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Article

Untangling the interactions between the Sustainable Development Goals in China

Junze Zhang [a,b], Shuai Wang [b], Prajal Pradhan [c], Wenwu Zhao [b], Bojie Fu [a,b,*]

[a] State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China
[b] State Key Laboratory of Earth Surface Processes and Resource Ecology, Faculty of Geographical Science, Beijing Normal University, Beijing 100875, China
[c] Potsdam Institute for Climate Impact Research (PIK), Member of the Leibniz Association, Potsdam 14473, Germany

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ABSTRACT

Understanding the interactions (synergies and trade-offs) among the Sustainable Development Goals (SDGs) is crucial for enhancing policy coherence between different sectors. However, spatial differences in the SDG interactions and their temporal variations at the sub-national scale are still critical gaps that need to be urgently filled. Here, we assess the spatial and temporal variation of the SDG interactions in China based on the systematic classification framework of SDGs. The framework groups the seventeen SDGs into three categories, namely "Essential Needs," "Objectives," and "Governance." Spatially, we found that the SDGs in "Essential Needs" & "Objectives" and "Essential Needs" & "Governance" generally show trade-offs in the eastern provinces of China. Synergies among all three SDG categories are observed in some central and western China provinces, which implies that these regions conform to sustainable development patterns. In addition, temporally, the synergies of the three SDG categories have shown a weakening trend in the last decade, mainly due to the regional differences in the progress of SDG7 (Affordable and Clean Energy). Overall, our results identify the necessity for provinces to enhance the synergies between SDG12 (Responsible Production and Consumption) and other SDGs to tackle the trade-offs between the "Essential Needs" and "Objectives." Meanwhile, promoting the progress of SDG7 will also contribute to balanced development across provinces.

1. Introduction

In September 2015, the United Nations released the Sustainable Development Goals (SDGs), a results-oriented framework for sustainable development that contains 17 goals, 169 targets [1]. The purpose of the SDGs is to encourage countries to utilize the framework to guide national planning, policymaking, and investment decisions and regularly monitor and report on progress from 2016 to 2030 for sustainable transformation [2]. However, despite the broad content of SDGs, the comprehensiveness and complexity may limit the potential for their achievement [3]. Recent studies show that there are complex interactions between the SDGs, which can generally be classified as synergies and trade-offs [4,5]. The former implies that advances in one goal could benefit progress in another, while the latter indicates that progress in one goal will hinder progress in another [5]. Nevertheless, these studies have mostly been global-scale analyses and have focused on simplified indicators [6–8]. Assessing the SDG interactions on a sub-national scale remains an important knowledge gap, which needs to be urgently filled to provide scientific evidence for formulating sustainable development policies at a sub-national scale.

As China is the world's largest developing country and the second-largest economy, its economic development and socio-environmental issues have always received widespread attention [9–11]. Recent assessments showed that China's sustainable development level is steadily increasing. For example, the SDG Index score in China, assessed by Bertelsmann Stiftung and Sustainable Development Solutions Network, has increased from 59.1 in 2016 to 72.1 in 2021 [12,13]. This increased score means that China has achieved 72.1% of the targeted value for SDGs [13]. However, some studies also pointed out that addressing the uneven SDG Index at the provincial scale in China is still a significant challenge [11,14]. It has been suggested identifying the synergies and trade-offs between the different SDGs would facilitate policy coherence and balanced development across provinces [3]. But existing studies have only assessed the SDG interactions at the national scale, which have overlooked the spatial differences in SDG interactions [15,16]. Considering that provinces may feature different strengths and dilemmas, assessing such differences could contribute to

* Corresponding author.
E-mail address: bfu@rcees.ac.cn (B. Fu).

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finding measures to advance the SDGs at a sub-national scale evenly. Additionally, previous studies are based on the SDG Index database, which usually has limited data availability and lacks a fit with the official SDG indicators framework [15,16]. Since the indicators at global or national scale may not be applicable at the sub-national scale [2], the use of indicators suitable for the provincial scale will be of further help in identifying the influencing factors that constrain the synergistic development across the SDGs.

Furthermore, no studies have analyzed the evolution of SDG interactions over time in China. Such information is crucial because the linkages between different sectors are often dynamic [17]. These linkages are vulnerable to multiple factors such as resource availability and policy coherence, which may cause the interactions to change over time [18–20]. Continuous monitoring of such changes will provide vital information for the adjustment of macro policies. Meanwhile, revealing the key SDGs that significantly affect the interactions can help explore adequate measures to transform trade-offs into synergies. These insights will provide valuable information for advancing the full implementation of SDGs at national and sub-national scales.

To fill the above-highlighted gaps, we quantified the spatial and temporal variability of the SDG interactions (synergies and trade-offs) in China. We aimed to address the following questions. First, what differences exist in the synergies and trade-offs of SDGs across provinces? Second, what are the time-varying characteristics of the SDG interactions in China? Third, what are the drivers for the change of SDG interactions? To answer these questions, we first constructed an indicator system applicable to the provincial scale in China according to the official SDG indicator framework requirements. We collected historical data of each indicator through different statistical departments, resulting in 88 indicators for 71 targets of the 16 goals (see Table S1 online).

To make the indicators comparable, we normalized the raw data to a score range of 0–100 by referring to the method applied in the SDG Index and Dashboards [12,21] (see details in Methods). Here, indicator score 0 means the baseline value, and 100 is the achievement of the target posed by the SDG. Subsequently, the indicator scores are finally aggregated into the SDG scores by the arithmetic mean method, and the SDG scores for each province were used for synergy and trade-off analysis based on the systematic classification framework of SDGs proposed by Fu et al. [3] (Fig. 1a, see details in Methods). The framework group 17 SDGs into three categories, namely "Essential Needs," "Objectives," and "Governance." We calculated the RV coefficients (see details in Methods) between the three SDG categories to identify the synergies and trade-offs among the three SDG categories through the multiple factor analysis. The analysis was done from temporal and spatial perspectives. Based on the results of our analyses, we also discussed how to promote the synergistic development of the SDGs, the existing deficiencies, and future perspectives.

2. Materials and methods

2.1. The systematic classification framework of SDGs

The systematic classification framework of SDGs is an important perspective to analyze the complexity of linkages among SDGs [3] (Fig. 1a). Past studies have mainly classified SDGs into social, economic, and environmental categories [22,23]. However, specific targets and indicators within each SDG may simultaneously have multiple social, economic, and environmental attributes [24]. For example, SDG8 (Decent Job and Economic Growth) is generally classified as "economic," but achieving SDG8 requires maintaining sustainable economic growth and reducing per capita material consumption, and the latter is related to the "environment". SDG6 (Clean Water and Sanitation), widely regarded as an "environmental" goal, but achieving SDG6 not only requires improving water quality but also ensuring the proper allocation of water resources and related services. Hence, relying on social, economic, and environmental perspectives to analyze the SDGs will not adequately reflect the holistic and indivisibility of SDGs. It may even keep supporting the past siloed management style, which will not be conducive to the overall implementation of the SDGs.

To remedy the deficiencies of the traditional classification of SDGs, Fu et al. [3] divided seventeen SDGs into three categories, including "Essential Needs," "Objectives," and "Governance," based on the theory of coupled human and natural systems. The "Essential Needs" are the needs that sustain human survival. It comprises SDG2 (Zero Hunger), SDG6 (Clean Water and Sanitation), SDG7 (Affordable and Clean Energy), SDG14 (Life below Water), and SDG15 (Life on Land). The "Objectives" refer to the demands for a spiritual dimension based on the satisfaction of necessary subsistence and consists of SDG1 (No Poverty), SDG3 (Health and Well-Being), SDG4 (Quality Education), SDG5 (Gender Equality), SDG8 (Decent Job and Economic Growth), SDG10 (Reduced Inequalities) and SDG16 (Peace, Justice and Strong Institutions). In addition, "Governance" represents the key coordination measures to ensure synergy between "Essential Needs" and "Objectives." It is composed of SDG9 (Industry, Innovation and Infrastructure), SDG11 (Sustainable Cities and Communities), SDG12 (Responsible Production and Consumption), SDG13 (Climate Action) and SDG17 (Partnerships for the Goals).

In short, this framework emphasizes that appropriate governance will ensure the minimization of essential inputs and the maximization of desired goals. In other words, achieving SDGs in the "Governance" category can coordinate the competition between SDGs in the "Essential Needs" and "Objectives" categories. This coordination facilitates the overall implementation of all SDGs [3]. However, the framework still has not been applied to quantitative assessment. Applying it to quantitative assessment timely can fill the research gap and compare the potential differences between qualitative analysis and quantitative assessment. Therefore, we quantify SDG interactions in China based on the systematic classification framework, combined with the corresponding statistical methods.

2.2. Data preparation and processing

To accurately quantify SDGs progress in each province, we reconstructed the assessment indicators applicable to China at the provincial scale based on the official SDGs indicator framework [25] and the relevant published literature [11,26]. Please see Supplementary Information 1 (online) for the specific principles of indicator selection. However, it should be noted that as SDG14 (Life below Water) is concerned with marine ecosystems, more than half of China's provinces lack indicators related to it. Hence, the relationships between SDG14 and the other SDGs have not been considered in this assessment. Overall, 88 indicators are included in this assessment, which corresponds to 71 SDG targets and 16 SDGs. We collected the historical data for all indicators from different statistical departments since 1990 or when statistics were available (see Table S1 online for details).

Given that the raw indicator data were not comparable with each other, we normalized the data to a score range of 0–100 by referring to the methodology in the report of SDG Index and Dashboards [21]. The normalization process requires setting target and baseline values for each indicator to eliminate the bias introduced by extreme values on the composite results (see Supplementary Information 1 online for details). Subsequently, we further considered the attributes of the indicator changes, including positive, negative, and intermediate [27]. A positive attribute means that

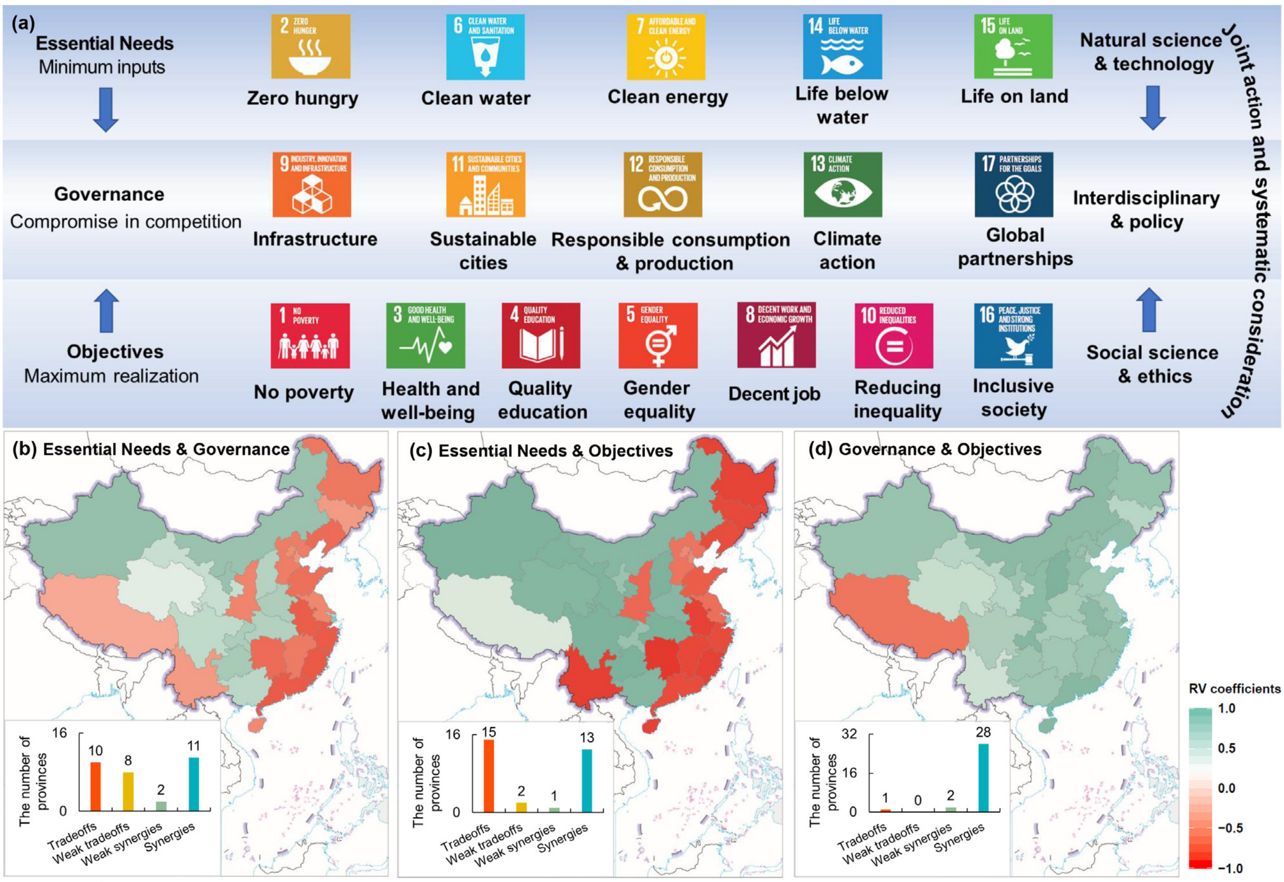

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Fig. 1. RV coefficients among different Sustainable Development Goal (SDG) categories in each province. (a) The SDGs systematic classification framework, which divided the seventeen SDGs into three categories, namely "Essential Needs", "Objectives", and "Governance" (Revised from Fu et al. [3]). Due to limitations in data availability, SDG14-related indicators were not available in all provinces, so this assessment did not consider SDG14 (Life below Water) in "Essential Needs." (b)–(d) The RV coefficients between "Essential Needs" & "Governance," "Essential Needs" & "Objectives," and "Governance" & "Objectives" in each province, respectively.

the larger the data, the better for sustainable development. A negative attribute means that the smaller the data, the better for sustainable development. An intermediate attribute means an intermediate value, and the smaller the difference from the value, the better for sustainable development. The indicators with different attributes were normalized separately using the following equation:

$$\text{positive}: x' = \frac{x - x_{\min}}{x_{\max} - x_{\min}} \times 100, \tag{1}$$

$$\text{negative}: x' = \frac{x_{\max} - x}{x_{\max} - x_{\min}} \times 100, \tag{2}$$

$$\text{intermediate}: x' = \left\{ \begin{array}{c} 100 - \frac{x_{\text{int}} - x}{\max(x_{\text{int}} - \min(x), \max(x) - x_{\text{int}})} \times 100, x < x_{\text{int}} \\ 100 - \frac{x - x_{\text{int}}}{\max(x_{\text{int}} - \min(x), \max(x) - x_{\text{int}})} \times 100, x > x_{\text{int}} \\ 100, x = x_{\text{int}} \end{array} \right\}, \tag{3}$$

where x is the original data value for each SDG indicator, $x_{\max}$ and $x_{\min}$ represent the target and baseline values of the original data for both positive and negative indicators, x_{int} is the target value of the original data for intermediate indicators, and x' is the normalized score for a given SDG indicator. After normalization, the scores for all indicators range from 0 (baseline value) to 100 (target value) points. This normalization ensures that the adjusted variables are ascending and easy to understand, i.e., the higher the score is closer to sustainability. For example, a score of 50 for an indicator indicates that it is 50% achieved [21].

After obtaining the scores of each indicator, these scores are aggregated into the scores of the corresponding SDGs targets using the arithmetic mean method. Then they are further aggregated into the scores of SDGs [21]. In the aggregation process, each indicator has the same weight, indicating that each indicator has the same importance and is not influenced by subjectivity [21]. We use these SDG scores for synergy and trade-off analysis. Additionally, the existing indicator data are not consistent over time due to the limitation of data availability. To reflect the actual characteristics of the indicator as much as possible, we limit our assessment to the period for which data are available (Table S1 online). After aggregation, it is found that the earliest data available for the indicators within SDG15 (Life on Land) are since 2004. Consequently, the period of the SDG scores used for assessment in each province is 2004–2018.

2.3. Analysis of SDG interactions

This study uses multiple factor analysis (MFA) to quantify the synergies and trade-offs between different SDG categories while identifying key SDGs that influence the interactions through significance tests. MFA is an emerging statistical method since the 1980s [28]. It is widely used to analyze correlations between multiple data sets by calculating the RV coefficients [29]. In statistics, the RV coefficient is often considered as multiple generalizations of the Pearson correlation coefficient (r_p), i.e., the square of r_p. Thus its values range from 0 (mutually independent) to 1 (totally homogeneous) [30]. Josse et al. [29] provide a detailed description of the process of calculating the RV coefficient and how it is tested.

We used the "MFA" function in the FactoMineR package of R 4.0.3 software for MFA analysis and significance testing [31]. Although the RV coefficients do not reflect the directionality of the interaction between different data sets, the "MFA" function gives a "partial axes" plot, which reflects the projection of the principal components of different data sets onto the global principal component analysis. The angles between the principal components of different data sets reflect the direction of the interaction, where acute angles represent positive correlations, obtuse angles are negative correlations and tend to be orthogonal to indicate low correlations [31]. Therefore, we judged the trade-offs and synergies between different SDG categories based on the angle between different first principal components in the "partial axes" plot. To avoid over-interpretation of correlations, different thresholds were set for the RV coefficients in this study. With reference to related studies [6,7], we defined the coefficient values located in four different intervals $[-1, -0.5]$, $(-0.5, 0]$, $(0, 0.5)$, and $[0.5, 1]$ as a trade-off, weak trade-off, weak synergy, and synergy, respectively. In addition, the "MFA" function also gives the r_p between individual SDGs in the calculation of RV coefficients to help us analyze the impacts of key SDGs on the overall interactions [31].

Based on the above assessment process, we quantified the spatial differences in the SDG interactions and their temporal variation in China, respectively. For the spatial differences, we used time-series data (2004–2018) of SDG scores for each province to calculate the RV coefficients between the three SDG categories for 31 provinces separately. The "partial axes" plots of three SDG categories and correlations among individual SDGs for each province are given in Supplementary Information 2 and 3 (online). The figures are listed in alphabetical order according to the names of 31 provinces. For the temporal variations, we calculated the RV coefficients between the different SDG categories over the period 2004–2018 using cross-sectional data of SDG scores for 31 provinces per year. The "partial axes" plots of three SDG categories and correlations among individual SDGs for each year are given in Supplementary Information 4 and 5 (online). The above two supplemental figures are in chronological order from 2004 to 2018.

3. Results

3.1. The spatial difference in SDG interactions

Our results show that the interactions between different SDG categories vary spatially across provinces. Overall, we found that the interactions between "Essential Needs" & "Governance" and "Essential Needs" & "Objectives" show trade-offs in most provinces (Fig. 1b, c), but synergies are mainly observed between "Governance" & "Objectives" (Fig. 1d). These results suggest that while in most provinces, the SDGs in the "Governance" category could contribute to the improvement of "Objectives," they have not reconciled the trade-offs between "Essential Needs" and "Objectives."

Specifically, for the interaction between "Essential Needs" & "Governance", Fig. 1b reveals that there are 18 provinces show trade-offs ($-1 \le RV \le -0.5$) and weak trade-offs ($-0.5 < RV \le 0$), which are mainly distributed among the provinces in eastern China; meanwhile, we could see that 13 provinces with synergies ($0.5 \le RV \le 1$) and weak synergies ($0 < RV < 0.5$) are mainly found in western China. The spatial distribution of interactions between "Essential Needs" & "Objectives" is similar to the distribution between "Essential Needs" & "Governance" but with a difference in the degree of interaction (Fig. 1b, c). The difference is that the RV coefficients between "Essential Needs" & "Objectives" show stronger interaction, with 15 provinces showing trade-offs and 13 provinces with synergies (Fig. 1c). In addition, from Fig. 1d, the results find that interactions between "Governance" & "Objectives" show synergies in 28 provinces; and the weak synergies are found in Qinghai and Yunnan provinces, with the RV coefficients are 0.489 ($P < 0.01$) and 0.451 ($P < 0.01$), respectively. However, there is a trade-off between "Governance" & "Objectives" in Tibet, as the RV coefficient is -0.573 ($P < 0.01$). Overall, our results suggest that as some provinces in western China could show synergies among the three SDG categories, this may imply that these provinces have more potential to implement SDGs as a whole.

3.2. Temporal variation of SDG interactions

We analyzed cross-sectional data on indicator scores by province from 2004 to 2018 to understand the temporal variation of SDG interactions. Interestingly, we found an "inverted U-shaped" trend in the synergies between different SDG categories (Fig. 2). The "inverted U-shaped" curves between "Essential Needs" & "Objectives" and "Governance" & "Objectives" are significant ($P < 0.01$) but not significant between "Essential Needs" & "Governance" ($P > 0.05$). The synergies between "Essential Needs" & "Objectives" and "Governance" & "Objectives" have gradually weakened over the past decade. However, Fig. 2 also shows that the RV coefficients between "Governance" & "Objectives" are higher than those between the other two SDG categories at different times. For example, the RV coefficient between "Governance" & "Objectives" is 0.396 ($P < 0.01$) in 2018, but only 0.109 ($P > 0.05$) between "Essential Needs" & "Governance," and 0.098 ($P > 0.05$) between "Essential Needs" and "Objectives," respectively (Fig. 2). This result indicates that there is still a positive interaction between "Governance" and "Objectives." However, there is almost no correlation in the other two SDG categories.

3.3. Drivers for Spatio-temporal variation of SDG interactions

We revealed the key SDGs that dominate SDG interactions' spatial and temporal variation by significance tests in the multiple factor analysis. Spatially, we found some similarities in the key SDGs affecting the overall interaction among different SDG categories across provinces. However, there were also slight differences between several provinces (Table 1). In general, SDG6 (Clean Water and Sanitation) and SDG15 (Life on Land) play a significant role in the "Essential Needs" across provinces. For the "Governance" category, SDG11 (Sustainable Cities and Communities) was substantial in 25 provinces. At the same time, SDG12 (Responsible Production and Consumption), SDG13 (Climate Action), and SDG17 (Partnerships for the Goals) were significant in nine different provinces. Moreover, in the "Objectives" category, SDG1 (No Poverty), SDG5 (Gender Equality), and SDG10 (Reduced Inequalities) have significant effects in 29, 28, and 26 provinces, respectively (Table 1). However, it should be noted that the trade-offs between "Essential Needs" and other SDG categories are mainly influenced by SDG15 (Life on Land) and SDG7 (Affordable and Clean Energy). Meanwhile, SDG6 (Clean Water and Sanitation) generally has synergies with SDGs within other categories. The trade-offs between "Governance" and other SDG categories are mainly influenced by SDG12 (Responsible Production and Consumption). In addition, SDG16 (Peace, Justice and Strong Institutions) dominated the trade-offs between "Objectives" and other SDG categories.

Regarding the temporal variation, the key SDGs affecting the RV coefficients between the three SDG categories at different stages showed some variability (Table 2). In the years with high RV

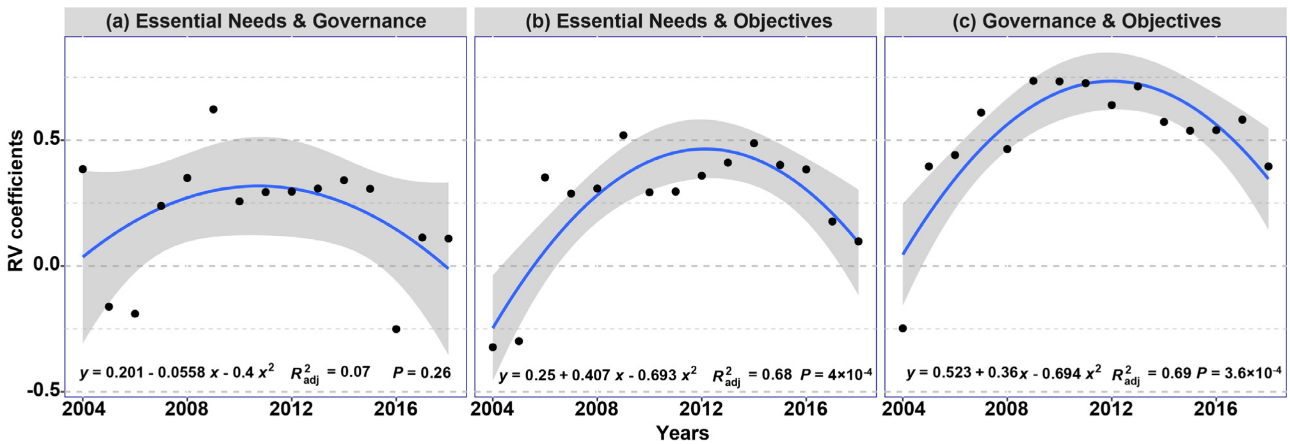

Fig. 2. The changing trend of RV coefficient among three Sustainable Development Goal categories from 2004 to 2018. (a)–(c) The changing trend of RV coefficients between "Essential Needs" & "Governance," "Essential Needs" & "Objectives," and "Governance" & "Objectives" from 2004 to 2018, respectively. The grey ribbon represents the 95% confidence interval of the regression curve (the blue line).

Table 1
Key Sustainable Development Goals (SDGs) affecting the RV coefficient among the SDG categories in each province.

Regions	Provinces	SDG categories		
		Essential Needs	Governance	Objectives
North China	Beijing	SDG6, SDG15	SDG13, SDG17	SDG1, SDG8, SDG10
	Tianjin	SDG6, SDG7	SDG12, SDG13, SDG17	SDG1, SDG5, SDG8, SDG10, SDG16
	Shanxi	SDG6	SDG11, SDG13	SDG1, SDG5, SDG8, SDG10, SDG16
	Hebei	SDG6	SDG11, SDG17	SDG1, SDG16
	Inner Mongolia	SDG6, SDG15	SDG11, SDG13	SDG1, SDG5, SDG8, SDG16
East China	Shandong	SDG6, SDG15	SDG11, SDG12	SDG1, SDG5
	Shanghai	SDG6, SDG15	SDG13, SDG17	SDG1, SDG5, SDG8, SDG10
	Zhejiang	SDG6, SDG15	SDG11, SDG17	SDG1, SDG5, SDG8, SDG16
	Anhui	SDG6, SDG15	SDG9, SDG11	SDG1, SDG4, SDG5, SDG8, SDG10
	Jiangsu	SDG6, SDG15	SDG11, SDG12, SDG17	SDG1, SDG5, SDG8, SDG10, SDG16
	Fujian	SDG6, SDG15	SDG11, SDG17	SDG1, SDG5, SDG8, SDG10
	Jiangxi	SDG6, SDG15	SDG11	SDG1 SDG4, SDG5, SDG8, SDG10
Central China	Hubei	SDG6, SDG7, SDG15	SDG9, SDG11	SDG1, SDG5, SDG6, SDG8
	Hunan	SDG6, SDG15	SDG11	SDG1, SDG4, SDG5, SDG10
	Henan	SDG6	SDG11	SDG1, SDG4, SDG5, SDG10
South China	Guangdong	SDG6, SDG15	SDG11, SDG13, SDG17	SDG1, SDG3, SDG5, SDG8, SDG10
	Guangxi	SDG6, SDG15	SDG11	SDG1, SDG4, SDG5, SDG10
	Hainan	SDG6, SDG15	SDG11, SDG17	SDG1, SDG5, SDG8, SDG10
Southwest China	Sichuan	SDG6, SDG7, SDG15	SDG11, SDG12	SDG1, SDG4, SDG5, SDG10, SDG16
	Yunnan	SDG7, SDG15	SDG11, SDG12, SDG13	SDG1, SDG4, SDG5, SDG10
	Chongqing	SDG15	SDG11, SDG13	SDG1, SDG4, SDG5, SDG10
	Guizhou	SDG6, SDG7, SDG15	SDG11	SDG1, SDG4, SDG5, SDG10
	Tibet	SDG7	SDG12	SDG5, SDG10
Northeast China	Heilongjiang	SDG6, SDG15	SDG11	SDG1, SDG6, SDG10, SDG16
	Jilin	SDG6, SDG15	SDG11	SDG1, SDG5, SDG10
	Liaoning	SDG6, SDG15	SDG11, SDG17	SDG1, SDG5, SDG10
Northwest China	Shaanxi	SDG6, SDG15	SDG11	SDG1, SDG5, SDG8, SDG10
	Xinjiang	SDG6, SDG15	SDG12, SDG13	SDG3, SDG5, SDG10, SDG16
	Qinghai	SDG6, SDG7, SDG15	SDG12	SDG1, SDG3, SDG5, SDG8, SDG10, SDG16
	Ningxia	SDG6, SDG7, SDG15	SDG11, SDG12	SDG1, SDG3, SDG5, SDG8, SDG10
	Gansu	SDG6, SDG7, SDG15	SDG11	SDG1, SDG3, SDG5, SDG8, SDG10

coefficients (e.g., in 2008, 2009, and 2014), SDG2 (Zero Hunger) and SDG6 (Clean Water and Sanitation) have a significant role in the "Essential Needs." They positively correlate with the SDGs in the other categories, thus making it possible to have a high RV coefficient between "Essential Needs" and the other two SDG categories. However, as the correlation between these SDGs (i.e., SDG2 and SDG6) and other SDGs weakened, SDG7 (Affordable and Clean Energy) gradually took a dominant role in "Essential Needs." The weak trade-offs and weak synergies between SDG7 (Affordable and Clean Energy) and other SDGs were mainly manifested, and thus weakening the synergies between "Essential Needs" and other SDG categories.

4. Discussion

The effectiveness of actions and policies to advance the SDGs depends fundamentally on grasping the SDG interactions [19,32]. Global-scale analyses have pointed out that there will be variations in the interactions of the SDGs across regions and demographics [5,7]. So far, the trade-offs between certain SDGs have hardly been transformed [6]. Hence, performing assessments at the sub-national scale is necessary to explore the pathways for shifting the trade-offs into synergies.

Our results found a striking spatial variation in the synergies and trade-offs among the SDGs in China, with the trade-offs

Table 2
Key Sustainable Development Goals (SDGs) affecting the RV coefficient among the SDG categories in different periods.

Years	SDG categories		
	Essential Needs	Governance	Objectives
2004	SDG7	SDG9, SDG12, SDG17	SDG1, SDG4, SDG5, SDG8
2005	SDG15	SDG9, SDG11, SDG12, SDG13	SDG1, SDG3, SDG5
2006	SDG2, SDG7	SDG9, SDG11, SDG12, SDG13	SDG1, SDG4, SDG5, SDG8, SDG10
2007	SDG2, SDG7	SDG11, SDG13, SDG17	SDG1, SDG4, SDG5, SDG8, SDG10
2008	SDG2, SDG6, SDG7	SDG12, SDG17	SDG1, SDG3, SDG4, SDG5, SDG8
2009	SDG2, SDG6, SDG7	SDG11, SDG12, SDG13, SDG17	SDG1, SDG4, SDG5, SDG10
2010	SDG2, SDG15	SDG11, SDG13, SDG17	SDG1, SDG5, SDG8, SDG10, SDG16
2011	SDG2, SDG7	SDG11, SDG13, SDG17	SDG1, SDG5, SDG8, SDG10, SDG16
2012	SDG2	SDG13, SDG17	SDG1, SDG4, SDG5, SDG10, SDG16
2013	SDG2, SDG7	SDG11, SDG13, SDG17	SDG1, SDG4, SDG5, SDG10, SDG16
2014	SDG2, SDG6, SDG7	SDG9, SDG12, SDG17	SDG1, SDG4, SDG5, SDG10, SDG16
2015	SDG2, SDG6	SDG12, SDG17	SDG1, SDG4, SDG8, SDG10, SDG16
2016	SDG2, SDG7	SDG9, SDG12, SDG17	SDG1, SDG4, SDG8, SDG16
2017	SDG7	SDG9, SDG12, SDG17	SDG1, SDG8, SDG10, SDG16
2018	SDG7	SDG12, SDG13, SDG17	SDG1, SDG10, SDG16

appearing significantly between "Essential Needs" & "Objectives," and "Essential Needs" & "Governance." These trade-offs are widely distributed in the eastern provinces of China. In contrast, the synergies appear in the central and western provinces of China. Although the eastern provinces have higher levels of sustainable development than those in the west [11], our results emphasize that progress made in these provinces for some SDGs may have come at the cost of other SDGs. Meanwhile, we found that SDG15 (Life on Land) significantly influences the trade-offs between "Essential Needs" & "Objectives." This finding exemplifies that past economic growth in these provinces has been detrimental to forest resources and biodiversity [33]. A series of ecological restoration projects being implemented in China is trying to increase forest cover. However, they still have little effect in protecting and restoring biodiversity [9,34]. China's Red List Index shows a declining trend, having fallen from 0.82 in 1993 to 0.73 in 2021 [35]. Hence, exploring win–win paths for ecological protection and economic development is always critical to address the trade-offs between "Essential Needs" & "Objectives."

Besides, the trade-off between "Governance" & "Essential Needs" is also noteworthy. Fu et al. [3] point out that the SDGs in the "Governance" category should play a coordinating role, i.e., reducing the consumption of "Essential Needs" while facilitating the maximum output of "Objectives." Yet, we found that although there are synergies between "Governance" & "Objectives" in most provinces, the trade-offs and weak trade-offs between "Governance" & "Essential Needs" are generally observed in the provinces of eastern China. This finding implies that the SDGs in the "Governance" category are not making progress as desired. The results of the significance analysis show that the trade-offs between SDG12 (Responsible Production and Consumption) and the SDGs in other categories play a significant influence. Past assessments have shown that SDG12 (Responsible Production and Consumption) is characterized by a decline in most provinces in China [11,26], implying that current consumption and production patterns are unsustainable. While improving consumption and production patterns mitigates the disruption of critical Earth system processes by human activities [36], it requires substantial changes to existing behavior patterns. A few also argue that it may even negatively impact current economic development [37]. Hence, how to change the consumption and production patterns of human beings rationally and avoid its adverse effects may be essential for the realization of all SDGs.

Interestingly, our results also showed that synergies between all three SDG categories are mainly present in western China. These findings imply that these provinces have more plausible development paradigms. However, the assessment by Xu et al. [11] has indicated that progress in implementing the SDGs in these provinces is relatively slow. Maintaining the current progress rate would not ensure that these provinces could fully achieve the SDGs. Although western China usually has better resource advantages, such as abundant coal, oil, natural gas, and solar energy resources, other aspects of the natural environment, such as dry climate and complex topography, are usually limit the local economic development [38]. Since the reform and opening-up, China's economic growth has benefited more from economic trade in the eastern plains and coastal provinces. However, the trade also required resources and energy support from the western region, thus increasing the pressure on resource extraction and environmental protection in the latter [10]. To promote the development of western provinces, the Chinese government has implemented a range of supportive policies, including infrastructure development, talent introduction, and ecological protection and restoration [39]. A combination of these efforts has led these provinces to exhibit synergistic interactions among SDGs. However, the potential challenge facing these regions may be accelerating the regional development process without breaking the synergy among the various SDGs.

Additionally, the assessment of SDG interactions from a cross-sectional perspective is gradually attracting attention. It could effectively reflect the consistency of development in different regions [6,18]. For China, we found that the synergy between different SDG categories has gradually decreased in the last decade. This decrease is partly caused by the differences in the progress or priority of different SDGs across provinces. Our results showed that while there is still a weak synergy between "Governance" and "Objectives" in 2018, there is almost no correlation between "Essential Needs" and other SDG categories. Through significance analysis, we found that the SDG that limits the synergy between "Essential Needs" and other categories is SDG7 (Affordable and Clean Energy). This may be due to the uneven progress of SDG7 across provinces, i.e., some provinces are faster while others are relatively slow, leading to that SDG7 having weak synergies and weak trade-offs with the SDGs in other categories.

Past assessment has shown that the score of SDG7 performs better in the Northwest and Southwest provinces and relatively poorly in other provinces [11]. Indeed, thermal power generation is still the dominant form of electricity generation in China, accounting for nearly 75% of total electricity generation each year. Nonetheless, clean energy generation is relatively low, and it is distributed unevenly across provinces due to the constraints of the natural environment [40]. For example, solar power is widely distributed in Northwest China, where has stronger solar radiation. Hydroelectric power is primarily concentrated in the Southwest provinces of China, where have the advantage of complex topography and an abundance of river flows [40,41]. In addition, although nuclear power generation is more efficient and promising, there are only eight provinces in China with nuclear power generation facilities due to the scarcity of uranium resources and the complexity of operating technologies [40,42]. Given the uneven progress of SDG7 in China, we, therefore, speculate that promoting a balanced development of SDG7 may be an effective way to promote synergies between "Essential Needs" and other SDG categories. Meanwhile, considering that Chinese government's commitment to achieving peak carbon emissions by 2030 and carbon neutrality by 2060, accelerating the development of clean energy is crucial. However, achieving carbon neutrality also requires more research to ensure that the expansion of clean energy does not compromise the consumption of other natural resources, such as water, food, and forests. Thus, advancing SDG7 (Affordable and Clean Energy) through the framework of the Food-Energy-Water (FEW) nexus would be an effective measure [43].

5. Conclusions

In this study, we quantify the synergies and trade-offs between three SDG categories ("Essential Needs", "Governance", and "Objectives") in China from both temporal and spatial perspectives and reveal the key SDGs that play the dominant role in the different interactions. Spatially, the interactions between different SDG categories somewhat differ across provinces, but enhancing synergies between SDG12 (Responsible Production and Consumption) and other SDGs will contribute to the implementation of SDGs in all provinces. Temporally, due to the differences in the development of SDG7 (Affordable and Clean Energy) in each province, the synergy between different SDG categories shows a weakening trend in the last decade. Therefore, it is of great significance to promote clean energy in each province to achieve the synergy among SDGs. However, we cannot ignore the uncertainty of the current results since applying different classifications may have a significant impact on the results, while indicator selection is also one of the other influencing factors. Even so, the current results do reflect essential issues in China's progress toward sustainable development. Hence, our quantitative evidence could provide general guidance for SDGs achievement and the evolution of future sustainable development policies in China.

Although we initially quantify the spatial and temporal characteristics of SDG interactions in China. There are still some important gaps that need to be filled in the future. First, it is noteworthy that there are also synergies and trade-offs among SDGs within each category which are not discussed in this study. For example, for the "Essential Needs," the linkages between SDG2 (Zero Hungry), SDG6 (Clean Water and Sanitation), and SDG7 (Affordable and Clean Energy) correspond to the FEW nexus. If the linkages of the FEW nexus with other SDGs are further considered, some informative insights can also be detected. But this is beyond the scope of the current study, as we are concerned with applying the systematic classification framework of SDGs to quantitative assessments to inform national macro-management policies. Second, this study is an assessment at the goal level, yet to promote policy coherence across different sectors, there is a need to conduct relevant studies at the indicator level, including the non-linear relationships, threshold effects, and causality between different indicators. Overall, the assessment framework used in this study does provide some novel insights for understanding the SDG interactions on a sub-national scale, and it is also applicable to other countries and regions. Timely monitoring and assessing the interactions between SDGs at different scales is crucial for adjusting sustainable development policies. It will continue to be a research subject that requires attention even after 2030.

Conflict of interest

The authors declare that they have no conflict of interest.

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Author contributions

Bojie Fu designed the study. Junze Zhang collected the data. Junze Zhang, Shuai Wang, Prajal Pradhan, and Wenwu Zhao performed most of the data analysis. Bojie Fu coordinated and supervised the study. Junze Zhang, Prajal Pradhan, and Bojie Fu drafted the manuscript. All authors reviewed the manuscript and approved it for submission.

Appendix A. Supplementary materials

Supplementary materials to this article can be found online at https://doi.org/10.1016/j.scib.2022.01.006.

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Junze Zhang is currently a postdoctor at the Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences. He received his Ph.D. degree in the field of Physical Geography from Beijing Normal University in 2021. His research focuses on ecosystem services, ecological restoration, and sustainable development.

Bojie Fu is a distinguished professor in Chinese Academy of Sciences and Faculty of Geographical Science, Beijing Normal University. His research focuses on landscape patterns, ecological processes, ecosystem services and human well-being, and sustainability.