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Assessing global sustainability performance, imbalance, and coordination over space and time

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Zhenci Xu[1,2,14], Xiuzhi Chen[3,4,14], Qutu Jiang[1,14], Xutong Wu[5], Nishan Bhattarai[6], John Mullen[7], Zhongbin B. Li[8], Georgina G. Gurney[9], Shuxin Li[10], Canbing Li[11], Tuo Yin[3], Sumin Bian[12], Jian Zhang[13], Siqi Han[3], Yunkai Li[3] ✉ & Jianguo Liu[10] ✉

Adopted by 193 countries in 2015, the United Nations' 17 Sustainable Development Goals (SDGs) aim to address urgent global challenges by 2030. However, consistent and comprehensive assessments of countries' spatio-temporal performance, and of the balance and coordination among the SDGs, remain scarce. Here, we developed three indices—the Sustainable Development Relative Performance Index (SDRPI), Sustainable Development Gini Index (SDGI), and Sustainable Development Coordination Index (SDCI)—to measure global SDG performance, imbalances, and coordination over time and across space. Results show that most countries improved their sustainable development performance from 2000 to 2020, with imbalances narrowing and low-income countries achieving faster progress than high-income ones. Several Eastern European countries recorded the largest SDRPI gains, while Sweden, Spain, and Poland exhibited the lowest SDGI scores, reflecting minimal imbalances. Low-income countries also displayed strong coordination in SDG improvements. These findings underscore the urgency of targeted governance and policies to address underperforming SDG targets and foster balanced, coordinated global sustainable development.

Challenges, such as hunger, water scarcity, energy shortages, chemical pollution, gender inequality, and climate change threaten global sustainability[1–8]. For example, around 815 million people experience chronic food shortages[9], 4 billion face water scarcity[3], and 1.2 billion have no access to electricity[4]. To achieve global sustainability and improve human well-being, 17 Sustainable Development Goals (SDGs) were adopted by the United Nations (UN) General Assembly in 2015, to which 193 countries have committed[10,11]. The 17 SDGs are an expansion

[1]Department of Geography, The University of Hong Kong, Hong Kong, China. [2]HKU Shenzhen Institute of Research and Innovation, Shenzhen, China. [3]State Key Laboratory of Efficient Utilization of Agricultural Water Resources, College of Water Resources and Civil Engineering, China Agricultural University, Beijing, China. [4]Yellow River Research Institute, North China University of Water Resources and Electric Power, Zhengzhou, China. [5]State Key Laboratory of Earth Surface Processes and Disaster Risk Reduction, Faculty of Geographical Science, Beijing Normal University, Beijing, China. [6]Department of Geography and Environmental Sustainability, University of Oklahoma, Norman, OK, USA. [7]Departments of Educational Leadership, Administration, and Research and Geography, Planning, and Sustainability, Rowan University, Glassboro, NJ, USA. [8]School of Remote Sensing and Information Engineering, Wuhan University, Wuhan, China. [9]College of Arts, Society & Education, James Cook University, Townsville, QLD 4811, Australia. [10]Center for Systems Integration and Sustainability, Department of Fisheries and Wildlife, Michigan State University, East Lansing, MI, USA. [11]Department of Electrical Engineering, Shanghai Jiaotong University, Shanghai, China. [12]Cutting Edge Net for Biomedical Research and Innovation School of Engineering, Westlake University, Hangzhou, Zhejiang, China. [13]School of Life Sciences, State Key Laboratory of Grassland Agro-ecosystems, Lanzhou University, Lanzhou, Gansu, China. [14]These authors contributed equally: Zhenci Xu, Xiuzhi Chen, Qutu Jiang. ✉e-mail: yunkai@cau.edu.cn; liuji@msu.edu

and refinement of the eight Millennium Development Goals adopted in 2000 and offer a more detailed framework of sustainable development[12]. They provide a platform for sustainable development to facilitate global sustainability across scales.

Sustainable development and sustainability have garnered considerable attention from researchers and organizations worldwide[13,14], serving as the conceptual foundation guiding modern social, economic, and environmental paradigms. These include the green economy[15–17], circular economy[18–20], agricultural sustainability[21–23], and urban sustainability[24,25]. Sustainability is commonly structured around the three pillars of people, planet, and prosperity. Sustainable development traditionally emphasized the social, environmental, and economic dimensions, as well as their interactions. Various perspectives have been proposed for analyzing these pillars and their interactions, with three dominant perspectives emerging: weak, strong, and integrated sustainability[13,26]. Weak sustainability treats each pillar of sustainable development (social, environmental, and economic) as equally important, whereas strong sustainability attaches the greatest importance to the environmental pillar. Integrated sustainability, a perspective of sustainable development, introduces spillover effects as the fourth and critical pillar of sustainable development[13,27–29]. To analyze these sustainable development spillover effects across global regions, the index of sustainability elasticities has been developed[28,30]. Positive sustainability elasticities indicate the synergetic relationships, while negative values show trade-offs between regions. In the integrated sustainability perspective, the SDGs can align with each pillar of sustainable development, including social (SDGs 3, 4, 5, and 10), environmental (SDGs 6, 12, 13, 14, and 15), economic (SDGs 1, 2, 7, 8, 9, and 11), and spillover (SDGs 16 and 17) pillars of sustainable development[30]. As a global platform for sustainable development, the SDGs offer a unified and comprehensive framework for studying global sustainability in an integrated sustainability perspective[31–33]. To gain a deeper understanding and analysis of integrated sustainability, it is essential to first comprehend the performance of sustainable development across multiple levels, examining its imbalance and coordination over time.

Monitoring progress toward the SDGs has been conducted globally[34,35]. The UN Statistics Division has reported on the development and implementation of an indicator framework for the follow-up and review of the 2030 Agenda for Sustainable Development[36]. Complementing official UN monitoring efforts, the SDG Index and Dashboards, released annually since 2016 by the Sustainable Development Solutions Network (SDSN), play a crucial role in monitoring the performance of SDGs at both national and local levels[36–38]. Additionally, some assessments focus on a regional scale, such as the report released by Eurostat on the status of the 17 SDGs within the European Union and its Member States[39]. More recent studies have assessed SDG performance using a country-specific framework that provides comparisons at the subnational level. For instance, Allen et al.[40] conducted an independent, evidence-based assessment of Australia's performance in achieving the SDGs, using 144 indicators through an expert-driven consultative process.

Yet, there has been limited research on simultaneous, temporally consistent assessment of sustainable development performance, imbalance, and coordination at a global scale. In addition, previous methods for calculating SDG index scores have been overly simplistic, relying on equal weights and assuming linear relationships within and between variables. This approach may not accurately reflect complex and dynamic problems. Hence, there is an urgent need for information derived from consistent and rigorous assessments to guide policy and management interventions aimed at facilitating the transformation necessary to achieve global sustainability. This urgency is underscored by the fact that we have only five years remaining, one third of the time between 2015 and 2030, to realize the SDGs. In particular, assessing imbalances and coordination among nations and goals can help identify disparities in SDG performance and pave the way forward for coordinated improvement of the SDGs, ultimately leading to more effective policies for achieving overall sustainability.

To address these gaps, we have developed and innovated methods to create three indices: the Sustainable Development Relative Performance Index (SDRPI), the Sustainable Development Gini Index (SDGI), and the Sustainable Development Coordination Index (SDCI). These indices have been designed to enable a consistent spatiotemporal assessment of relative performance, imbalance, and coordination across different dimensions of sustainable development at the global and national levels over time.

SDRPI is based on, but extends beyond, the SDG Index proposed by SDSN and Bertelsmann Stiftung[36]. Unlike the SDG index, SDRPI is used to assess the relative performance (on a scale of 0 to 100) of the SDGs across countries. We employed the fuzzy logic model[41,42] to calculate the SDRPI scores because this model allows for ranking sustainable development without subjective judgment. Additionally, it can effectively handle uncertainties and ambiguities, making it suitable for evaluating situations where fuzzy relationships exist between indicators and challenges in determining their respective weights (see Methods). The second index, SDGI, is adapted from the Gini index[43], which is commonly used to represent income or wealth inequality within a population. The SDGI is specifically designed to measure the imbalance (or balance) in relative performance across the 17 SDGs in a given area. SDGI values range from 0 to 1, with lower values indicating consistent relative performance across the 17 SDGs and higher values indicating greater imbalance in relative performance across them. For example, if the performance for all 17 goals in an area is equal, the SDGI for the area would be 0, indicating a perfectly balanced performance. Finally, the third index is the SDCI, which utilizes network correlation analysis[44] to measure the coordination degree among changes in the relative performances of the different SDGs based on SDRPI scores over a time period. A higher SDCI score (ranging from 0 to 1) represents a greater coordinated improvement across the relative performance of different SDGs over time.

By assessing the spatiotemporal distribution of these three indices, we aim to answer important sustainability challenge questions: (1) How did SDG performance, as measured by the SDRPI, change over time and across different countries? How did these changes in SDG performance vary according to economic development levels or geographic locations across continents? (2) How did the imbalance among different SDG performances, in terms of the SDGI, vary across countries over time? (3) What is the spatial pattern of coordination in changes to the performance of different SDGs (indicated by SDCI) across countries?

To answer these questions, we collected data on 102 indicators related to the 17 SDGs for 115 countries from 2000 to 2020[45–49] during which all relevant data are available (Supplementary Table 1). We utilized the SDRPI and SDGI to assess spatiotemporal sustainable development relative performance and imbalances among these countries using global-scale data from 2000 to 2020. We then compared changes in SDRPI and SDGI scores over time between high-income and low-income countries, as well as across different continents (Asia, Africa, Europe, North America, South America, and Oceania). In addition, we employed the SDCI to analyze the coordination degree of changes in the relative performance of the 17 SDGs from 2000 to 2020 across countries.

Results

Our results show that the world experienced improvements in SDRPI scores from 2000 to 2020 (Fig. 1, Supplementary Table 2), with the global average SDRPI score rising from 28.5 to 39.8 (Fig. 3a). Approximately 90% of countries recorded an increase in their SDRPI scores. However, changes in SDRPI scores varied across different parts of the world, with notable improvements observed in both East Asia and Eastern Europe (Fig. 1f).

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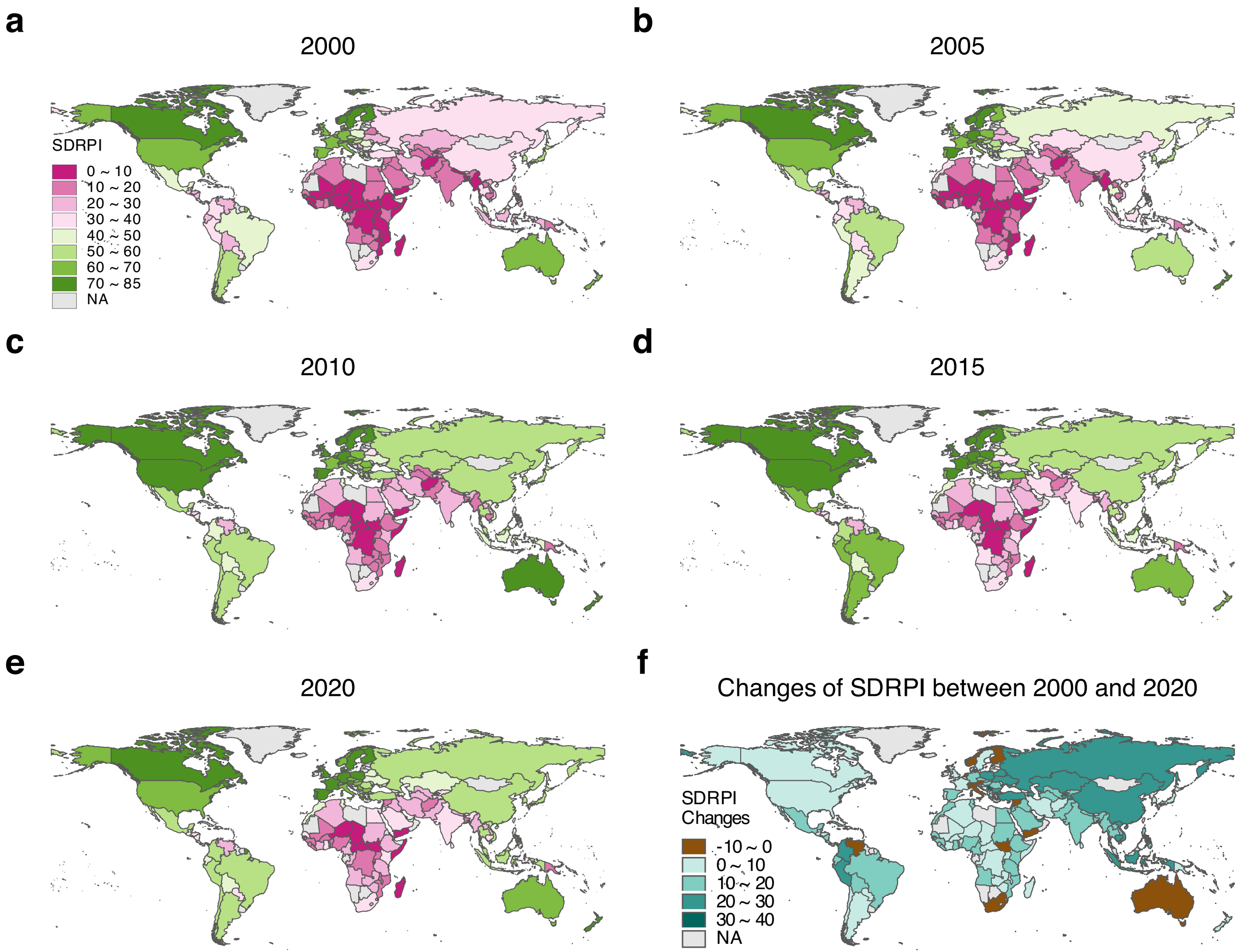

Fig. 1 | Sustainable Development Relative Performance Index (SDRPI) scores (0 to 100) across the world and their changes over 2000-2020. a–**e** refer to SDRPI in 2000, 2005, 2010, 2015, and 2020, respectively; **f** Changes in SDRPI between 2000 and 2020. Blank base map from publicly available Natural Earth vector map data (https://www.naturalearthdata.com/).

Regarding the SDGI, the imbalance among different dimensions of sustainable development performance decreased for most countries (Fig. 2f). The average SDGI scores of all countries fell from 0.43 in 2000 to 0.33 in 2020 (Fig. 3b). Nearly 85% of the countries experienced a decline in their SDGI scores, with the exceptions of a few, such as the Syrian Arab Republic, Norway, and the Netherlands (Fig. 2f).

There were substantial variations in SDRPI and SDGI scores among countries (Figs. 1, 2 Supplementary Tables 2 & 3). In 2020, Sweden, Spain, and Germany achieved the top three SDRPI scores, while South Sudan, the Central African Republic, and Somalia had the lowest scores. Regarding changes in SDRPI scores from 2000 to 2020, Serbia, Azerbaijan, and Belarus showed the most noticeable increases. In contrast, Norway, the Syrian Arab Republic, and Australia exhibited the largest decreases during this period (Fig. 1f). In terms of SDGI, Yemen, South Sudan, and Somalia had the highest scores, indicating considerable imbalances among different SDGs in 2020. Conversely, Sweden, Spain, and Poland exhibited the lowest levels of imbalances (Fig. 2f).

High-income countries typically maintained higher SDRPI scores and lower SDGI scores than low-income ones over time (Fig. 3c, d). However, the growth rate in SDRPI scores for low-income countries consistently outpaced that of high-income countries, and the decline in SDGI scores for low-income countries generally exceeded that of high-income countries. This indicates a narrowing gap in both SDRPI and SDGI between high-income and low-income countries over time.

In 2020, countries in Europe, Oceania, and South America showed a higher median SDRPI score compared to those in other continents 2020 (Fig. 3e). Conversely, countries in Africa, particularly in the central region, continued to lag behind the rest of the world in terms of their SDRPI scores. In addition, countries in Africa had a higher median SDGI score than those on other continents, highlighting a substantial imbalance in sustainable development across the continent (Fig. 3f).

The SDCI scores for a country represent the degree of coordination among changes in the performance of different individual SDGs within that country. Generally, low-income countries, particularly those in Africa and Asia, exhibited higher SDCI scores than high-income countries (Fig. 4, Supplementary Table 4). This may be attributed to the rapid growth experienced by these countries, which often have abundant resources and considerable room for improvement, enabling them to promote multiple SDGs simultaneously. In contrast, high-income countries have already achieved a higher level of development, leaving less untapped potential and making it more challenging to advance multiple SDGs at the same time.

Discussion

Our study offers a comprehensive assessment of global sustainable development dynamics, focusing on the relative performance, imbalance, and coordination of SDGs. The findings indicate a gradual global transition toward sustainability, with a narrowing gap between high-income and low-income countries. Low-income nations exhibited high

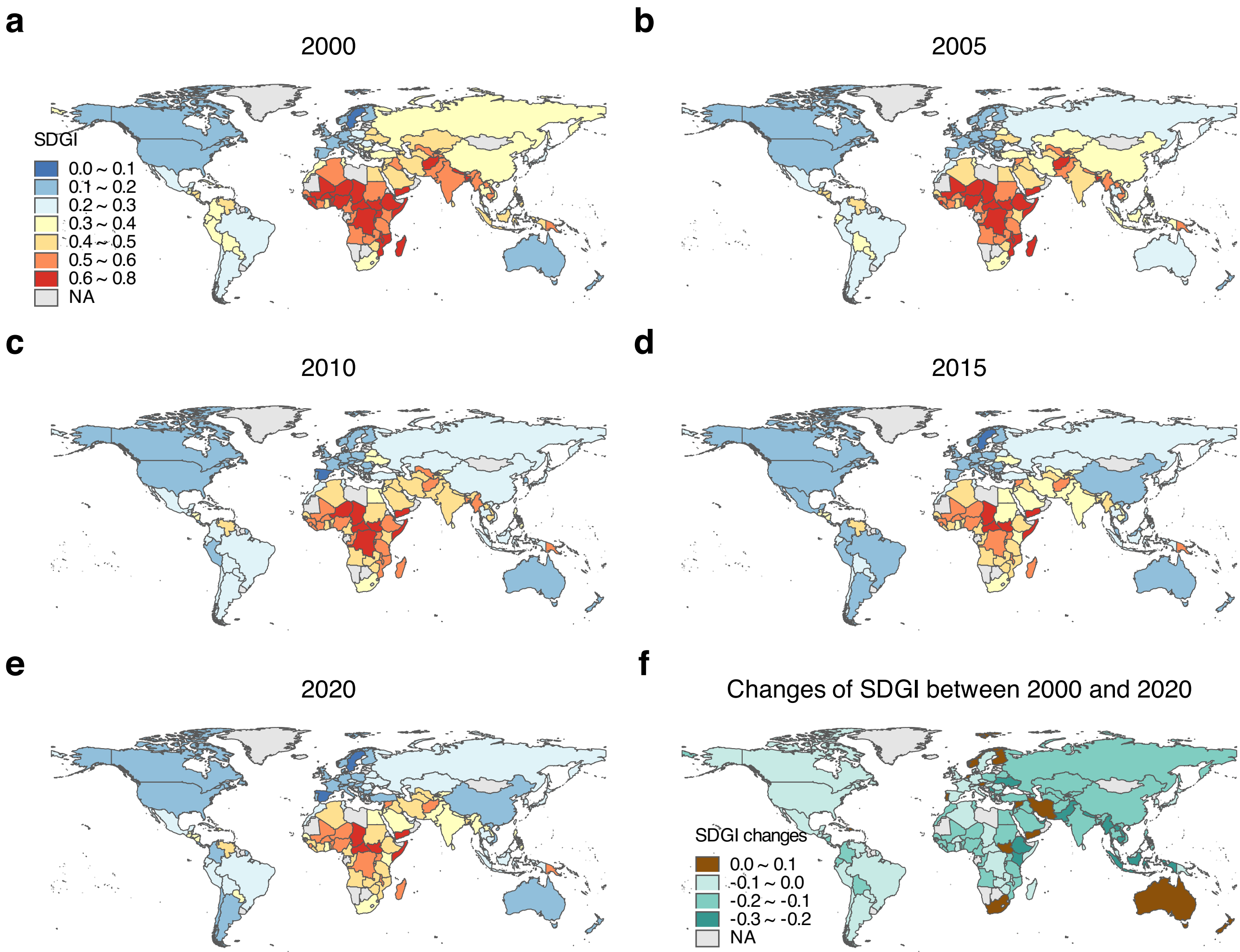

Fig. 2 | Sustainability Development Gini Index (SDGI) scores (0 to 1) across the world and their changes over time. a–e refer to SDGI in 2000, 2005, 2010, 2015, and 2020, respectively; **f** Changes in SDGI between 2000 and 2020. Blank base map from publicly available Natural Earth vector map data (https://www.naturalearthdata.com/).

coordination in SDG performance, as measured by SDCI. However, substantial imbalance persists, as evidenced by high variability in SDRPI and SDGI scores between countries (Supplementary Figs. 1–4). Each of the three proposed indices possesses distinct characteristics and interacts with the others (Supplemental Discussion), carrying profound implications for both local and global SDG governance and the analysis of synergies and trade-offs.

Unlike the SDG Index, our specially constructed SDRPI addresses the issue of indicator collinearity and introduces the fuzzy logic model to eliminate the need for computing indicator weights. The integration of the fuzzy logic model in structuring the SDRPI can reduce subjective judgment and uncertainties, as well as enhance the robustness of evaluation outcomes and minimize the risk of substantial fluctuations due to changes or anomalies in individual parameters[42,50]. In addition, while the proposed SDRPI does not directly illustrate within-country inequalities, it provides a foundation for assessing such disparities. As finer-scale data become available, such as at the provincial or grid level, the relative performance of SDGs within a country can be evaluated spatially and explicitly. Subsequently, by examining the variations among SDRPI in different regions, we can identify within-country inequalities. This is crucial for the 'Leave-No-One Behind' principle, as substantial variations in SDGs' performance may exist within a country's borders. It is important to identify not only the countries that are lagging behind but also the specific regions within those countries. This approach could facilitate the development of targeted interventions based on local urgent issues, priorities, and resource endowments, among other factors.

The proposed SDRPI, SDGI, and SDCI have profound implications for SDG governance. The SDRPI can help identify a country or region's performance regarding the SDGs. This can guide policymakers in setting priorities, identifying areas of strength, and addressing weaknesses, thereby ensuring no one is left behind, in line with the central tenet of the SDGs. For instance, the three lowest-ranking countries (i.e., South Sudan, Central African Republic, and Somalia) consistently appear among the poorest performers in the SDG Index[49]. These nations struggle with issues, such as poverty, hunger, water scarcity, and undernourishment. Political conflicts, corruption, and climate change severely hinder their progress toward achieving the SDGs[51–53]. Hence, prioritizing SDG 1 and SDG 2 in these and other lagging African countries could foster potential synergistic effects from SDGs 6, 7, 16, and 17 through international support and cooperation[54]. Conversely, the SDGI can reveal imbalances between different SDG goals and targets within a country, facilitating the development of targeted strategies to promote more balanced development. The SDCI highlights the coordination of improvements in SDG performance, which can provide insights into potential synergies in sustainable development. This information can be used to develop integrated policies that consider the interlinkages among the SDGs. By offering a more comprehensive and nuanced understanding of a country's performance and challenges in achieving the SDGs, these indices can enhance effective and targeted SDG governance.

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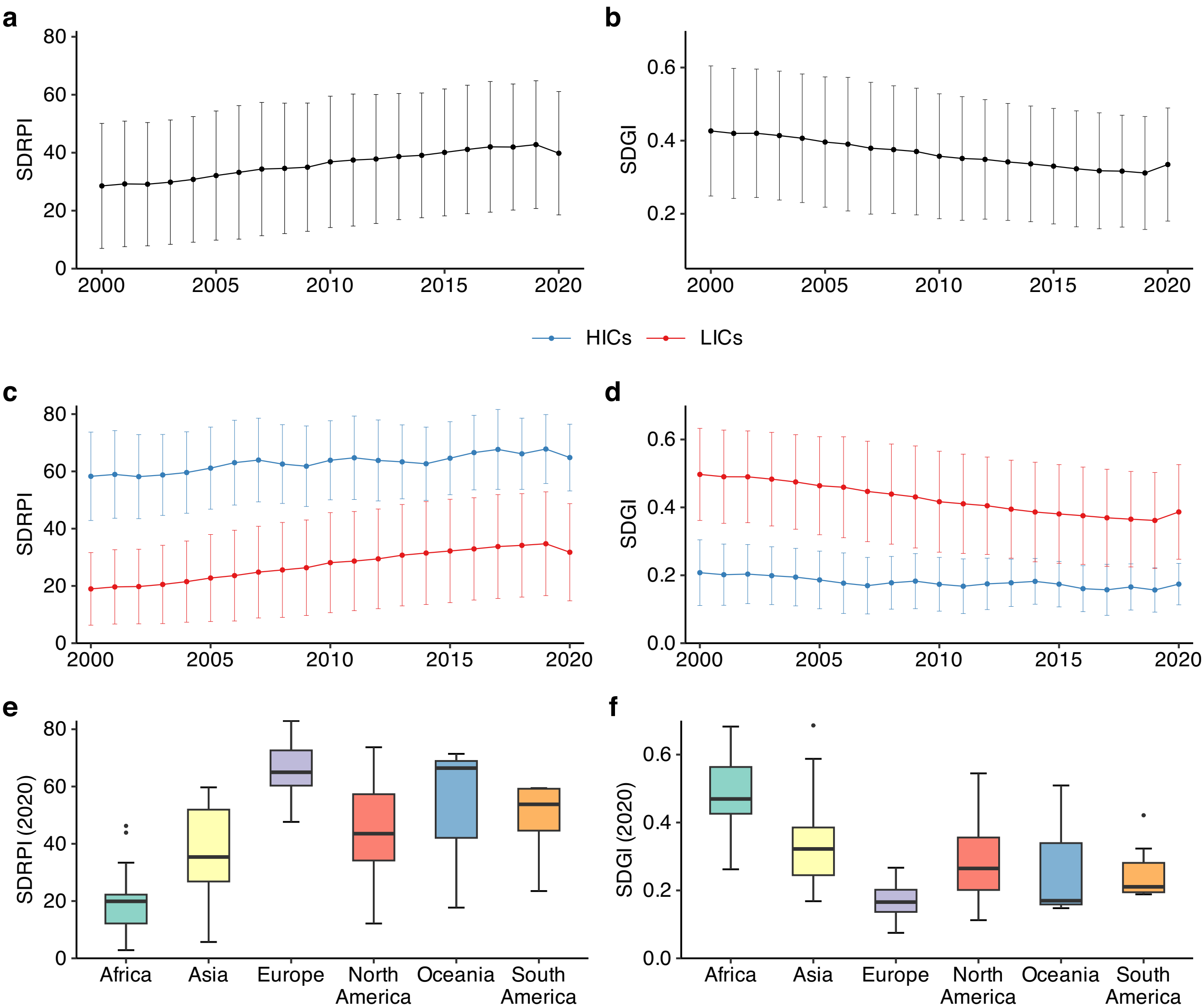

Fig. 3 | Trend of Sustainable Development Relative Performance Index (SDRPI) and Sustainable Development Gini Index (SDGI) and their changes across country groups. a Trend of global average SDRPI (2000–2020). **b** Trend of global average SDGI (2000–2020). **c** Comparison of SDRPI between high-income countries (HICs) and low-income countries (LICs, including all non-HICs), using the World Bank's income classification to distinguish country groups. **d** Comparison of SDGI changes between HICs and LICs. **e** Comparison of SDRPI among different continents in 2020. **f** Comparison of SDGI among different continents in 2020. The error bars in (**a**–**d**) indicate the conventional standard deviation. In each boxplot, the central rectangle spans the first quartile Q1 to the third quartile Q3, which is the interquartile range (IQR; IQR = Q3 - Q1), while the segment inside the rectangle shows the median. When the maximum observed scores are greater than Q3 + 1.5*IQR, the upper whisker would be Q3 + 1.5*IQR. Otherwise, the upper whisker would be the maximum observed score. When the minimum observed scores are less than Q1-1.5*IQR, the lower whisker would be Q1-1.5*IQR. Otherwise, the lower whisker would be the minimum observed score.

From an integrated sustainability perspective[13,26,28,55], spillover effects serve as critical drivers of sustainable development across national, regional, and global scales. The observed narrowing of sustainability gaps between high-income and low-income countries in this study might be attributed to cross-border spillover effects, propelled by globalization and openness[28,30,56]. In a globalized world, economic exchange, trade, and technology transfer foster mutual progress in sustainability, creating synergistic effects across regions and nations. This finding aligns with the argument that globalization plays a constructive role in advancing global sustainable development, facilitated by the advancement in transportation, communication, and international relations[27,56]. Such dynamics underscore a need for a shift from the place-based governance to flow-based governance, enabling global policymakers to better manage sustainable development spillover effects on a global scale[55]. Recent studies have examined the spillover effects associated with transboundary SDG interactions through various transmission channels (e.g., trade, tourism, wildlife transfer, river flow, ocean currents, and air flow)[57–59], as well as the impact of international trade on sustainable development[56]. SDG spillover indicators with available data covering consecutive time series from 2000 to 2020 have been incorporated into the SDRPI calculation. For instance, spillover indicators, such as "exports of hazardous pesticides" (tons per million population) for Target 3.9 and "exports of plastic waste" (kg/capita) for Target 16.1 are part of this assessment.

Economic growth, technological innovation, improved resource-use efficiency, and a focus on environmental conservation are likely to have a positive impact on sustainable development. Economic growth is often viewed as a prerequisite for development, providing the resources needed for investments in areas like health (SDG 3), education (SDG 4), and infrastructure (SDG 9)[49,60]. Technological innovation, including renewable energy technologies can help mitigate climate change (SDG 13), while digital technologies can improve access to information and services (SDGs 10 and 11)[61,62]. By using resources more efficiently, such as increasing the use of electric vehicles and

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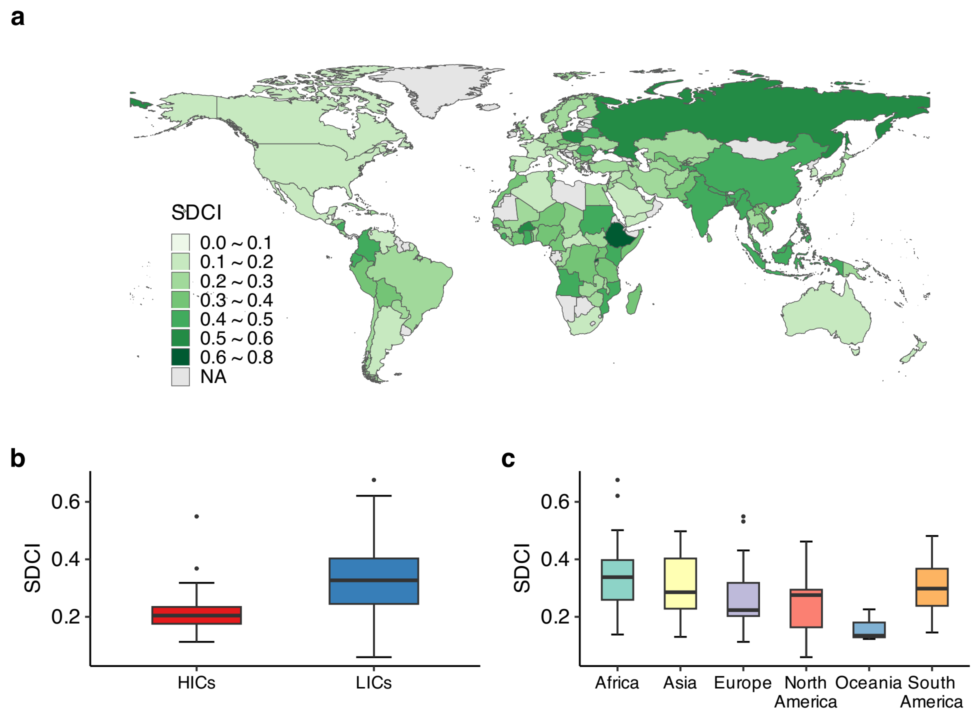

Fig. 4 | Sustainable Development Coordination Index (SDCI) scores (0 to 1) across the world and their differences across country groups. a Map of global SDCI, which is calculated based on historical SDRPI scores, 2000–2020). **b** Comparison of SDCI between high-income countries (HICs) and low-income countries (LICs). **c** Comparison of SDCI among different continents. Blank base map from publicly available Natural Earth vector map data (https://www.naturalearthdata.com/).

reducing divorce and household proliferation[63–65], we can reduce environmental degradation and ensure that resources are available for future generations. A focus on environmental conservation safeguards many services that ecosystems provide, from clean water and air to carbon sequestration (SDGs 14 and 15)[66,67]. These drivers are often interrelated and are all essential for achieving the SDGs. It is crucial to recognize the synergies among these goals and to pursue policies that advance multiple SDGs simultaneously. For example, the Global Sustainable Development Report[68] highlights seven SDGs that exhibit particularly strong synergies: SDG 1 (No Poverty), SDG 3 (Good Health and Well-being), SDG 4 (Quality Education), SDG 5 (Gender Equality), SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), and SDG 17 (Partnerships for the Goals). These goals are consistently linked to mutual benefits or recognized as catalysts for progress. Thus, strategic interventions targeting these synergistic goals could foster comprehensive progress and yield substantial gains across several other goals. For countries exhibiting high growth rates, such as Serbia, Azerbaijan, and Belarus, variations in sustainable development may stem from a diverse array of factors. These factors include differences in policy implementation, geographical conditions, levels of economic development, resource distribution and utilization, and historical structural inequalities (Supplementary Discussion). Future research could focus on predicting global SDG progress by considering time series trends (Supplementary Fig. 12) and changes in influencing factors, such as technological advancements, climate change, social transformations, and financial stimuli.

Based on the SDRPI scores at the target level, Targets 7.2 (increase renewable energy), 9.1 (develop quality, reliable, sustainable and resilient infrastructure), 9.5 (enhance scientific research and upgrade the technological capabilities of industrial sectors), and Target 17.18 (enhance capacity-building support to low-income countries to increase substantially the availability of high-quality, timely and reliable data) exhibited relatively poor performance (Supplementary Figs. 1, 2). This indicates that greater emphasis should be placed on the development of renewable energy[69,70] and the transformation of infrastructure[71], as well as on strengthening scientific research and improving data availability[72,73], especially in low-income countries, for the effective implementation and monitoring of the SDGs. While designing intervention measures, it is essential to consider the synergies and trade-offs associated with the SDGs. Understanding the interlinkages between these Goals enables governments and decision-makers to prioritize actions that leverage the impacts of the SDGs and targets with strong synergies. For instance, promoting Target 7.2 through the development of renewable energy sources, such as wind and solar power, can create synergistic effects for SDGs 7 and 13[62,74]. Conversely, the construction and placement of wind and solar facilities may also have potential negative impacts on the natural environment, causing biological disturbances[75,76] that could hinder the achievement of SDG 14 and SDG 15. Effective governance and policies must take into account lagging regions and indicators, while also considering the possible synergies and trade-offs of interventions aimed at promoting progresses[77–80]. Such an approach could help maximize synergistic effects and achieve coordinated sustainable development.

Future research should refine the proposed indices by integrating cross-border spillover effects and their associated indicators. Advanced analytical approaches, such as integrated sustainability and spillover indices, could be leveraged to systematically analyze spillover effects from a more holistic perspective[28,30]. Unlike traditional sustainability assessments that focused narrowly on social, environmental, and economic dimensions, integrated sustainability introduces an explicit spillover pillar, capturing the effects of globalization and interdependencies across regions. This innovation facilitates a deeper analysis of social, environmental and economic interactions, enabling a more comprehensive assessment of sustainable development spillover effects[81,82]. For instance, empirical analysis of sustainable development spillover effects between North America and the Middle East and North Africa (MENA) shows positive outcomes, indicating their relationship is synergistic rather than characterized by trade-offs[28]. These findings align with the SDGs, particularly SDG 16 (Peace, Justice, and Strong Institutions) and SDG 17 (Partnerships for the Goals), which emphasize international cooperation as a catalyst for global sustainability. Further research could further quantify these spillover effects at both the country and city levels, leveraging statistical and spatial indicator datasets and sustainability elasticities indices. Such analyses can uncover the complex interactions of social, environmental, and economic factors, providing policymakers with critical insights to manage sustainability spillover effects and strengthen partnerships. In addition, by applying the metacoupling framework[83] (e.g., human–nature interactions within and between neighboring and distant countries) and incorporating different channels of transboundary SDG interactions, researchers have found that high-income countries contributed considerably to about 61% total SDG interactions worldwide[31]. Spillover effects are an important element of the metacoupling framework, which helps to promote sustainability worldwide[84]. Notably, transboundary synergistic effects through international trade are ~15% more pronounced with trade partners outside their borders compared to those that are neighboring countries. By considering international trade and the relative performance of environment-related SDG targets under both trade and no-trade scenarios, researchers found that trade between distant countries plays a greater role in achieving these global SDG targets than trade between adjacent countries[56]. These findings underscore that fostering regional alliances and multilateral cooperation under globalization and regional openness is a strategic imperative for accelerating progress toward the SDGs and addressing global imbalances. In addition, future research should prioritize the effective use of the increased availability of data to cover a broader range of SDG targets and indicators while improving assessment methodologies, including bound selection and expansion of time-series data. It is also important to assess how synergies and trade-offs among the SDGs, as well as interactions between countries, influence sustainable development performance both nationally and globally. Analyzing the interrelationships among sustainable development performances of different countries can provide a comprehensive understanding of the mechanisms driving global sustainable development dynamics. This knowledge can inform policies aimed at adopting a coordinated and multilateral governance approach to reduce the performance gaps among countries and advance global SDGs.

This study innovatively devises the SDRPI, SDGI, and SDCI to evaluate global SDG performance, imbalances, and coordination. The methods developed in this study also serve as a reference for monitoring future sustainable development performance, addressing imbalances, and promoting coordinated improvement over longer time spans, contingent upon the availability of relevant new data. Achieving all 17 SDGs for the entire world by 2030 requires targeted policies and governance that consider country-specific context and imbalances across dimensions. We hope that this study could help future global SDG monitoring efforts, providing valuable insights for policy planning, development, implementation, and evaluation.

Methods

Since over 53% of the SDG targets lack specific target values, measuring progress toward achieving all 17 SDGs is quite challenging. Some previous studies[85,86] that aimed at assessing progress towards the SDGs selected the average of top performers or top percentage performers as 'target values'. This approach only monitored relative progress toward top performers but not absolute progress toward SDGs. To address this issue, we developed the Sustainable Development Relative Performance Index (SDRPI) using a fuzzy logic model to measure relative performance in sustainable development across countries. Based on the spatiotemporal SDRPI scores, we then constructed the SDGI, which draws on the Gini index to assess the imbalance (or balance) in relative performance across 17 SDGs in a given area. In addition, we developed the SDCI using correlation network analysis to evaluate the degree of coordination among changes in the relative performances of different SDGs, based on SDRPI scores over time.

Indicator selection and data sources

Our indicator set comprises a total of 102 indicators, covering 72 targets. In the indicator framework, no indicators are reused, and each has a relatively independent meaning. We followed rigorous procedures to select indicators from different indicator sources for the years 2000–2020. All of these sources employed strict protocols for indicator selection, involving consultation and/or stakeholder involvement. The study period, 2000–2020, was chosen due to the greater quantity and higher quality of available data, which is crucial for conducting a time-series assessment. Assessment of SDRPI across space and time was deemed essential. The indicators were primarily sourced from four main sources: Global Indicator Framework for the SDGs and Targets of the 2030 Agenda for Sustainable Development[87]; SDG Index and Dashboards Report[46,47,49]; Indicators and a Monitoring Framework for the SDGs: Launching a Data Revolution for the SDGs[45]; and other international authoritative sources, such as the World Bank[88], Food and Agriculture Organization (FAO) of UN[89], World Health Organization (WHO)[90], International Labour Organization (ILO)[91], and International Energy Agency (IEA)[92]. We gathered all available data for consistent indicators across countries for the study period from these authoritative sources and others listed above (see details in Supplementary Table 5).

Criteria for selecting indicators

1. Alignment with specific SDG targets: each indicator must reflect the spirit of a specific SDG target, ensuring its relevance to policy development.
2. Global relevance and applicability: the indicators selected should be suitable for monitoring performance across a wide range of countries. These indicators must be globally comparable, allowing for direct comparisons of performances among countries.
3. Statistical rigor: data must be derived and processed in a statistically reliable and robust manner.
4. Credibility of sources: indicators must originate from international authoritative sources, that involve stakeholder engagement and/or expert discussions to ensure their reliability and clarity. No indicator in our study was constructed by the authors. The priority sources of the selected indicators were (1) the Global indicator framework for the SDGs and targets of the 2030 Agenda for Sustainable Development[87], (2) the SDG Index and Dashboards reports, (3) Indicators and a Monitoring Framework for the SDGs: Launching a Data Revolution for the SDGs[45], and (4) other international authoritative sources.
5. Availability of time series data: data must be accessible throughout the study period.
6. Indicator independence: indicators must not have overlapped or included relationships. Specifically, no indicators can be reused across multiple SDGs.

Normalization and bound selection

A standardized normalization procedure was applied to all indicators, based on methodologies utilized in the SDG Index and Dashboards[36,46,49]. The upper bound for each indicator was determined using an enhanced decision tree, which involved two key steps:

1. For SDG targets with officially defined target values or official descriptions of absolute thresholds indicating the principle of "leave no one behind", we used these absolute official target values as the upper bounds. Examples are provided in Table 1.

Table 1 | Example targets with official defined target value or official description about absolute threshold indicating the principle of "leave no one behind"

SDG Targets	Indicator	Target value
Target 1.1 By 2030, eradicate extreme poverty for all people everywhere, currently measured as people living on less than US$1.25 a day	Poverty headcount ratio at international poverty lines (% of population)	0%
Target 4.1 By 2030, ensure that all girls and boys complete free, equitable, and quality primary and secondary education leading to relevant and effective learning outcomes	Primary completion rate (% of relevant age group)	100%

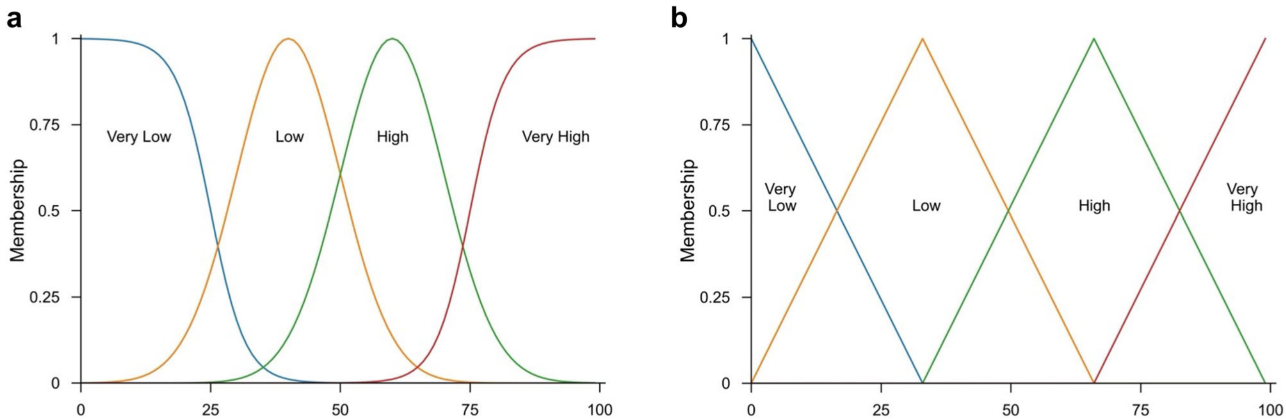

Fig. 5 | Fuzzy logic model of indicators and targets in the SDG framework. a Membership function of the heuristic categories for each indicator. **b** Membership function of the heuristic categories for each target.

2. For all other indicators, the upper bound was determined using the median value ± 2MAD (Mean Absolute Deviation). The upper bound was set as the median value plus twice the MAD if the higher value indicates better performance. Conversely, if a higher value indicates poorer performance, the upper bound was set as the median value minus twice the MAD. Following the Empirical Rule criterion, which helps identify and exclude extreme values, the boundaries of the interval were defined as the upper or lower limits of the data. Values falling outside this interval were considered abnormal endpoint values. We adopted this method because it can effectively identify optimal values within a reasonable scope across countries while excluding abnormal values. This approach has been validated and applied in numerous previous studies[93–95].

To determine the lower bounds, we followed a two-step process:

1. For indicators used in the SDG Index and Dashboards report, we adopted the lower bound specified in that report[47].
2. For the remaining indicators, the lower bound was established based on the annual performance of the bottom 2.5% of countries from 2000 to 2020. This criterion aligns with the methodology used in the SDG Index and Dashboard report for selecting lower bounds.

Calculation of SDRPI scores

We introduced the fuzzy logic model to generate SDRPI, eliminating the need to calculate indicator weights. This method has been widely used to aggregate indicators while removing subjective judgement[41]. It computes target scores considering the distinct characteristics of data distribution among different fuzzy sets of indicators at the target level. For example, reducing new HIV infections (per 1000 uninfected population), the incidence of tuberculosis (per 100,000 people), and the prevalence of obesity (BMI ≥ 30, % of adult population) could all contribute to the performance assessment of Target 3.3.

As a systematic tool, the fuzzy logic model is capable of handling subjective judgments, uncertainties, and ambiguities during calculations, thereby ensuring an objective ranking of sustainable development performance[42]. The specific target calculation method and underlying assumptions are detailed as follows:

Step 1: First, we categorized the indicator scores and target scores. Drawing from the research literature that utilizes the fuzzy logic model for indicator-based studies[42], these scores are typically categorized into 3–5 heuristic groups. A larger number of heuristic categories allows for improved decision-making and problem-solving scenarios, making them suitable for increasingly complex issues. However, this also requires greater computational resources, and it is generally found that choosing four categories is a suitable enough balance between result accuracy and computational complexity. Consequently, in this study, we divided the target scores into four fuzzy sets: very low, low, high, and very high. Similarly, the indicator values were classified into the same four fuzzy sets. The purpose of this classification is to effectively address the threshold uncertainty issues arising from different fuzzy sets[96].

Step 2: Second, we then determined the membership functions of different fuzzy sets for both indicators and targets, including the shapes and parameters of these functions. Following Cisneros-Montemayor et al[41], we assumed the four indicator fuzzy sets (very low, low, high, and very high) to be left sigmoid, normal, normal, and right sigmoid, respectively, with breakpoints at 0, 33, 66, and 100, as shown in Fig. 5a. The shapes of the four target fuzzy sets (very low, low, high, and very high) were assumed to have shapes of left trapezoid, triangle, triangle, and right trapezoid, respectively. The breakpoints for these sets are 0, 33, 66, and 100, as shown in Fig. 5b. We applied this combination of normal and triangular membership functions to effectively accommodate the complex distribution characteristics of indicators and address the interpretative needs of targets, ultimately helping to reduce calculation uncertainty.

Step 3: Finally, we implemented the target calculation method. In this study, we derived the target scores corresponding to the indicators by considering the data distribution characteristics among different fuzzy sets of targets and indicators. We calculated the target scores using the indicator membership as weights, using the following

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equation:

$$Score_{target,j} = \frac{\sum_{i=1}^{n} M(Score_{indicator,i}) \times capacity[M(Score_{indicator,i})]}{\sum_{i=1}^{n} M(Score_{indicator,i})} \quad (1)$$

where $Score_{target,j}$ indicates a specific target score, while $Score_{indicator,i}$ denotes the score of a specific indicator of that target. M denotes the membership function for a particular indicator, *capacity* refers to the inverse function of a target membership function, and n represents the number of indicators included in a target. The country-level SDRPI scores were calculated from the target scores using the following equations:

$$Score_{SDG,k} = \sqrt[m]{\prod_{j=1}^{m} Score_{target,j}} \quad (2)$$

$$SDRPI = \sqrt[17]{\prod_{k}^{17} Score_{SDG,k}} \quad (3)$$

where $Score_{SDG,k}$ represents the score for a specific SDG, and m refers to the number of targets associated with that SDG. SDRPI was calculated as the geometric mean of scores across the 17 SDGs, representing the relative performance of SDGs at the national level. The geometric mean, also adopted by Human Development Index (HDI), not only reduces the level of substitutability between goals and targets, but also acknowledges the intrinsic differences across various dimensions compared to a simple average[97].

Calculation of SDGI scores

This study developed the SDGI, drawing inspiration from the Gini coefficient, to measure the balance degree of different sustainable development at goal, target, and indicator levels. The Gini coefficient, developed by statistician and sociologist Corrado Gini, is a statistical measure of income or wealth inequality within a population[43]. The coefficient ranges from 0 to 1, with 0 representing perfect equality (everyone possesses the same income or wealth) and 1 representing perfect inequality (one person holds all the income or wealth, leaving none for others). The Gini coefficient is widely used in various disciplines, such as economics[98], energy[99], and resource management[100], to analyze and compare income or wealth disparities and energy or resource consumption inequalities among different countries, regions, or groups. It is an essential tool for understanding the extent of economic inequality and formulating policies aimed at reducing poverty and fostering social and economic justice. Due to differences in resource endowments and development capabilities among countries, as well as variations in policy orientations over different time periods, imbalances in SDG performance are evident. Therefore, introducing the Gini coefficient can help effectively quantify this imbalance, leading to the creation of the SDGI. This index can measure the imbalance in the relative performance of SDGs at both the country level and the SDG level. The SDGI is calculated as:

$$SDGI = \sum_{i=1}^{n} S_i C_i + 2\sum_{i=1}^{n} S_i(1 - P_i) - 1 \quad (4)$$

where *SDGI* represents the Gini coefficient of scores of different SDGs. In the study, we categorized 17 SDGs into groups according to their number. S_i and C_i are the proportions of SDG scores and the mean score of each group, respectively, while P_i refers to the cumulative proportion of the mean score of each group, with "i" indicating each respective group (n = 1, 2, 3, 4…). Similar to the Gini coefficient, the SDGI ranges from 0 and 1. An SDGI value of 0 indicates perfect equality among SDGs (every SDG possesses identical scores), whereas 1 indicates absolute imbalance (where one goal achieves a score of 100 while all others score 0). As SDGI scores increase, the degree of imbalance in SDG performance also increases.

Calculation of SDCI scores

We also developed the SDCI to measure the coordination degree among changes in different SDGs' relative performances based on SDRPI scores over a given time period. The SDGs are intricately interconnected, potentially leading to synergies or trade-offs where achieving one SDG might facilitate or impede the progress of another. We used Spearman's rank correlation coefficients to signify these relationships: a positive value denotes a synergy, while a negative value signifies a trade-off. The absolute value of the correlation coefficient represents the strength of the coordination relationship. Since this study considers the possibility of future coordinated enhancement of multiple SDGs based on observed coordination, only positive values were utilized in constructing the SDCI. A larger SDCI value indicates a higher likelihood of coordinated improvements across multiple SDGs in a country. Unlike Pearson's correlation analysis, Spearman's analysis can capture the nonlinear correlation between the variables and is less influenced by outliers, making it widely applicable across various disciplines[101]. For each country, we calculated Spearman's correlation between each pair of SDGs and used the significant correlation coefficients ($p < 0.05$[44], $r > 0.5$[102]) for additional analyses.

The Spearman's correlations for each country were converted into a network graph object and subsequently analyzed using the R package called igraph[103]. In this network, the nodes represent the 17 interactive SDGs (or 16 SDGs for landlocked countries), and links between nodes represent positive or negative correlations between two nodes and their respective weights (Supplementary Fig. 5). We calculated the connectivity for the synergy networks as the ratio of existing links to all possible links in the network. This measure was weighted by the absolute value of the correlation coefficient, reflecting both the number and strength of the correlations[104]. Higher connectivity within synergy networks indicates greater coordination in the improvements of different SDGs' performance from 2000 to 2020[44].

Uncertainty and sensitivity analysis

Following the methods outlined in Xu et al.[85], we analyzed all possible combinations of SDG indicators across all possible numbers of SDG indicators. This assessment helped evaluate the influence of diverse numbers of indicators and their combinations on the SDG scores. Assessing the resulting distribution of SDG scores for 2017, we found that as the number of indicators increased, variation (or uncertainty) in the SDG score decreased. Notably, the median SDG score showed a tendency to stabilize when the number of indicators per SDG was two or more (Supplementary Fig. 13).

We conducted sensitivity analysis[105] to assess the sensitivity of SDRPI to data from alternative years and countries. We used the sensitivity index as described in Xu et al.[85]. In this sensitivity analysis, we recalculated SDRPI by systematically altering the value of each indicator by decreasing and increasing it by 10% for six countries at the national level. These countries include Australia, Brazil, China, Germany, Nigeria, and the USA, and were chosen due to their substantial population sizes across different continents. The findings indicated the sensitivity of SDRPI to changes in original data values of the indicators below 0.2 (Supplementary Fig. 14).

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

All data are available from the corresponding author upon request. Data that support the findings of this study are available within the paper and its Supplementary Information.

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Code availability

The codes can be accessed from the corresponding author upon request.

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Author contributions
Z.X. and J.L. designed the research, analyzed the results, and wrote the paper. X.C., T.Y., S.H. and Y.L. contributed to data collection and analysis. Z.X., X.C. and J.L. determined indicators. Z.X., J.L., Q.J., X.C., X.W., N.B., Z.L., G.G.G., J.M. and S.B. revised the manuscript. Z.X., J.L., G.G.G., C.L., Z.L., N.B., S.B. and S.L. provided comments on the manuscript. J.Z. checked the uncertainty and sensitivity analysis. All authors reviewed the manuscript.

Competing interests
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Additional information
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Correspondence and requests for materials should be addressed to Yunkai Li or Jianguo Liu.

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