4   | C32   | Human resources       | C %                           | SB, opt = 0, worst = 40 |
| SDG5   | C34   | Human resources       | C %                           | LB, opt = 50, worst = 10 |
| SDG6   | A22   | Social stability      | A %                           | LB, opt = 100, worst = 0 |
| SDG6   | B22   | Pollution emission    | B m²/10,000 yuan              | LB, opt = 100, worst = 0 |
| SDG7   | B21   | Pollution emission    | B tonnes of standard coal equivalent/10,000 yuan | LB, opt = 0, worst = 2 |
| SDG8   | A13   | Living standards      | A %                           | LB, opt = 0, worst = 20.9 |
| SDG8   | C10   | Economic development  | C 10,000 yuan per person      | LB, opt = 140,211, worst = 15,000 |
| SDG8   | C11   | Economic development  | C %                           | LB, opt = 20, worst = 0 |
| SDG8   | C14   | Economic development  | C %                           | LB, opt = 81, worst = 20 |
| SDG8   | C33   | Human resources       | C %                           | LB, opt = 81.7, worst = 20 |
| SDG9   | A30   | Infrastructure        | A km/km²                      | LB, opt = 5.36, worst = 0 |
| SDG9   | B42   | Ecological construction| B %                         | LB, opt = 8, worst = 0 |
| SDG9   | C21   | Economic vitality     | C %                           | LB, opt = 6.17, worst = 0 |
| SDG9   | C22   | Economic vitality     | C per 10,000 persons          | LB, opt = 57.3, worst = 0 |
| SDG9   | C23   | Economic vitality     | C per 1,000,000 persons       | LB, opt = 12,410.08, worst = 0 |
| SDG9   | C25   | Economic vitality     | C %                           | LB, opt = 70, worst = 20 |
| SDG10  | A11   | Living standards      | A dimensionless               | LB, opt = 100, worst = 0 |
| SDG10  | A14   | Living standards      | A m² per person               | LB, opt = 48.3, worst = 18 |
| SDG10  | A31   | Infrastructure        | A cars per person             | LB, opt = 19.63, worst = 0 |
| SDG10  | B30   | Environmental governance| B μg/m³               | SB, opt = 8, worst = 153 |
| SDG10  | B32   | Environmental governance| B %                     | LB, opt = 100, worst = 0 |
| SDG10  | B40   | Ecological construction| B %                        | LB, opt = 48.7, worst = 0 |
| SDG10  | B41   | Ecological construction| B m² per person              | LB, opt = 20.38, worst = 0 |
| SDG11  | B20   | Pollution emission    | B ton per 100,000,000 yuan   | SB, opt = 0, worst = 535 |
| SDG11  | B23   | Pollution emission    | B ton per 100,000,000 yuan   | SB, opt = 0, worst = 2 |
| SDG12  | A28   | Social stability      | A per 100,000 persons         | SB, opt = 0, worst = 150 |
| SDG12  | A29   | Social stability      | A %                           | SB, opt = 0, worst = 20 |
| SDG15  | B10   | Natural resources     | B %                           | LB, opt = 33, worst = 0 |
| SDG15  | B11   | Natural resources     | B %                           | LB, opt = 66.8, worst = 4.87 |
| SDG15  | B12   | Natural resources     | B %                           | LB, opt = 0.97, worst = 27.51 |
| SDG16  | A24   | Social stability      | A per 10,000 persons          | SB, opt = 0, worst = 30 |
| SDG17  | C12   | Economic development  | C %                           | LB, opt = 25, worst = 0 |
| SDG17  | C13   | Economic development  | C %                           | LB, opt = 95.6, worst = 50 |
| SDG17  | C24   | Economic vitality     | C %                           | LB, opt = 0, worst = 145.32 |

Similarly, if a city scored 0.75 on a particular index, then the city was three-quarters of the way toward achieving optimal results for that index.

(2) Giving weight to each SDG. When evaluating the three major aspects of the model and the overall sustainable development level, the same weight is given according to the indicators. This is because the aim is for all of the SDGs to be achieved by 2030. Giving the indicators equal weights reflected the commitment of decision-makers to treat the SDGs equally and as a "complete and indivisible" set of goals.

(3) Construct the weighting matrix based on the index system of sustainable development in the three fields:

\[ R = (r_{ij})_{n \times m} \]

\[ r_{ij} = W_j \times Y_{ij} \]

Here, \( R \) is the weighting matrix of each measure index of sustainable development, and \( W_j \) is the weight of sustainable development index \( Y_j \).

(4) According to the weighting matrix \( R \), determine the optimal scheme \( Q^+_j \) and the worst scheme \( Q^-_j \):

\[ Q^+_j = (\max r_{i1}, \max r_{i2}, \ldots, \max r_{im}) \]  

\[ Q^-_j = (\min r_{i1}, \min r_{i2}, \ldots, \min r_{im}) \]

(5) Calculate the Euclidean distances \( d^+_j \) and \( d^-_j \) between each measurement scheme and the best \( Q^+_j \) and worst \( Q^-_j \) schemes, respectively:

\[ d^+_j = \sqrt{\sum_{i=1}^{m} (Q^+_j - r_{ij})^2} \]
(6) Calculate the relative proximity between each measurement scheme and the ideal scheme:

\[ C_i = \frac{d_i^*}{d_i^* + d_i} \]

(8)

\[ C_i = C_i \times 100 \]

(9)

where \(0 < C_i < 100\) and a larger value of \(C_i\) indicates a higher sustainable development level for a given region in year \(i\) (Yuan, Zeng, and Chen 2019).

**Grey relational degree and index offset degree**

Grey relational analysis is a method used to measure the degree of correlation between different factors based on the similarity or difference between the trends in the factors. If the two factors have the same degree of synchronization, it indicates a high degree of correlation. Conversely, if the factors are not well synchronized, the degree of correlation will be low (Liu, Dang, and Xie et al., 2019). The correlation degrees between each sequence to be compared and its reference sequence are sorted from large to small. The larger the degree of correlation, the greater the consistency between the changes in the sequence being tested and the reference sequence is (Gao, Zhao, and Sun et al. 2020). The calculation formula of grey correlation degree is as follows:

\[ \xi(k) = \frac{\min \min \vert x_0(k) - x_i(k) \vert + \rho \times \max \max \vert x_0(k) - x_i(k) \vert}{\vert x_0(k) - x_i(k) \vert + \rho \times \max \max \vert x_0(k) - x_i(k) \vert} \]

(10)

\[ R_i = \frac{1}{n} \sum_{k=1}^{n} \xi_i(k) \]

(11)

where, \(x_i(k)\) is the sequence being compared; \(x_0(k)\) is the reference sequence, \(i = 1, 2, \ldots, n\); \(k\) is the series length; \(0 < \xi_i(k) \leq 1\); and \(\rho\) is the resolution coefficient. Usually, \(0 < \rho < 1\), and most commonly, \(\rho = 0.5\). The average value method for the correlation coefficient is used to combine the calculated correlation degrees for all the points in the curve into one value. The calculated average value is taken as the relational degree between the reference sequence and the comparison sequence. \(R_i\), the relational degree of index \(i\), reflects the relative importance of this index, and \(\xi_i(k)\) is the coefficient of the relational degree between the sequence being compared and the reference sequence.

This paper introduces the offset degree index, namely \(1 - Y_{ij}\), to show which indicators are in urgent need of improvement. Indicators with higher values of this index are the indicators in each province that are in urgent need of improvement.

**Spatial variation analysis**

In this study, two types of spatial autocorrelation coefficient and spatial hot spot analysis were used to calculate the spatial distribution patterns in sustainable development at the provincial level in China. Combining a Moran scatter plot and a cold/hot spot distribution diagram, the spatial distribution of the cold spots and hot spots could be identified, and local differences in spatial patterns could be visualized using a geographic information system. The two types of spatial autocorrelation coefficients used were the global spatial autocorrelation coefficient, Moran’s I, which was used to determine the characteristics of the spatial distribution of the sustainable development levels within each province in the research area, and the local spatial autocorrelation coefficient, local Moran’s I, which was primarily used to explore the degree of correlation between the sustainable development level of the study area as a whole and the corresponding level for adjacent locations within a given sub-region (Huijiang 2020; Wang, Liao, and Liu 2010; Yang et al. 2012). A Getis-Ord Gi* spatial hot spot analysis reflects the distribution of hot spots and cold spots in the local space used in a research object (Pan and Yin 2011; Feng et al. 2018). This study detected whether there were hot spots and cold spots in the sustainable development levels within the study area — i.e., whether there were high and low concentrations of a particular sustainable development level (Namayande, Nejadkoorki, and Namayande et al. 2016; Wang, Yang, and Wang et al. 2016).

The formulas used for calculating the global spatial autocorrelation coefficient (Moran’s I), the local spatial autocorrelation coefficient (local Moran’s I), and Gi* are as follows:

\[ \text{Moran’s } I = \frac{n \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} (x_i - x) (x_j - x)}{(\sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij}) (\sum_{i=1}^{n} (x_i - x)^2)} \]

(12)

\[ \text{Local Moran’s } I_i = x - x \sum_{i=1}^{n} i(x_i - x)^2 \sum_{j=1}^{n} w_{ij} (x_j - x) \]

(13)

\[ G_i^* = \frac{\sum_{j=1}^{n} w_{ij} x_j - x \sum_{j=1}^{n} w_{ij}}{\sqrt{n}} \]

(14)

Here, \(n\) is the total area, \(x_i\) and \(x_j\) are the values of the sustainable development levels \(i\) and \(j\), respectively, for the whole study area, \(x\) is the average level for the
whole study area, \( w_{ij} \) is the spatial weight matrix between levels \( i \) and \( j \) within the study area, and \( s \) is the standard deviation. In this study, we used the distance function to calculate the spatial weight for each province.

**Correlation analysis**

In this study, SPSS 25.0 was used to evaluate the Spearman non-parametric correlation between the three major aspects of the model and the overall sustainable development level, economic development level, and green development level. The correlation analysis was based on the scores in the three major aspects of sustainable development and the overall development level. We explored the relationships between the gross domestic product (GDP), human capital (HC, as measured by the nominal human capital in the China Human Capital Index Report, 2019) (China Research Center for Human Capital and Labor Economics 2019), the business environment index (BEI, as measured by the business environment index in the China Business Environment Index Report 2018) (WANBO Economic Research Institute 2018), and the correlation between the green development index (GDI, as measured by the green development index proposed in the Bulletin of Annual Evaluation Results of Ecological Civilization Construction in 2016) (National Bureau of Statistics 2017) and the human development index (HDI, as given by the data in the Special Edition of China Human Development Report) (United Nations Development Program 2019).

**Results**

**Temporal differentiation characteristics in the results of the evaluation of sustainable development at the provincial level**

The methods described above were used to evaluate sustainable development levels of Chinese provinces in 2010, 2015, and 2018. According to our calculations (see Table 2), the average level of sustainable development in the 31 provinces in China was 49.98 in 2010, 54.29 in 2015, and 57.18 in 2018. In recent years, the sustainable development levels of China’s provinces have been rising, especially since 2015; this substantial progress is closely related to the actions that China has taken to implement the 2030 Agenda for Sustainable Development. The Chinese government has taken a series of top-level design, strategic docking, and mechanism guarantee actions and has incorporated the 2030 Agenda into the 13th five-year plan as well as national medium- and long-term overall development plans. In addition, as reflected in its overall social, economic, and environmental planning, in February 2018 and May 2019, the State Council approved the construction of innovative zones for demonstrating the national sustainable development agenda in Shenzhen, Taiyuan, Guilin, Chenzhou, Lincang, and Chengde. They put in place a local, sustainable development index system with key targets and indicators to provide Chinese experience of sustainable development at home and abroad and promote regional and national sustainable development. **Table 3** shows the overall sustainable development level and the sustainable development level scores corresponding to the three major aspects of our model for the years 2010, 2015, and 2018. There was little change from year to year in the sustainable development levels of the provinces in the three highest and lowest positions.

Based on the number of provinces at each level each year, a chart showing the distribution of provinces with various sustainable development levels was made (Figure 3). The overall sustainable development level, and the sustainable development levels corresponding to the three major aspects of the model, increased from a lower level to a higher level between 2010 and 2015 and again between 2015 and 2018. However, overall, the level of sustainable development for the different provinces was relatively low. Only two provinces were at a “higher” level of development, indicating that most provinces in China still need to enhance innovation and cultivate the power of development.

**3.2 Spatial differentiation characteristics in the results of the evaluation of sustainable development at the provincial level**

**Regional patterns in sustainable development in China**

Based on the optimal value and the worst value improved equal-weight TOPSIS model, the overall sustainable development score for each province in China was obtained. These scores were then classified using the Jenks optimal natural fracture method in ArcGIS10.2, which ensured that the classification standards used for different periods were consistent. The spatial and temporal patterns in the sustainable development levels in 2010, 2015, and 2018 were thus obtained (Figure 4). Figure 4 shows that the sustainable development levels of China’s provinces present
Table 3. Overall sustainable development level and ranking of sustainable development level scores for the three major aspects of the model. (Only the top and bottom three provinces are listed in each case.)

| Year | Top three regions | Overall sustainable development level | Sustainable development level in the field of human welfare | Sustainable development level in the field of resources and environment | Sustainable development level in the field of development power |
|------|------------------|---------------------------------------|----------------------------------------------------------|-------------------------------------------------|-------------------------------------------------------------|
| 2010 | Beijing, Shanghai, Tianjin, Qinghai, Gansu, Xinjiang | Beijing, Shanghai, Tianjin | Guangdong, Zhejiang, Fujian | Beijing, Shanghai, Tianjin |
| 2015 | Beijing, Zhejiang, Jiangsu, Shandong, Tianjin, Qinghai, Xinjiang, Tibet | Beijing, Zhejiang, Shandong | Hainan, Guangdong, Fujian | Beijing, Shanghai, Tianjin |
| 2018 | Beijing, Guangdong, Shandong, Xiangxi, Tibet, Xinjiang | Beijing, Tianjin, Zhejiang | Guangdong, Hainan, Fujian | Beijing, Shanghai, Tianjin |

Figure 3. Distribution of the number of provinces with different sustainable development levels. Sustainable development is abbreviated as “SD”

A contiguous spatial pattern and that the overall level of sustainable development is higher in the eastern part of the country than in the central and western regions, which indicates that provinces with similar levels of development may be spatially related. Therefore, spatial autocorrelation and hot spot analysis could explore the spatial distribution of the provincial sustainable development levels. Figure 5 shows the spatial distribution of the sustainable development levels corresponding to the three major aspects of the model. Figure 5 shows the levels of human welfare and resources and environment development do not vary much between China’s provinces. Also, the level of sustainable development to economic power across the country is relatively poor.

Distribution by spatial zone—Three major economic belts
China is divided into the eastern, central, western, and northeastern economic regions. The east region includes the ten provinces (and cities) of Beijing, Tianjin, Hebei, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, Guangdong, and Hainan. The central region includes the six provinces of Shandong, Henan, Anhui, Jiangxi, Hubei, and Hunan. The west region includes the eleven provinces of Inner Mongolia, Shaanxi, Ningxia, Gansu, Xinjiang, Sichuan, Yunnan, Guizhou, Guangxi, Tibet, and Qinghai, and the city of Chongqing. Finally, the northeast region includes Liaoning, Jilin, and Heilongjiang provinces. Figure 6 shows the overall sustainable development and development levels corresponding to the three major aspects of the model for the three major economic regions in 2010, 2015, and 2018.

In terms of the overall level of sustainable development and the sustainable development level for the three individual aspects, the eastern economic region is mostly ranked first out of the four major regions. The western regions rank lowest in terms of the overall sustainable development level and the levels corresponding to the three individual aspects of development. The northeastern region has higher scores than the central region for both the overall sustainable development and individual aspects. In terms of changes in development level, the overall sustainable development score and the score for sustainable development in human well-being for the western region increased the fastest; the scores for sustainable development in resources and environment increased fastest in the northeastern region. The score for development power improved fastest in the eastern region.

Spatial relevance analysis
Global spatial autocorrelation. Based on the overall sustainable development level scores for the 31 provinces in China and using the inverse distance function to establish the spatial weight matrix, the global Moran’s I values for these scores for 2010, 2015,
were obtained as 0.288702, 0.174631, and 0.059652, respectively, with \( p < 0.006 \). The overall statistical value of Moran’s I coefficient lies in the range \([-1, 1]\). The closer this value is to 1, the greater the positive correlation between the spatial units; the closer this value is to –1, the more negative the correlation between the spatial units. If the value of Moran’s I is close to or equal to 0, it indicates that spatial units’ attributes are not related to each other. Our results showed that the level of sustainable development had a positive spatial correlation at the provincial level. The results also showed that when the spatial agglomeration state, the generally low level of the sustainable development of the adjacent provinces is low, high overall sustainable development level of the province is close to the highest value distribution of spatial agglomeration provinces. The value of Moran’s I fell slightly from 2010 to 2018. Thus, since 2010, the spatial differences in the provincial levels of sustainable development have increased. The degree of spatial agglomeration has slightly decreased.

**Local autocorrelation.** A Moran scatter diagram can be used to identify and show the agglomeration state as well the distribution of cold and hot spots in a given region. Considering the overall sustainable development level of each province as the abscissa, the spatial lag value as the ordinate and the average

![Figure 4](image-url)

**Figure 4.** Maps showing the spatial distribution of the overall level of sustainable development for each province in China in (a) 2010, (b) 2015, and (c) 2018. In order to display the results more clearly, the abbreviations of each province are used here, and the specific meanings are shown in Table 4.
value of the horizontal and vertical coordinates of the scatter points as the origin, we can divide a plane space map into four basic quadrants: quadrants 1 and 3 correspond to high–high and low–low aggregation, respectively; quadrants 2 and 4 correspond to low–high and high–low anomalies, respectively. Using ArcGIS10.2 and Excel 2016, agglomeration evolution maps for these four classes of sustainable development at the provincial level in China were drawn for the period 2010 to 2018. The results are shown in Figure 6. The “high–high” (HH) and “low–low” (LL) quadrants in the Moran scatter plot indicate where the level of overall sustainable development at the regional level in China had a strong positive spatial correlation; that is, it was homogeneous (had an agglomerated distribution pattern). The “high–low” (HL) and “low–high” (LH) quadrants correspond to a strong negative spatial correlation, indicating areas where there was spatial heterogeneity (a discrete distribution pattern) in the level of sustainable development at the regional level during the research period. From the Moran scatter plot for the period 2010 to 2018, the distribution of the 31 provinces among the HH, LL, HL, and LH quadrants in 2010, 2015, and 2018 can be seen. The number of provinces located in the HH and LL quadrants is greater than that in HL and LH quadrants. The level of overall sustainable development also has a high regional concentration. Clusters of high values in the east of China and low values in the central and western

Figure 5. Maps showing the spatial distribution of the sustainable development levels corresponding to the three major aspects of the model for each province in China in (a) 2010, (b) 2015, and (c) 2018.
regions can be seen. The HH quadrant corresponds to high values and provinces with relatively high levels of overall sustainable development. These provinces are located close to one another, mainly in China’s eastern and northern coastal areas. The LL quadrant corresponds to low values and to provinces with a relatively low level of overall sustainable development. These provinces are also located close to one another, mainly in the northwest and southwest of the country. The LH quadrant contains local low-value outliers: these correspond to provinces where the overall sustainable development level is low, but the level in neighboring provinces is high. Conversely, the HL quadrant contains high-value outliers: these correspond to provinces where the overall sustainable development level is high, but the level in neighboring provinces is low.

**Hot spot analysis.** Using ArcGIS10.2, we analyzed the cold and hot spots in the distribution of sustainable development levels by province and the cold and hot spot areas with the agglomeration effect. The results of the analysis of the Getis–Ord Gi* spatial hot spots are shown in Figure 8. Red indicates that the sustainable development level of the province (city) constitutes a hot spot; blue indicates that this level constitutes a cold spot. Figure 7 shows that there are “cold areas” centered on Tibet, Qinghai, Xinjiang, and Gansu and “hot areas” centered on Jiangsu, Zhejiang, Anhui, and Shanghai.

**Results of the analysis of the gray correlation degree and offset degree index**

Using the indicator data for 2018 and the overall sustainable development level of each province as the parent sequence and the original indicator data as the subsequence, we calculated the gray correlation degree for each indicator. The offset degree for each indicator was also then calculated. The indicators with the three highest values of the gray correlation degree and offset degree index for each province and the four major economic regions are shown in Table 4 and Table 5, respectively. The highest values indicate, which indicators provinces should improve their performance.

**Correlation analysis**

We used Spearman’s non-parametric correlation analysis and SPSS 25.0 to evaluate the correlation between the three main aspects of sustainable development, the overall level of development, the level of economic development, and the level of green development. Table 6 shows the analytical results.

The GDI includes six aspects: resource utilization, environmental governance, environmental quality, ecological protection, economic growth quality, and green living. The BEI is subdivided into seven aspects: natural environment, infrastructure, financial environment, talent environment, technological innovation environment, cultural environment, and living environment. Finally, the HDI is divided into three dimensions: the health index, education index, and per capita income index. The BEI, GDI, HDI, and sustainable development level all show very significant positive correlations with the overall level of sustainable development, which indicates that, overall, the levels of sustainable development for each province obtained in this study are consistent with the results obtained for the green development, business environment, and HDIs. However, the sustainable development target indicators established in this study cover a relatively wide range, whereas these three indexes only cover some of the aspects included in the indicators and are lacking concerning social indicators and the momentum of development.

**Discussion**

In this study, 49 indicator variables from 10 pillars in three fields were selected and the improved equal-weight TOPSIS method was used to comprehensively evaluate the sustainable development levels of the 31 provinces in China. The results and analysis of the paper are as follows.
In 2010, 2015 and 2018, the level and driving force of sustainable development in China’s provinces and autonomous regions, resources and the environment all improved, and in particular, great progress was made in human well-being. The score of sustainable development in the field of human well-being is high, while the score of sustainable development in the field of development driving force is low, indicating that the level of development driving force in China’s provinces and regions is low, and innovation-driven development needs to be strengthened.

There was a gap between the four economic regions of China. In 2010, 2015, and 2018, the level of overall sustainable development and the level of sustainable development corresponding to the three main aspects that were investigated were higher in China’s eastern economic region than in its western region. However, the gap between the level of overall sustainable development and sustainable development in the other two areas seems to be gradually narrowing, except for the drive behind the development. The regions with high levels of sustainable development are mainly located in the southeast coastal region, whereas the regions with low levels of sustainable development are mainly found in the northwest.

The values of the global Moran’s index for the overall level of sustainable development in China’s provinces in 2010, 2015, and 2018 showed that the spatial correlation for China’s provincial overall sustainable development level was positive but weakening. Analysis of the LISA index showed that the local correlation between the sustainable development levels of Chinese provinces is more obvious. A large number of high–high and low–low clusters were found. Provinces with higher and lower sustainable development levels form spatial clusters. From 2010 to 2018, the sustainable development “cold spots” in China were mainly concentrated in Tibet, Qinghai, and Gansu, whereas the “hot spots” were mainly concentrated in Jiangsu, Zhejiang, and Shanghai.

The results for the offset degree index discussed in this paper help indicate the direction in which future efforts in each province should be made. Chinese provinces – for example, Xinjiang, which has a low level of sustainable development – should continue paying attention to indicators with high gray correlation degrees and increase enrollment in higher education and the output from scientific and technological innovation. Each province should take action to improve the performance of the indicators with large offset.
degree indexes. For example, Guangxi should reduce emission levels and increase the number of years that its citizens spend on education and strengthen training and the development of human resources.

(5) In implementing the Sustainable Development Agenda, China needs to focus on human well-being, resources and the environment, and the driving force behind development. In particular, measures need to accelerate sustainable development related to resources and the environment. In particular, the eastern region of China should explore ways to speed up resource and environmental development and the overall level of sustainable development without compromising sustainable human development and well-being. In the central region, the steady improvement in sustainable development is related to the three aspects of people’s livelihoods, resources, and environment, and the driving force behind development should be maintained. Assuming that the sustainable development level of resources and environment is maintained, the western region of China should strive to increase the motivation needed to raise the level of sustainable development and continuously improve the sustainable development level in relation to human well-being. The northeastern region should strive to implement the Northeast Revitalization Strategy and improve the level of scientific and technological innovation and related infrastructure.

In short, the correlation analysis performed in this study produced results consistent with the evaluation results produced by national government departments and research institutions and applicable in the following ways. First, correlation analysis can be used to determine the different aspects of sustainable development levels during different periods using a common basis that produces overall scores. Therefore, the research results can identify areas that are performing well or poorly from the perspective of sustainability; changes in sustainable development levels with time can also be identified. Results of this type can provide basic data that can be used in macro-analyses of the sustainable development levels in China’s provinces. Second, in this study, overall sustainable development was decomposed into the three aspects of human well-being, resources and environment, and development power. The results obtained provide information relevant to the levels of sustainable development related to these three aspects. However, at the same time, this study’s results depend on the framework and variables and the data, which
were available for these variables. Future research will experiment with the modification or addition of variables and with different weight ratios for the variables and pillars as these can change according to local conditions and backgrounds. This will allow the most appropriate evaluation methods for different situations to be developed.

The coronavirus (COVID-19) pandemic has put enormous pressure on the global economy and business activity. This has led to serious negative financial consequences, declining levels of GDP in many countries, and increasing poverty and hunger worldwide. COVID-19 not only threatens the achievement of the SDGs but also the progress toward the SDGs that has already been made (World Bank 2020). Therefore, despite the tremendous efforts being made both within and outside China to contain the pandemic, sustainability in the post-COVID-19 era should not be taken for granted. In fact,
sustainability and the achievement of the SDGs are now more important than ever. It is necessary to explore the possible impact of COVID-19 on the implementation of SDGs at and below the national level. However, due to the incomplete publication of provincial-level data in China in 2020, the currently available data are not suitable for assessing provincial-level sustainable development in China in 2020. However, some scholars have discussed the influence of COVID-19 on the implementation of SDGs and the solution path through qualitative analysis. Gao (2021) pointed out that the scientific methods applied by Chinese scientists in sustainable development are in line with the Humbrian holistic view of nature, but in the face of sustainable development challenges such as COVID-19, China should still encourage and monitor public participation, prioritize poverty eradication, and regard well-being as the ultimate goal of sustainable development. Yin et al. (2021) pointed out that ecosystem services (ESs) are the basis of SDGs, ESs are beneficial to all SDGs, and discussed the way to integrate ESs into socio-economic development and promote the achievements of SDGs after influenza pandemic. Noting that the pandemic and global lockdown/restriction disrupted the flow of ESs and altered human ESs demand, threatening the efforts for the SDGs. It is suggested that priority be given to urgent issues such as health care, livelihood and resource security, and in the long run, promote harmony between man and nature in order to achieve SDGs, enhance ESs and promote SDGs through local community efforts, ESs accounting, and ecosystem restoration. Based on the available data, COVID-19 has held back China’s economy in terms of development power, with GDP falling by 1.6% year-on-year in the first half of 2020 at comparable prices. In terms of human welfare, as a global health emergency, the COVID-19 pandemic has greatly affected the sustainable development of society by endangering people’s quality of life, human well-being, and health and safety. In 2020, China’s registered urban unemployment rate was 4.2%, which is the first increase in the unemployment rate since 2015. From many perspectives, the different impacts of COVID-19 on resources and the environment have produced challenges and opportunities for sustainability. For example, the pandemic has had a positive impact on the environment and air quality. In 2020, the average number of “good air” days in 337 cities at and above prefecture-level in China increased by 5.0 percentage points year-on-year. The average concentration of PM2.5 fell by 8.3% year-on-year. However, there has been a negative impact on waste production and other outputs. According to UN Secretary-General António Guterres, COVID-19 requires global solidarity, good governance, and a shared sense of responsibility. This humanitarian crisis requires coordinated, decisive, inclusive, and innovative policy action by the world’s major economies (United Nations 2020). The possibility of other similar emergencies in the future also requires China and its provinces to take proactive measures to minimize the impact of such emergencies on sustainable development.

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