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Country-level evenness measure in assessing progress towards Sustainable Development Goals (SDGs)

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Achieving the United Nations' Sustainable Development Goals (SDGs) requires an overall and well-balanced achievement of all SDGs rather than cherry-picking a few. While it is vital to assess the evenness of SDGs achievement, such analysis, particularly on a global scale, is still evidently absent from the existing literature. To remedy such a scholarly gap, this paper measures the evenness of SDGs achievement for 193 countries from 2010 to 2019 by adapting the evenness assessment method originating from ecology and biodiversity literature. Our analyses regarding the country-level SDG evenness index scores (EIS) indicate a significant heterogeneity across countries. Global South countries usually underperform in the evenness of 17 goals, while a significant portion of Global North countries also suffer from the unbalanced developments in SDGs. By integrating the evenness measures into the conventional global SDG monitoring framework, this study identifies *six* development paths in pursuing the SDGs and shows that maintaining the overall SDGs improvements while balancing the development of each goal is practical but has not taken place in at least 35% of countries. We estimate that the SDG evenness and average performance could further increase by 3.5 p.p. and 2.1 p.p., or 74 percent and 50 percent of the growth in the baseline continue past paths scenario, respectively, if each country could follow the effective development path of frontier counterparts with similar income levels. Our SDG evenness measures, complemented by inter-temporal cross-country analyses, could inform policies and cooperation strategies to identify the weaknesses in sustainable development, boost effective growth, and protect unevenly developed countries. Future research could further develop these measures to provide deeper insights into achieving rapid and well-balanced development of SDGs at various levels.

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Introduction

The United Nations introduced the 17 sustainable development goals (SDGs) in 2015 (United Nations 2015), which constitute a global initiative designed to address a range of pressing challenges facing the world, with the ultimate target of eliminating poverty, safeguarding the planet, and ensuring prosperity for all by 2030, scholars and international organizations have explored a wide range of methods to assess countries' progress towards the SDGs and inspiring potential policies. However, despite that the uneven development of SDGs may compromise the overall achievement of SDGs, the existing assessments of SDGs have largely neglected the distributional characteristics among SDG indicators (Liu et al. 2021). For example, the annually published *Sustainable Development Report* (SDR) (Sachs et al. 2021) uses SDG Index scores based on the arithmetic mean of all 17 SDGs scores to track and rank the progress towards SDGs of all UN member states, which might be biased and over-optimistic if large variances exist among 17 SDGs scores (Liu et al. 2021). To be more specific, a comprehensive achievement of sustainable development implies that a satisfactory achievement has been made on any single SDG, even the most underperformed one. However, the mean value of 17 SDGs may be exaggerated by some SDGs with superb performance while concealing the poor achievement of other SDGs. In particular, a country might have half of all SDGs achieving a score of 100 (the best performance), while the other half might only get a score of 0 (the worst performance), resulting in an SDG Index of 50. Due to its heavily unbalanced achievements, such a country cannot be regarded as being halfway to achieving the SDGs.

The concept of *evenness* in ecology describes the distribution of relative abundance among species in the measurements of biodiversity (Smith and Wilson 1996; Tuomisto 2012), which could be used to augment the existing SDGs assessments by accounting for the distributional characteristics among SDG indicators. Extending beyond ecology, geographers apply the concept of evenness to analyze the spatial patterns of socio-economic phenomena and broader human activities. These patterns often exhibit notable agglomeration concentrated at specific locales and dispersion across different places. The spatial configurations of socio-economic activities, whether agglomerated or dispersed, are frequently attributed to cumulative causation or multiplier effects, contributing to spatial unevenness in regional economic growth (Haggett 1965; Myrdal 1957; Richard Chorley 1967). Considering that the concept of development should encompass more than just economic growth, the evenness of broader development, as represented by the discourse of the SDGs, warrants further investigation. In this sense, evenness could be used to augment the existing evaluation of SDGs achievement by investigating the differences in performance among the 17 SDGs, which take the critical perspective of synergic and trade-off interactions between SDGs into consideration. The inclusion of the evenness dimension in SDGs assessments can diminish the potential overestimation of SDG performance by using the SDG mean value only. It may also assist policymakers in implementing adaptive strategies to better achieve SDGs by allocating more resources to weaker SDG indicators (Liu et al. 2021). Evenness offers new insights on tracking countries' progress towards SDGs, responding to an urgent need to analyze and monitor the SDGs in an integrated and balanced way.

While assessing the evenness of SDGs achievement is important, such analysis devoted to measuring the evenness, particularly on a global scale, is still evidently absent from existing literature. Since the SDGs were introduced as "the blueprint to achieve a better and more sustainable future for all", researchers have eagerly attempted to provide various comprehensive measures to monitor the progress towards SDGs at global, national and subnational levels (Sachs et al. 2021; Schmidt-Traub et al. 2017; United Nations 2020; World Banks 2020; Xiao et al. 2022; Xu et al. 2020). Notably, the accomplishment of SDGs is not a to-do list containing 17 tasks which could be completed one by one. The progress in one specific SDG may promote or hinder progress in other SDGs. Given that, the correlations between the 17 SDGs have attracted much academic discussion (Dawes 2022; Lusseau and Mancini 2019; Nilsson et al. 2016; Pradhan et al. 2017; Schmidt-Traub et al. 2017; Wu et al. 2022). Based on the correlations between SDGs, a holistic understanding of SDGs is required while monitoring the implementation and progress of SDGs (Biggeri et al. 2019; Fu et al. 2019). The correlations between the 17 SDGs may amplify the pre-existing development gaps between SDGs and cause a greater unevenness in the general achievement of SDGs. The mean value of 17 SDGs providing only an overall score is not enough and the evenness across different SDGs has been thought of importance in accomplishing the eventual sustainable development (Liu et al. 2021). While the measurements of evenness have been well established in the research on ecology and biodiversity (Smith and Wilson 1996; Tuomisto 2012), the solely existing research on measuring SDG evenness focuses merely on China (Liu et al. 2021). To address the existing gap, three key questions were explored in this paper. First, the inquiry delved into the proper measurement of Sustainable Development Goal (SDG) evenness at the country level. Second, attention was given to the integration of the evenness index into monitoring and tracking the balanced growth of SDGs at the country level. Third, consideration was extended to how the SDG evenness index might influence the developmental trajectories of distinct income groups of countries, as classified by the World Bank, facilitating more efficient SDG achievement by 2030.

Here, we provide the measures of SDG evenness for 193 countries from 2010 to 2019 by adapting the evenness assessment method originating from ecology and biodiversity literature (Smith and Wilson 1996; Tuomisto 2012). The researched countries covered 98% of the global GDP and 99% of the world's population in 2019 according to the World Bank. We use an improved radar chart method to construct the SDG evenness index score (EIS, more details on generating the index, see Methods). The indicators for each SDG are extracted from the widely used SDG database provided by the *Sustainable Development Report* (Sachs et al. 2021). Based on the proposed country-level SDG evenness index, our study presents quantitative evidence of the spatio-temporal patterns of SDGs balanced growth by exploring the evolution of evenness scores for each country. We pay particular attention to comparing the difference between SDG evenness measures and the SDG Index from the *Sustainable Development Report* (referring to the mean index score thereafter, MIS) in assessing countries' progress towards SDGs, the latter has been widely utilized by scholars, governments and international organizations to monitor the SDG achievements of countries (e.g., (Sachs et al. 2021; Xu et al. 2020). By doing so, we illustrate how accounting for the evenness dimension may contribute to the global effort in tracking countries' progress towards SDGs, and promote SDGs by distinguishing the differences in the development paths of different countries. Given the approaching deadline of 2030, we also estimate the global sustainable development potential by simulating the SDG performance up to 2030 when underperforming countries could adopt the mean-evenness integrated effective growth paths, and identify underlying handles that policymakers could utilize to boost sustainable development for different country groups.

Our results reveal a substantial heterogeneity across countries in terms of SDG evenness. Low-income countries usually suffer

from greater SDG unevenness compared to middle- and high-income countries and the gaps have widened in the last decade. The analysis of the growth path of each country suggests that maintaining the overall SDGs improvements while balancing the development of each goal is practical but has not taken place in at least 35 percent of countries. We estimate that the evenness and mean index scores could further increase by 3.5 p.p. and 2.1 p.p. if each country could follow the effective development path of frontier countries with similar income levels. This is significant given that the actual improvements of mean index score and evenness index score were only 4.9 p.p. and 4.1 p.p. respectively in the baseline continue past paths scenario by 2030. The result illustrates evenness as an attention-worthy perspective in the evaluation of sustainable development achievement. The SDG evenness scores and the related inter-temporal cross-country analyses presented in the paper could inform policies and cooperation strategies to identify the deficiencies in sustainable development, boost effective growth, and protect unevenly developed countries. Moreover, the evenness framework could be further developed in future research aiming at an exhaustive probe into well-balanced SDGs achievements at various levels.

This paper contributes to the scholarship of SDGs in two ways. First, the country-level evenness index scores presented in this study provide a valuable addition to the existing SDG Index that has been widely utilized by scholars and international organizations (Asadikia et al. 2021; Dawes 2022; Sachs et al. 2019; Xu et al. 2020). Tracking progress towards SDGs is crucial for ensuring transparency and accountability at all levels of governance, and shaping new strategic policy visions for sustainable development. The constructed SDG evenness measures, if properly applied and updated, have the potential to guide balanced development in each country to achieve the SDGs by 2030. Second, the analysis of SDG evenness across countries, such as identifying uneven countries and the six different development paths proposed in this study, can assist national decision-makers in prioritizing resources and targeting interventions in areas where progress is lagging. Furthermore, the study emphasizes the potential for enhancing relevant international cooperation to address common challenges and opportunities and facilitate learning and collaboration across countries. The proposed binary framework, which combines both overall and evenness measures, offers new insights on tracking countries' progress towards SDGs in an integrated manner, which helps promote global sustainable development while accounting for synergies and trade-offs among 17 goals.

Method

Data. We adopt the SDG assessment framework (Sachs et al. 2021) and collect the same set of indicators used in global time trend analysis in the Sustainable Development Report (SDR) 2021 to describe the progress of SDG for 193 countries from 2010 to 2019 (Sachs et al. 2021). Since 2015, the annual SDR has provided the most up-to-date data to track and rank the performance of all UN member states on the SDGs (Sachs et al. 2021). The SDG index scores and rankings reported in SDR have been widely utilized by scholars, governments, and international organizations to monitor countries' sustainable development (Asadikia et al. 2021; Dawes 2022; Sachs et al. 2019; Xu et al. 2020). The indicators collected in the SDR dataset are internationally comparable and applicable to all countries. Official data from national governments constitutes around two-thirds of their data, which helps to ensure that concepts, collection methods, and results are consistent and comparable. The remaining data comes from unofficial sources collected by universities, NGOs, and private sector organizations using a variety of techniques, which can be used to bridge some of the data gaps in official sources. For SDG 12 and SDG 10 which lack sufficient time-series data in SDR, we retrieve the representative SDG indicators from the United Nations Statistics Division (United Nations 2020) and World Bank Atlas of Sustainable Development Goals (World Banks 2020). In total, we use 67 series for all 17 SDGs. The full list of the indicators and their data source are reported in Supplementary Table S1. We decided to exclude the post-2020 dataset in this paper because we wish to present the typical pattern of SDG evenness without the shock of COVID-19 and there existed missing SDG data for some countries during the pandemic period at the point of our writing. However, the authors will continue to update and publicly share the data and related analyses in the future to closely monitor the impact of global events and development trends in the recent few years on the SDG evenness and the overall SDG achievement.

Method

The scores of 17 SDGs. Following Sachs et al. (2021), we generate the score of all 17 SDGs using the standard Composite Index Analysis Method, which has been widely utilized in existing scholarship and many international organizations to generate the cross-entity comparable index. Calculating the SDG index comprises three steps: (i) establish performance thresholds and censor extreme values from the distribution of each indicator; (ii) rescale the data to ensure comparability across indicators (normalization); (iii) aggregate the indicators within SDGs.

We adopt the upper bound as a result of a five-step decision tree and the lower bound as the 2.5th percentile of the distribution. For more details on the five-step decision tree in selecting the upper bound, see (Sachs et al. 2021). The values of upper and lower bounds for all the used variables are presented in Supplementary Table S1. After establishing the upper and lower bounds, variables are transformed linearly to a scale between 0 and 100 using the following rescaling formula for the range [0, 100]:

$$x' = \frac{x - \min(x)}{\max(x) - \min(x)} \times 100, \quad (1)$$

$$x' = \frac{\max(x) - x}{\max(x) - \min(x)} \times 100, \quad (2)$$

where x is the raw data value; max/min denotes the upper and lower bounds respectively; and x' is the normalized value after rescaling. Equation (1) is valid for indicators with higher values representing better performance (e.g., percentage of the population with access to electricity); Eq. (2) is valid for indicators with lower values representing better performance (e.g., poverty rate). The rescaling equation ensures that all rescaled variables are expressed as ascending variables (i.e., higher values denote better performance). In this way, the rescaled data become easy to interpret and compare across all indicators: a country that scores 50 on a variable is halfway towards achieving the optimum value; a country with a score of 75 has accomplished three-quarters of the best achievement. After normalizing the indicators, we adopt the authentic mean within SDGs to calculate scores for each SDG, which is denoted as r_j, where $j = 1, 2, \ldots, 17$.

Measuring the overall progress in 17 SDGs: SDG mean index score (MIS). The authentic mean or geometric mean has been widely used to generate a single aggregate measure in Composite Index Analysis. The Human Development Index (HDI) is perhaps the most obvious and well-known example (United Nations Development Programme 2020). A notable advantage of a single aggregate measure is that it provides a straightforward and easy-to-interpret summary of overall performance that might be

difficult to discern from analyzing multiple targets and indicators that often overlap and move in different directions. For comparison with the SDG evenness, we use the authentic mean across 17 SDGs to construct the generally used mean index score (MIS) as in policy reports such as (Sachs et al. 2021), and academic studies such as (Xu et al. 2020):

$$MIS_i = \frac{1}{17}\sum_{j=1}^{17} r_{i,j}, \tag{3}$$

Where i refers to the number of countries in our sample, $i = 1, 2, \ldots, 193$.

Accounting for the evenness: SDG evenness index score (EIS). We adopt the improved radar chart method from the ecology and biodiversity literature to assess the evenness dimension in sustainable development. Previous studies have demonstrated that the improved radar chart method has better performance than other methods (Li et al. 2008; Smith and Wilson 1996). The method also has a clear geometric interpretation and simple mathematical representation.

The improved radar chart method explores the nature of radar charts in visualizing the 17 SDGs. The perimeter in the radar chart stands for the evenness among all 17 SDGs while the radius of each SDG indicates the score of each SDG. The commonly used SDG mean index is represented by its area. The area (S) and perimeter (L) of the radar chart are expressed mathematically as follows:

$$S_i = \sum_{j=1}^{17} S_{i,j} = \sum_{j=1}^{17} \frac{1}{17}\pi r_{ij}^2,\ j = 1, 2, \ldots, 17, \tag{4}$$

$$L_i = \sum_{j=1}^{n} L_j = 2\left|r_{i,\max} - r_{i,\min}\right| + \sum_{j=1}^{n} \tfrac{1}{17} 2\pi r_{ij},\ j = 1, 2, \ldots, 17 \tag{5}$$

Where $r_{\max}$ and $r_{\min}$ respectively denote the maximum and minimum among 17 SDG scores. The r_j refers to the score of the j^{th} SDG. Notably, the doubled value of the difference between $r_{\max}$n and $r_{\min}$ refers to the part of the perimeter other than the total length of all arcs (the total length of all lines between two adjacent arcs). Evenness score refers to the ratio between the total area of the radar chart formed by the 17 SDGs and the area of a circle with the same perimeter (the evenest distribution of all SDGs with the same perimeter):

$$ES_i = S_i / \left[\pi\left(L_i/2\pi\right)^2\right] \times 100 = 400\pi S_i / L_i^2, \tag{6}$$

Where S_i and L_i are derived from Eqs. (4) and (5) respectively. The ratio between S_i and L_i are multiplied by 100 to obtain the ES_i, the evenness score comparable with the SDG mean index score which ranges from 0 to 100. The area of the radar chart with a fixed perimeter reaches its largest (100) when it is a circle, that is when all SDGs have the same score, and decreases with increasing unevenness among all radii (referring to scores of all 17 SDGs in the present study).

Incorporating evenness measures to monitor the balanced growth in SDG. After constructing the temporal SDG evenness index scores (EIS) for 194 countries, this article accounts for how the evenness could contribute to global efforts in monitoring the progress toward sustainable development goals. We extend the conventional single aggregate measure (solely based on mean index score, MIS) to the binary analysis framework (combine MIS with EIS). By plotting the levels and dynamics of MIS (x-axis) and EIS (y-axis) in a unified two-dimensional diagram, we reveal the development pathways for all the countries from 2010 to 2019. To facilitate the analysis, we follow (Liu et al. 2021) and broadly classify all the countries into six types based on the slope of the growth path. We define the perfect pathway, which means a completely even improvement in all 17 SDGs, as the vector with a slope of one. We divided the 90-degree space centered on the perfect pathway into two 45-degree ranges (Supplementary Fig. S1). Based on such divisions and the defined perfect pathway, that is the central 45° line, five subgroups could be further identified, namely *uneven* ($0° < \theta < 22.5°$), *slightly uneven* ($22.5° < \theta < 37.5°$), *relatively ideal* ($37.5° < \theta < 52.5°$), *slightly underdeveloped* ($52.5° < \theta < 67.5°$) *uneven* and *underdeveloped* ($67.5° < \theta < 90°$). The rest of the countries with either a decrease in MIS or EIS are classified as *others*.

Scenario analysis: adopting the effective development paths from the frontier countries. In the scenario analysis, we assess the impact of the different development pathways that countries adopt on the EIS and MIS and estimate the growth potential of 17 SDGs for each country by 2030. We formulate the following four scenarios. Scenario 1 (S1) is called the group frontier scenario, which is the most desirable scenario, where all countries follow the path of the top 20% of countries in each income group. To be more specific, in this scenario, we first select the top 20% countries in each income group according to their performance over the sample period, according to their averaged growth of MIS and EIS in the 2010s; second, we generate the most desirable growth pathway of every income group through averaging the MIS and EIS scores of the top 20% countries; third, we apply the most desirable growth pathway for the remaining 80% countries in each income group to calculate the possible changes in global EIS and MIS and simulate the potential SDG scores of each country by 2030. Scenario 2 (S2) is called the moderate catch-up scenario, whose process is similar to S1. In S2, we generate the average development pathway of the top 50% of countries in each income group and simulate what if the remaining 50% of countries follow the pathway of countries in the first half. Scenario 3 (S3) is the leaving-no-one-behind scenario. Different from the S1 and S2, we take the development pathway of the country with median mean-evenness integrated SDG performance in each income group as the simulation criteria instead of the pathways of top countries. S3 provides the results if the countries with less satisfactory SDG performance (below intermediate level) follow the paths of median countries. The continue past paths scenario (S4) assumes the existing trends in the 2010s will continue until 2030. Similar scenarios and settings conducted in this research have been recently applied to simulate sustainable development paths or CO_2 reduction capacity in other studies (Shan et al. 2018; Shen et al. 2023; Xiao et al. 2022).

Results

The evenness index scores (EIS) provide an assessment of a country's overall magnitude of SDG evenness by summarizing the distributional properties of progress towards 17 SDGs for each country (more details on constructing the EIS, see Methods). The index score signifies a country's position between the least even (0) and the most even (100) in achieving a balance across the 17 SDGs. That is, a *lower* score means a nation is less even, and a higher score means a nation is more even. We calculate SDG evenness measures for 193 countries from 2010 to 2019 and report the results of 2019 (Fig. 1, baseline) as the baseline status of SDG evenness for each country.

In subsection "The SDG evenness across countries", we report the quantitative evidence of the spatio-temporal patterns of balanced growth in SDGs by exploring the evolution of EIS for

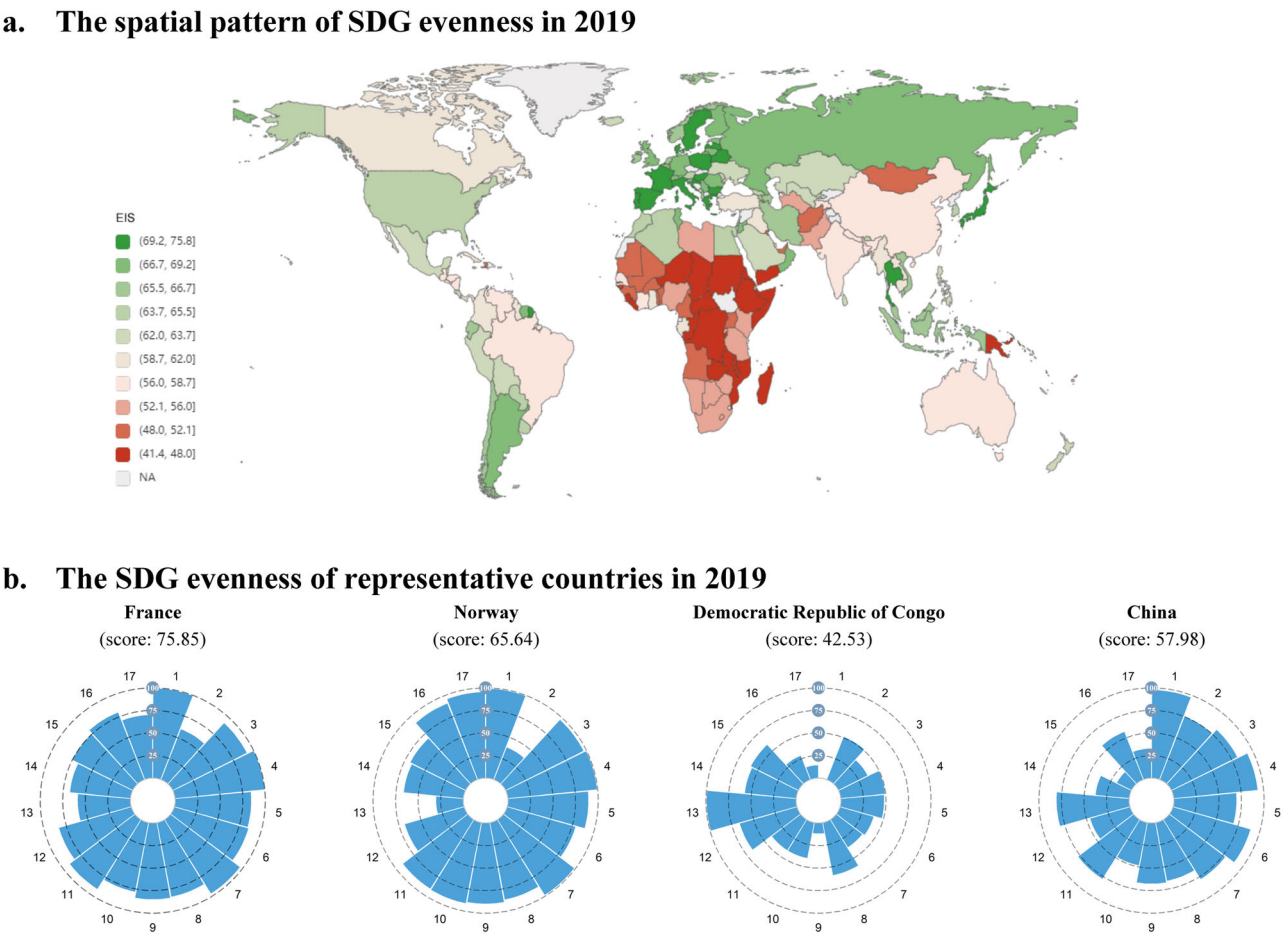

Fig. 1 The evenness index score (EIS) across countries. a We adopt the quantile classification scheme so that each category has an equal number of countries, i.e. clusters of high scores above average in green, and clusters of low scores below average in red. The values of EIS for individual countries are reported in Supplementary Table S2. NA, data not available. For more details on constructing the EIS, see Methods. **b** The SDG1 for the Democratic Republic of the Congo is 0.43.

each country. In subsection "Tracking countries' progress towards SDGs with evenness measures", we pay particular attention to comparing the difference between SDG evenness measures and mean index scores in assessing countries' progress towards SDGs. We illustrate how accounting for the evenness dimension may contribute to the global effort in tracking the progress towards SDGs, and promote SDGs by distinguishing the differences in the development paths of various countries. In subsection "Simulation of the SDG performances up to 2030 when adopting themean-evenness integrated development paths", given the approaching deadline of 2030, we simulate the SDG performance up to 2030 when adopting the mean-evenness integrated effective growth paths, and identify underlying handles that policymakers could utilize to boost sustainable development for different country groups.

The SDG evenness across countries. Figure 1a reveals the significant spatial heterogeneity of SDG evenness across countries. The results show that the Global North generally performs better in achieving a balance across the 17 SDGs than the Global South, indicating a North-South division regarding the SDG evenness. The list of countries with the highest evenness score was dominated by Global North countries (Fig. 1a, Supplementary Table S2). All top 20 countries, except Thailand, were the Organization for Economic Cooperation and Development (OECD) countries. Three European countries topped the 2019 evenness score: France, Sweden, and the Czech Republic (Supplementary Table S2). These countries outperformed other countries because of their relatively advanced economic development levels as well as their capability and willingness to coordinate all 17 SDGs in pursuing sustainable development. Notably, even economically developed OECD countries might encounter significant challenges in achieving balanced growth in all 17 SDGs. Many OECD countries, such as Australia, Norway, and the USA, were seriously exposed to the challenges related to SDG13 (Climate action), SDG2 (Zero hunger, with the full title of "End hunger, achieve food security and improved nutrition and promote sustainable agriculture"), SDG12 (Responsible consumption and production), and SDG10 (Reduce inequality). Figure 1b displays the disaggregated SDG structure that leads to the distinct evenness status among Global North countries, using France and Norway as examples. Although both countries exhibited good performance in overall SDG reflected by satisfactory mean values of 17 SDG scores, France shows notable endeavors in balancing them. In contrast, Norway shows a disproportionately low score in the indicators of Prevalence of obesity (23.1%), Human Trophic Level (2.526), and Sustainable Nitrogen Management Index (0.845) for SDG 2, and CO_2 emissions from fossil fuel combustion and cement production (7.969 tCO_2/capita), and CO_2 emissions embodied in imports (5.994 tCO_2/capita) for the SDG 13 (Supplementary Table S1). These differences between France and Norway led to France as rank #1, and Norway as rank #54 from the SDG evenness perspective although they had similar rankings

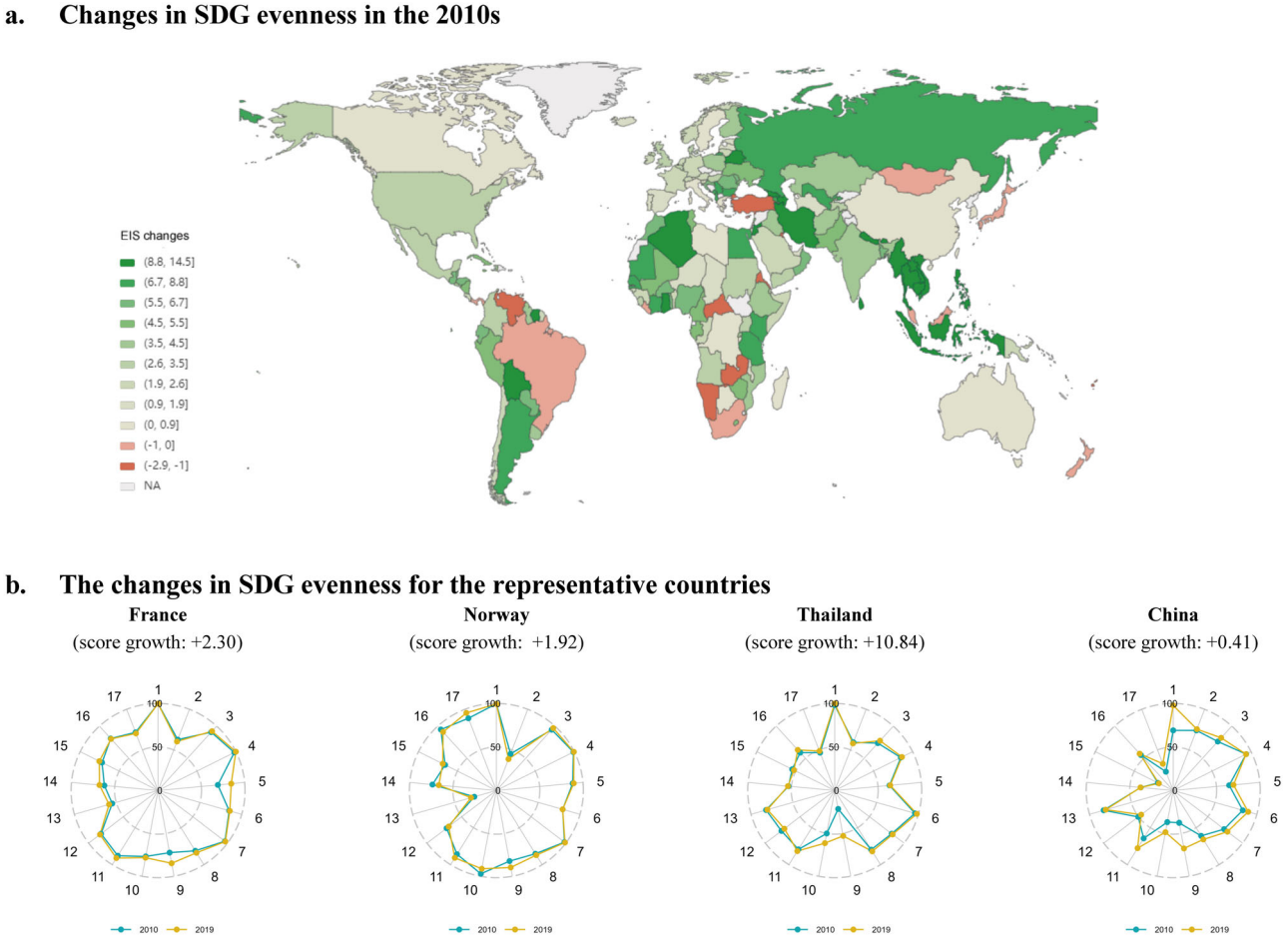

Fig. 2 Performance of change in SDG evenness in the 2010s. a The spatial pattern of changes in SDG evenness index score between 2010 and 2019 for 193 countries. For more details on constructing the EIS, see Methods. NA, data not available. **b** The blue line refers to the values of each SDG in 2010, and the orange line refers to 2019.

(no. 7 for Norway and no. 8 for France) in terms of SDG Index measured by mean value in the 2021 *Sustainable Development Report* (Sachs et al. 2021).

Global South countries tend to have a lower level of evenness in sustainable development, which is mainly due to their poor performance on social and economic SDGs, such as SDG1, SDG9, SDG4, and SDG7 (Fig. 1a, Supplementary Table S2). Meanwhile, Global South countries, in particular low-income countries, generally have good performance on environmental SDGs, such as SDG13, SDG14, and SDG15. Overall, compared to the Global North, Global South countries lack adequate economic, fiscal, and technological capacity, and sufficient international assistance, to advance their underperformed SDGs, which leads to their overall unbalanced status of 17 SDGs. Eritrea, Democratic Republic of the Congo, Somalia, Central African Republic, and Niger are the latest 5 countries in terms of SDG evenness (Fig. 1b, Supplementary Table S2). In contrast, emerging markets such as China and India have moderate evenness in SDG developments (Fig. 1b, Supplementary Table S2).

In addition to the status quo of national SDG evenness, the temporal changes in each country's SDG evenness are also extremely noteworthy, which reflects whether a country has attempted to prioritize the development of relatively backward SDG indicators while making progress towards SDGs. Figure 2a shows temporal changes in SDG evenness score in the 2010s for the sample countries, and Fig. 2b details the changes of 17 SDGs and evenness for some representative countries. Our findings show that the dynamics of SDG evenness in a country in the 2010s may not be necessarily relevant to its general socio-economic development level and its current SDG evenness status. Even the European countries, which were economically developed and had the best performance of SDG evenness, had made merely below-average progress in terms of SDG evenness in the 2010s. It might be because of the relatively high SDG evenness at the beginning of the sample period, which had restricted the improvement space in these countries. In contrast, developing countries in the Global South topped the list of evenness improvement. For example, Southeast Asian countries have witnessed the fastest growing SDG evenness, such as Thailand, Vietnam, and Indonesia. In the sample decade, the shortcomings of these countries, such as SDG9, SDG10, SDG1, and SDG2, had been rapidly improved alongside the process of economic development, thus enhancing the SDG evenness. For example, while maintaining the advanced SDGs, Thailand's main shortcomings, SDG9 and SDG10, had been significantly improved in the 2010s (Fig. 2b). In contrast, countries such as China were rapidly achieving their goals such as SDG 1 and SDG 9 thanks to unrivaled economic growth (Fig. 2b), resulting in a significant improvement in overall SDGs. Particularly, initiatives and policies, such as 'The China Rural Poverty Alleviation and Development Program (2011–2020)' and the 'Targeted Poverty Alleviation Strategy' have greatly contributed to the achievement of SDG 1 (Li et al. 2016; Zhang et al. 2020). However, its pre-existing shortcomings regarding SDG10, SDG14, and SDG15 had

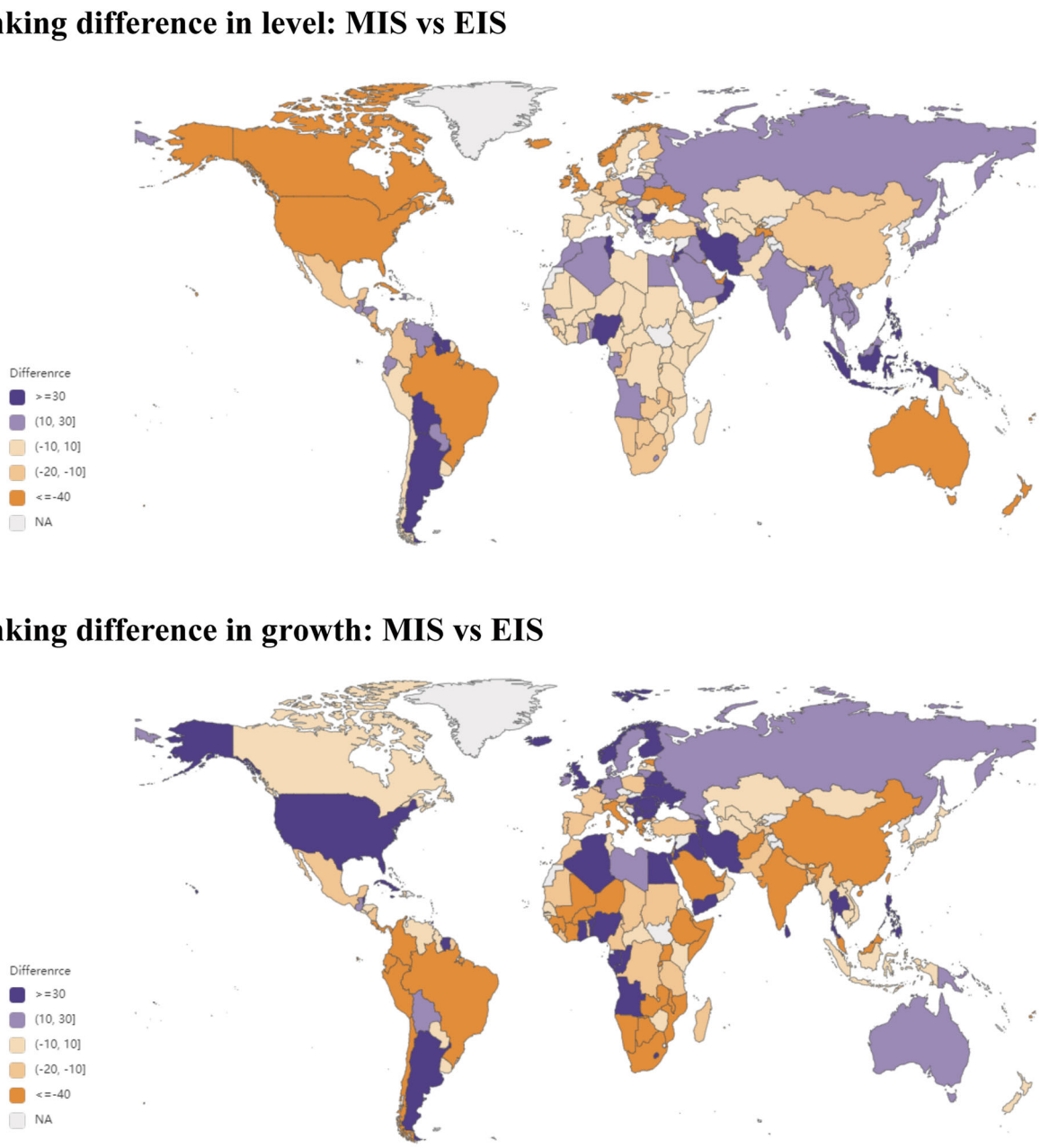

Fig. 3 Incorporating evenness measures to track the balanced growth in SDGs. Figure **a** shows rankings difference based on two measures of evenness index score (EIS) and mean index score (MIS) in assessing the countries' progress towards SDGs in 2019. A positive value means a country scores a higher rank in terms of SDG EIS compared to MIS in assessing its progress towards SDGs, and vice versa. Figure **b** focuses on the changes, and displays countries' rankings difference between growth in EIS and MIS in the 2010s. NA data not available.

limited improvements, leading to moderate improvements in SDG evenness.

Tracking countries' progress towards SDGs with evenness measures. In this section, we show how accounting for evenness measures could benefit global efforts in tracking the countries' progress toward SDGs. First, we pay particular attention to comparing the difference between the SDG evenness index score (EIS) and mean index score (MIS) in assessing the SDGs. The latter has been widely used as an aggregate measure to monitor and rank the progress toward SDGs across countries or regions by scholars, governments, and international organizations (Asadikia et al. 2021; Dawes 2022; Sachs et al. 2019; Xu et al. 2020). Second, we show how integrating the evenness measures into the conventional global SDG monitoring framework could prevent the states and related organizations from being over-optimistic about SDG achievements and benefit more deficiency-dependent strategies towards SDGs by distinguishing the differences in the development paths of different countries.

Figure 3a shows the rankings difference between the two measures of EIS and MIS in assessing the progress towards SDGs in 2019. A positive value means a country scores a higher rank in terms of EIS compared to MIS in assessing its progress towards SDGs, and vice versa; Fig. 3b focuses on the changes, and displays countries' rankings difference between growth in EIS and MIS in the 2010s. While the SDG EIS in general positively correlated with the MIS, Fig. 3a shows that significant gaps exist between the

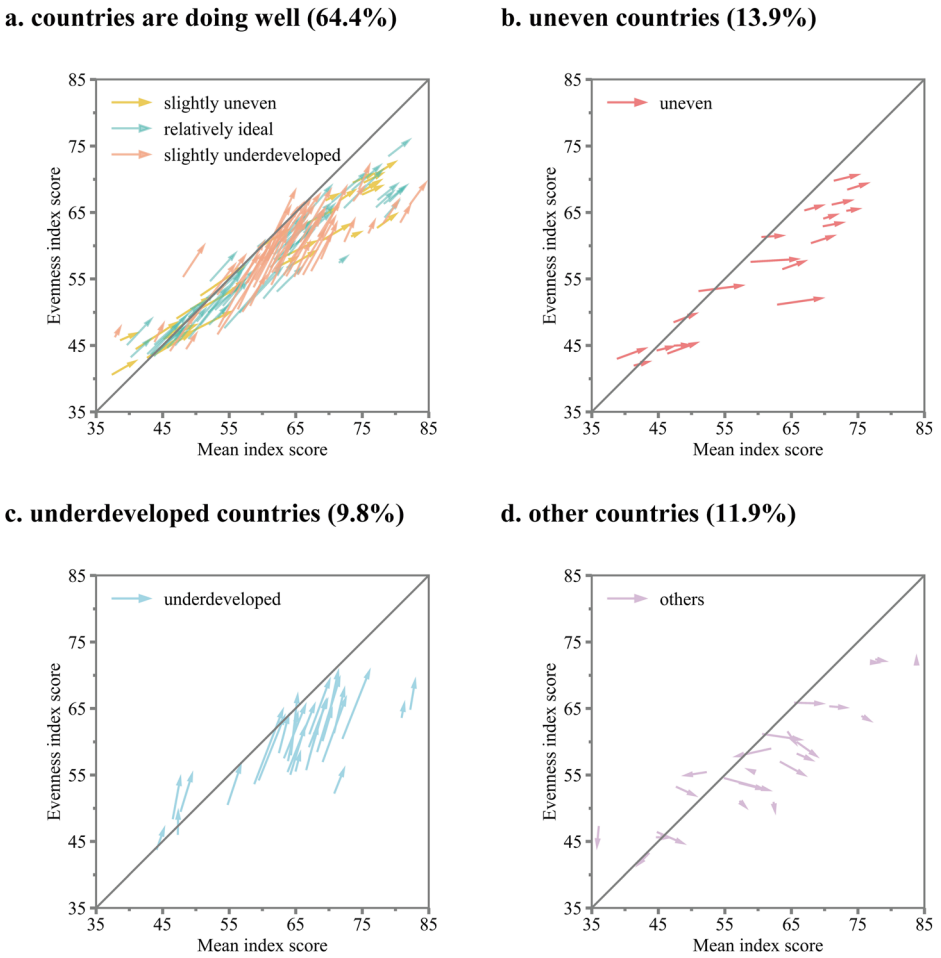

Fig. 4 Incorporating evenness measures to monitor the balanced growth in SDG. Vector diagram visualizing the development pathways of 193 countries in the 2010s according to countries' performance in both averaged growth in 17 SDG and evenness dimension; The gray diagonal marks the defined perfect pathway with a slope of 1, and the colored arrows visualize the pathways of countries. For more details on the defined six growth paths, see Methods. **a** Countries are doing well. **b** Uneven countries. **c** Underdeveloped countries. **d** Other countries.

two evaluation criteria. Focusing on the single year of 2019, the average (absolute) ranking difference between the two SDG evaluation criteria is about 20. In particular, while three Nordic countries (Denmark, Sweden, and Finland) topped the SDG MIS in 2019, they have significantly lower rankings in terms of the SDG EIS. Only 2 of the top 10 countries in EIS are also recorded as top 10 countries in MIS. Luxembourg, the United Arab Emirates, and Australia were noted as the three countries with the largest negative ranking gaps between EIS and MIS. That is to say, the three countries had a high level of overall sustainable development but with significant unevenness. The unbalanced development was mainly caused by poor performance in SDG12 (Lower Responsible Consumption and Production), SDG13 (Climate Action), and SDG2 (Zero Hunger). Suriname, Jordan, and Indonesia were the three countries with the largest positive ranking gap. The results show that although they show a well-balanced development among different SDGs, the overall SDG level of these countries is less satisfactory.

Figure 3b shows the gaps between the two evaluation criteria of EIS and MIS were even larger when considering the temporal patterns that monitor the progress toward SDGs in the 2010s. The average ranking difference between EIS growth and MIS growth was about 43. The results highlighted that countries with rapid growth in MIS were not necessarily accompanied by balanced development. Such results underscored a certain degree of tradeoff among the SDGs. For example, countries such as China and India were rapidly achieving their goals such as SDG 1 and SDG 9 thanks to their unrivaled economic growth, resulting a significant growth in MIS. However, their pre-existing shortcomings regarding SDG10, SDG14, and SDG15 had limited improvements, leading to the MIS growth outperforming the EIS growth. Overall, our findings reveal the significant gaps between the two evaluation criteria, and demonstrate that the SDG evenness measure could provide a valuable addition to the existing SDG MIS in assessing and guiding global sustainable development.

After identifying the difference between the evenness and mean value of 17 SDGs in assessing the countries' performance, we present the development path for each country by developing a bivariate assessment framework with both the dimensions of overall and evenness of 17 SDGs. We identify *six* types of development paths in achieving the SDGs according to countries' performance in both averaged growth in 17 SDG and evenness dimension (More details on six growth paths, see Methods). The results are presented in Fig. 4. Our results documented those 49 (25.4%) countries, such as France and Germany, have achieved *relatively ideal* growth paths, with a balance between the mean and evenness in all 17 SDGs along their developments. Additionally, 48 (24.9%) and 27 (13.9%) countries have been able to achieve an almost balanced relationship between SDG overall development and evenness, respectively falling into the category of *slightly underdeveloped* or *slightly uneven*. However,

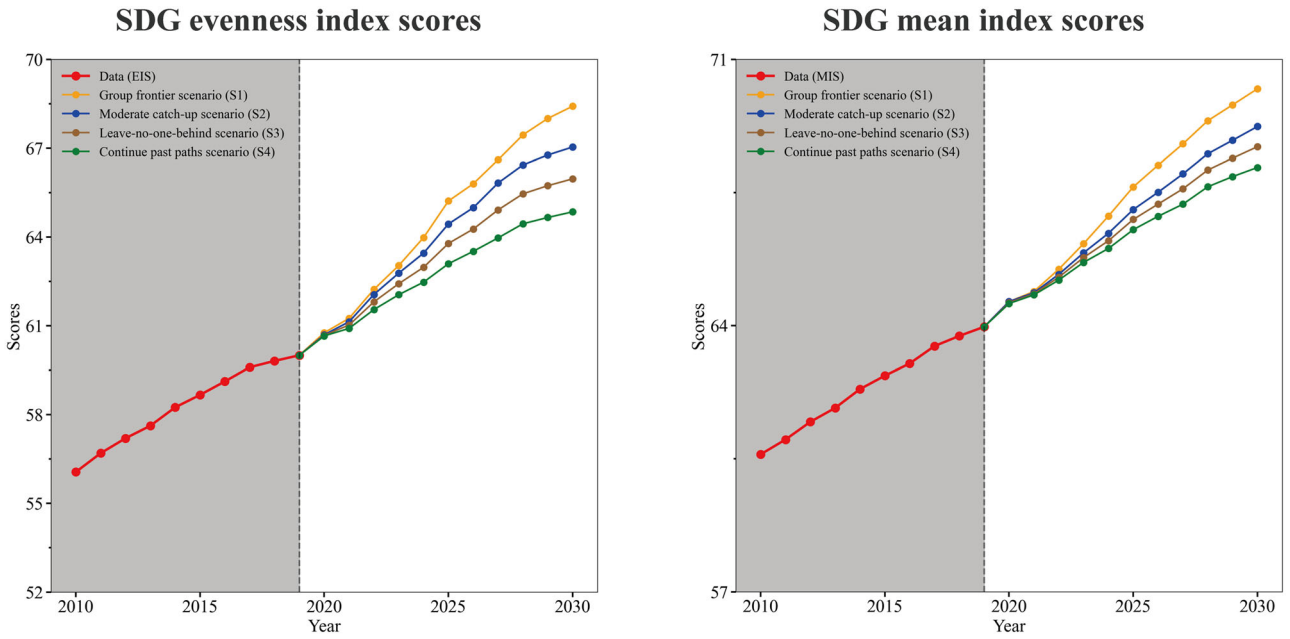

Fig. 5 Performance of global SDG evenness and mean index scores in the 2010s and the scenario-based projections up to 2030. The performance of global averaged EIS and MIS in the 2010s are on the left side of each graph, while the simulations of the global EIS and MIS for 2030 are on the right side.

there are still a considerable number of countries that have moved forward in only one dimension of progress in SDGs while ignoring the other. 27 (13.9%) countries have belonged to the category of *underdeveloped* and 19 (9.8%) countries have been identified as the category of *uneven*. At the same time, 23 (11.9%) countries have moved backwards in either the development dimension or the evenness dimension, which were defined as *others*. In sum, we identify at least 35% of all the countries have underperformed due to their unbalanced development paths. Our results show different growth paths that countries have adopted in pursuing the SDGs. The results suggest that maintaining the overall SDGs improvements while balancing the development of each goal is practical but has not taken place in at least 35% of countries (*underdeveloped* + *uneven* + *other countries*). Thus, there are potential opportunities to improve the countries' SDG performance by having underperforming countries strive to learn from higher achieving countries in adopting the mean-evenness integrated effective development paths.

Simulation of the SDG performances up to 2030 when adopting the mean-evenness integrated development paths. Given the approaching deadline of 2030, this study conducted a scenario analysis to simulate the SDG performance up to 2030 when underperforming countries learn from the frontiers by adopting the mean-evenness integrated effective development paths. By doing so, we also identify underlying handles that policymakers could utilize to boost sustainable development for different country groups. In particular, we formulate the following four scenarios: The group frontier scenario (S1) is the most desirable scenario in which each country follows the growth paths of the top 20% of countries within its income group (e.g., top countries within the low-income group). The group top 20% country are selected by integrated changes in EIS and MIS in the 2010s; for more details and explanations, see Methods. In a moderate catch-up scenario (S2), each country follows the growth paths of the top 50% of countries within its group. The leave-no-one-behind scenario (S3) focuses on what if those left-behind countries in each income group catch up with the average paths of their group. The continue past paths scenario (S4) assumes the existing trends in the 2010s will continue until 2030. Similar scenario settings have been recently applied to simulate sustainable development paths or CO_2 reduction capacity (Shan et al. 2018; Shen et al. 2023; Xiao et al. 2022).

Figure 5 shows that if countries continue the past paths (S4), the global EIS and MIS of SDGs would increase respectively by 4.9 p.p. and 4.1 p.p. from 2019 to 2030. Notably, an extra increase of 3.5 p.p. could have been witnessed in the global SDG EIS and 2.1 p.p. in MIS if all countries had followed the effective development paths of their frontier fellows (S1), although the scale and drivers of mitigation vary between countries and country groups (Fig. 6). Similarly, the moderate catch-up scenario (S2) delivers significant benefits as well, with EIS and MIS additionally improved by 2.1 p.p. and 1.0 p.p. respectively. The leave-no-one-behind scenario (S3) indicates the most limited improvements of both MIS and EIS among scenarios 1 to 3, which, however, has been measurable enough. More precisely, the EIS and MIS could have further increased respectively by 1.1 p.p. and 0.5 p.p. compared to the baseline continue past paths scenario (S4). Note that S3 is also the least challenging scenario among the first three as only the bottom countries needed to catch up with the median level of their group.

The identified drivers of effective development vary across different income groups of countries. The top five drivers of all income groups are reported in Fig. 7, which depends on their average contribution to the additional growth of EIS and MIS in scenarios 1–3, compared to the baseline scenario 4. For high-income countries, the key drivers of their effective development include SDG9 (the improvement in the Industry, Innovation and Infrastructure), SDG10 (Reduced Inequality), and SDG5 (Gender Equality); while for low-income and lower-middle-income countries, the major drivers are SDG1 (No Poverty) and SDG4 (Quality Education). For the upper middle-income countries, in addition to the drivers overlapping with high- and low-income countries, SDG14 (Life Below Waters) and SDG16 (Peace, Justice and Strong Institutions) also play important roles. Meanwhile, learning from the top runners will significantly deliver more increments in SDG performance for low-income and lower-

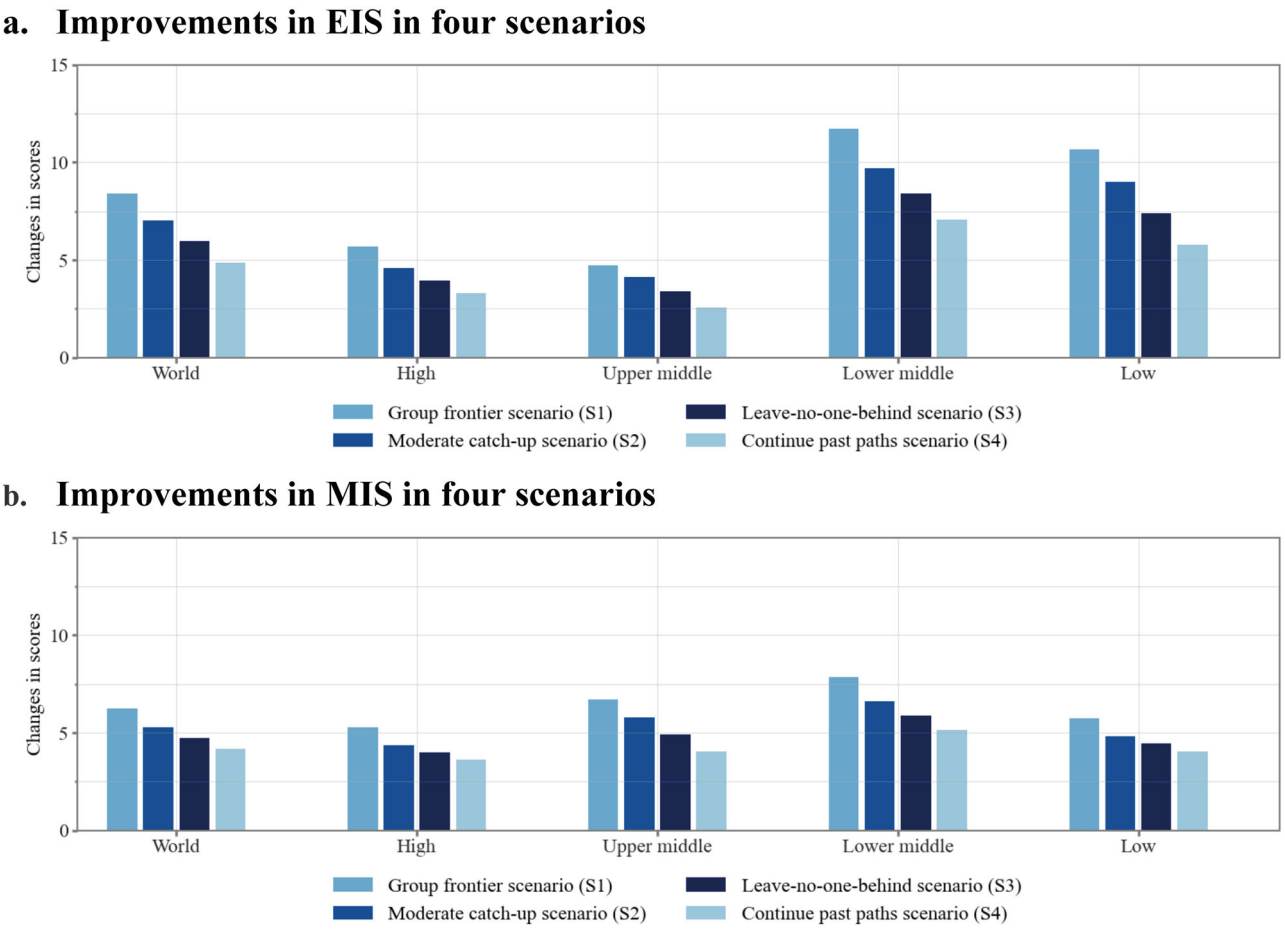

Fig. 6 Simulation of increments in EIS and MIS by 2030 across income groups. The classifications of countries according to their income levels are provided by the World Bank. **a** Improvements in EIS in four scenarios. **b** Improvements in MIS in four scenarios.

middle-income countries than others, showing the importance of promoting the within-group catch-up for these countries. In sum, our results suggest that policymakers should carefully deploy appropriate handles to stimulate effective sustainable development according to the status quo of different countries.

Conclusion

Sustainable development goals (SDGs) emphasize a holistic achievement across every single goal instead of selectively completing a few. Thus, a balanced progress of SDGs is as important as the overall progress of SDGs. However, there have been very few assessments that consider the perspective of evenness, although the measure of evenness could efficiently help monitor the progress of SDGs achievement and further inform future policy-making and relevant implementations. Here, we adapt the evenness concept from the scholarship of ecological systems and biodiversity to assess sustainable development, through which the SDG evenness index of 193 countries from 2010 to 2019 is generated. The revealed spatio-temporal patterns of SDG evenness could facilitate national policy-making regarding sustainable development and relevant international cooperation. The constructed evenness scores could complement the SDG Index provided by the *Sustainable Development Report* (Sachs et al. 2021), which has been widely utilized by scholars and international organizations to track and rank the countries' progress toward SDGs (Asadikia et al. 2021; Dawes 2022; Sachs et al. 2019; Xu et al. 2020).

Our results suggest that a high mean value of SDG is not necessarily associated with a high SDG evenness, which holds true even for developed OECD countries, as highlighted in Section 3.1. The slowest progress of SDG evenness has been usually witnessed in low-income countries. As outlined in Section 3.2, the investigation of the development paths of countries suggests that maintaining the overall improvements while enhancing the evenness during achieving SDGs is practical but has not taken place yet in at least 35% of all countries. According to our scenario analyses, the global MIS and EIS of SDGs could have experienced an extra increase of 3.5 p.p. and 2.1 p.p. respectively compared to the baseline continue past paths scenario, if all countries could have followed the effective development path of frontiers countries with similar income levels. Our study suggests that it is critical to include the measure of evenness in assessing and guiding the process toward achieving SDGs. The proposed monitoring framework containing MIS and EIS can be used to identify geographical disparities and deserves further academic examinations to provide deeper insights into rapid and balanced progress toward SDGs.

Based on our findings, it's crucial to highlight the importance of prioritizing social and economic SDGs for nations in the global South, as they are fundamental for both SDG advancement and maintaining balance. Economic development acts as a catalyst for fostering coordinated progress in SDG attainment among countries in this region, as evidenced by the experiences of Thailand, China, and India. In particular, initiatives like 'The China Rural Poverty Alleviation and Development Program (2011–2020)' have demonstrated success and can serve as models for other

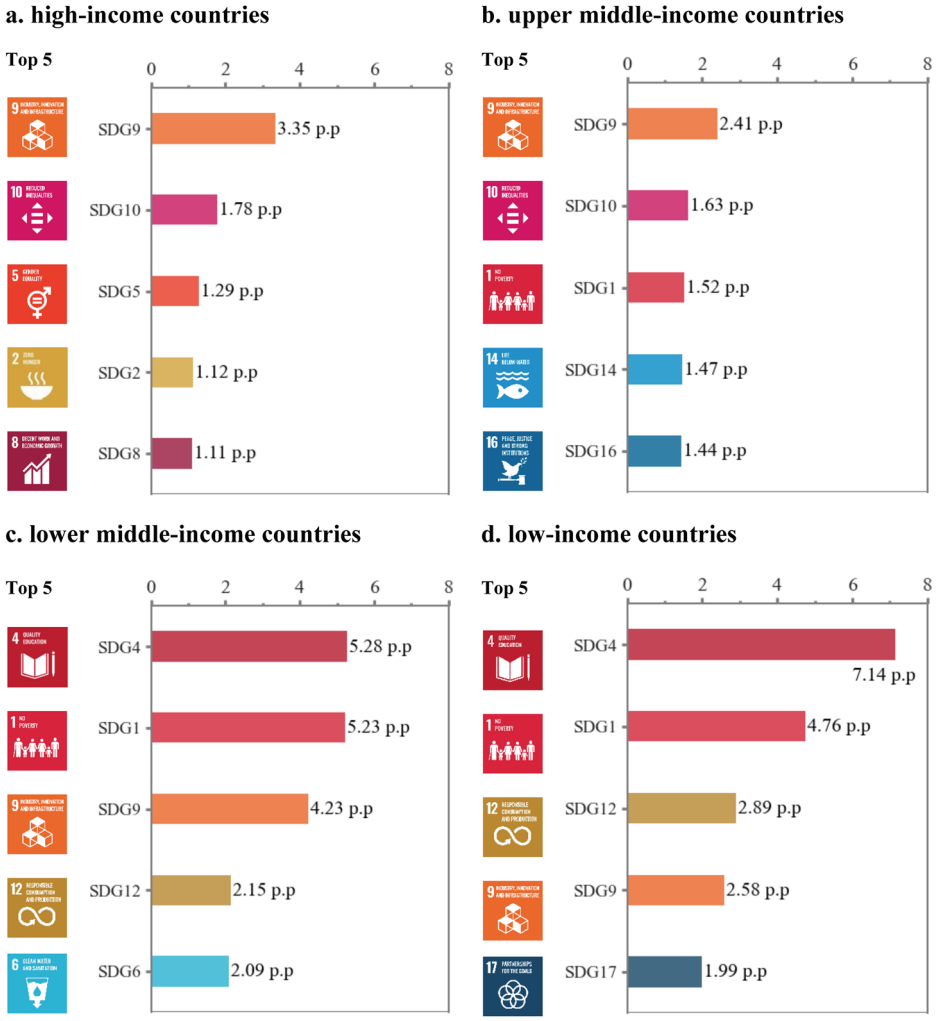

Fig. 7 Top 5 drivers for different income country groups. The top 5 drivers are selected based on their averaged contributions to the increments in scenarios #1 to #3, compared to the baseline scenario #4. **a** High-income countries. **b** Upper middle-income countries. **c** Lower middle-income countries. **d** Low-income countries.

global South countries with poor SDG evenness indexes. Conversely, countries in the global North should prioritize environmental dimensions to achieve a more balanced development trajectory. In particular, initiatives like Germany's designated task force through the German Coal Commission (GCC) and Canada's task force on just transition for Canadian coal power workers, focused on SDG 13 (Climate Actions), can provide valuable insights. These strategies can be adapted and applied to other countries in the global North to ensure environmental goals are pursued without compromising progress on other social and economic SDGs. Our findings emphasize the importance of tailored strategies and collaborative efforts to address the diverse needs and challenges faced by countries at different stages of development. By addressing the specific challenges faced by each nation within the context of their socio-economic and environmental circumstances, policymakers and stakeholders can better support inclusive and resilient pathways towards achieving the SDGs on a global scale.

Our evenness measures of SDGs capture the nature of synergies and trade-offs among economic, social, and environmental dimensions of sustainable development. As discussed in Section 3.3, the accomplishment of the Agenda 2030 requires a balanced and integrated achievement of all SDGs. Therefore, we establish the evenness score as an aggregate framework to analyze and monitor the SDGs, which effectively makes up for existing evaluation approaches of SDG achievements, particularly the mean scores presented in SDG annual reports. Given that the EIS proposed by this paper illustrates the notable policy impact on SDGs, the EIS helps ensure transparency and accountability of governance of sustainable development across international, national and sub-national scales, and shedding fresh insights into the making of development strategies. While this paper admits the critical and influential role of the SDG Index introduced by the *Sustainable Development Report* (Sachs et al. 2021), the EIS remedies its weakness, that is the neglect of the trade-offs and synergies between single SDGs or between targets/indicators within single goals. For example, economic growth in China and India, driven by industrialization and infrastructure development, has historically been associated with increased carbon emissions due to the reliance on fossil fuels. This interaction between economic growth and carbon emissions highlights the challenge of achieving a balance between economic prosperity and environmental sustainability. Addressing trade-offs among SDGs requires a comprehensive and integrated approach, including prioritization of goals and targets, targeted policy interventions, dialogue between stakeholders, and further research on the interlinkages among SDGs (Lusseau and Mancini 2019; Moreno et al. 2023; Nilsson et al. 2016). By identifying leverage points and

intervention opportunities, countries can design policies and programs that address underlying drivers of trade-offs while promoting positive outcomes across multiple goals. Given the year 2030 as the firm deadline for SDGs, there remain only seven years to deliver the unprecedented joint mission of human beings. Accelerating sustainable solutions backed by multidimensional SDG measures are required to solve the biggest challenges in the world, including poverty, gender, climate change, and inequality (United Nations 2022).

The concept of evenness in SDGs is also in line with the vital principle of "leaving no one behind", but focusing on helping the disadvantaged goals and targets instead of population. Overall, as a globally common goal, sustainable development will not be achieved if any single goal or target fails to do so. For nations in the Global North, Climate Actions (SDG 13) constitute a major obstacle, while in the Global South, goals related to fundamental human needs such as No Poverty (SDG 1), Zero Hunger (SDG 2), and Good Health and Well-being (SDG 3) are hindrances. It is noteworthy that recent global events, such as the COVID-19 pandemic and the Russo-Ukrainian Conflict, have potentially exacerbated lagged SDG in affected countries. For example, the Russo-Ukrainian Conflict in 2022 led to an increase in energy and food prices worldwide, which adversely impacted the provision of basic living necessities for disadvantaged populations in low-income countries, which increased the unevenness of SDGs in these countries (Bai et al. 2022). The post-COVID-19 recovery efforts in the Global North may also have detrimental effects on Climate Actions, as these efforts may follow 'dirty recovery' paths that come at the expense of increased CO_2 emissions (Le Billon et al. 2021; Shan et al. 2021). The remarkable dynamic impacts of COVID-19 and the Russo-Ukrainian Conflict on SDG evenness point out the necessity to continuously monitor and probe SDG evenness in the contemporary era full of uncertainties. Nonetheless, these crises provide an opportunity for countries to re-evaluate their policies, strategies, and implementation plans to ensure the attainment of SDGs.

Data availability

All datasets and code used in this paper would be available upon reasonable request, including (a) Data tables required to calculate SDG evenness measures across 193 countries from 2010 to 2019; (b) Python and R code. The database compiled by Sustainable Development Report 2021 (Sachs et al., 2021) is publicly available and can be downloaded from their website (https://www.sdgindex.org/reports/sustainable-development-report-2021/).

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References

Asadikia A, Rajabifard A, Kalantari M (2021) Systematic prioritisation of SDGs: Machine learning approach. World Dev 140:105269. https://doi.org/10.1016/j.worlddev.2020.105269

Bai Y, Costlow L, Ebel A, Laves S, Ueda Y, Volin N, Zamek M, Masters WA (2022) Retail prices of nutritious food rose more in countries with higher COVID-19 case counts. Nat Food 3:325–330. https://doi.org/10.1038/s43016-022-00502-1

Biggeri M, Clark DA, Ferrannini A, Mauro V (2019) Tracking the SDGs in an 'integrated' manner: A proposal for a new index to capture synergies and trade-offs between and within goals. World Dev 122:628–647. https://doi.org/10.1016/j.worlddev.2019.05.022

Dawes JHP (2022) SDG interlinkage networks: Analysis, robustness, sensitivities, and hierarchies. World Dev. 149:105693. https://doi.org/10.1016/j.worlddev.2021.105693

Fu B, Wang S, Zhang J, Hou Z, Li J (2019) Unravelling the complexity in achieving the 17 sustainable-development goals. Natl Sci Rev 6:386–388. https://doi.org/10.1093/nsr/nwz038

Haggett P (1965) Locational analysis in human geography. London: Edward Arnold

Le Billon P, Lujala P, Singh D, Culbert V, Kristoffersen B (2021) Fossil fuels, climate change, and the COVID-19 crisis: pathways for a just and green post-pandemic recovery. Climate Policy. https://doi.org/10.1080/14693062.2021.1965524

Li H, Li A, Zhang B, Zhang T, Zhang X (2008) A fuzzy comprehensive evaluation method of maintenance quality based on improved radar chart. 2008 ISECS International Colloquium on Computing, Communication. Control Manag 1:638–642

Li Y, Su B, Liu Y (2016) Realizing targeted poverty alleviation in China: People's voices, implementation challenges and policy implications. China Agric Econ Rev 8:443–454

Liu Y, Du J, Wang Y, Cui X, Dong J, Hao Y, Xue K, Duan H, Xia A, Hu Y, Dong Z, Wu B, Zhao X, Fu B (2021) Evenness is important in assessing progress towards sustainable development goals. Natl Sci Rev 8:nwaa238. https://doi.org/10.1093/nsr/nwaa238

Lusseau D, Mancini F (2019) Income-based variation in Sustainable Development Goal interaction networks. Nat Sustain. https://doi.org/10.1038/s41893-019-0231-4

Moreno J, Van de Ven D-J, Sampedro J, Gambhir A, Woods J, Gonzalez-Eguino M (2023) Assessing synergies and trade-offs of diverging Paris-compliant mitigation strategies with long-term SDG objectives. Glob Environ Change 78:102624. https://doi.org/10.1016/j.gloenvcha.2022.102624

Myrdal G (1957) Economic Theory and Underdeveloped Regions. University Paperbacks. Methuen, London

Nilsson M, Griggs D, Visbeck M (2016) Policy: Map the interactions between Sustainable Development Goals. Nature 534:320–322. https://doi.org/10.1038/534320a

Pradhan P, Costa L, Rybski D, Lucht W, Kropp JP (2017) A Systematic Study of Sustainable Development Goal (SDG) Interactions. Earths Fut. 5:1169–1179. https://doi.org/10.1002/2017EF000632

Richard Chorley PHR (1967) Socio-economic Models in Geography. Methuen & Co. Ltd., Routledge

Sachs J, Kroll C, Lafortune G, Fuller G, Woelm F (2021) The Decade of Action for the Sustainable Development Goals: Sustainable Development Report 2021. Cambridge University Press. https://doi.org/10.1017/9781009106559

Sachs JD, Schmidt-Traub G, Mazzucato M, Messner D, Nakicenovic N, Rockström J (2019) Six Transformations to achieve the Sustainable Development Goals. Nat Sustain. https://doi.org/10.1038/s41893-019-0352-9

Schmidt-Traub G, Kroll C, Teksoz K, Durand-Delacre D, Sachs JD (2017) National baselines for the Sustainable Development Goals assessed in the SDG Index and Dashboards. Nat Geosci. https://doi.org/10.1038/NGEO2985

Shan Y, Dabo G, Klaus H, Bo Z, J DS, Lichao J, Jianghua L, Zhu L, Neil F, Zhifu M, Jing M, Xiangzheng D, Yuan L, Jintai L, Heike S, Helga W, Joachim SH (2018) City-level climate change mitigation in China. Sci Adv 4:eaaq0390. https://doi.org/10.1126/sciadv.aaq0390

Shan Y, Ou J, Wang D, Zeng Z, Zhang S, Guan D, Hubacek K (2021) Impacts of COVID-19 and fiscal stimuli on global emissions and the Paris Agreement. Nat Clim Change 11:200–206. https://doi.org/10.1038/s41558-020-00977-5

Shen Y, Shi X, Zhao Z, Sun Y, Shan Y (2023) Measuring the low-carbon energy transition in Chinese cities. iScience 26:105803. https://doi.org/10.1016/j.isci.2022.105803

Smith B, Wilson JB (1996) A Consumer's Guide to Evenness Indices. Oikos 76:70–82. https://doi.org/10.2307/3545749

Tuomisto H (2012) An updated consumer's guide to evenness and related indices. Oikos 121:1203–1218. https://doi.org/10.1111/j.1600-0706.2011.19897.x

United Nations (2015) Transforming Our World: The 2030 Agenda for Sustainable Development. https://sdgs.un.org/2030agenda

United Nations (2020) SDG indicators, United Nations Global SDG Database. https://unstats.un.org/sdgs/indicators/database/

United Nations Development Programme (2020) Human Development Report 2020. https://hdr.undp.org/content/human-development-report-2020

United Nations (2022) The Decade of Action. https://www.un.org/sustainabledevelopment/decade-of-action/

World Banks (2020) SDG Atlas 2020. https://databank.worldbank.org/source/sustainable-development-goals-(sdgs)

Wu X, Fu B, Wang S, Song S, Li Y, Xu Z, Wei Y, Liu J (2022) Decoupling of SDGs followed by re-coupling as sustainable development progresses. Nat Sustain 5:452–459. https://doi.org/10.1038/s41893-022-00868-x

Xiao H, Xu Z, Ren J, Zhou Y, Lin R, Bao S, Zhang L, Lu S, Lee CKM, Liu J (2022) Navigating Chinese cities to achieve sustainable development goals by 2030. Innovation 3:100288. https://doi.org/10.1016/j.xinn.2022.100288

Xu Z, Chau SN, Chen X, Zhang J, Li Y, Dietz T, Wang J, Winkler JA, Fan F, Huang B, Li S, Wu S, Herzberger A, Tang Y, Hong D, Li Y, Liu J (2020) Assessing progress towards sustainable development over space and time. Nature 577:74–78. https://doi.org/10.1038/s41586-019-1846-3

Zhang H, Wu K, Qiu Y, Chan G, Wang S, Zhou D, Ren X (2020) Solar photovoltaic interventions have reduced rural poverty in China. Nat Commun 11:1969. https://doi.org/10.1038/s41467-020-15826-4

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Author contributions

Yunting Qi: Conceptualization; Writing – Original Draft; Writing – Review & Editing; Funding Acquisition; Supervision. Xunpeng Shi: Conceptualization; Formal analysis; Writing – Review & Editing. Yanan Chen: Software; Investigation; Formal analysis; Data Curation; Writing – Original Draft; Visualization. Yifan Shen: Conceptualization; Methodology; Investigation; Formal analysis; Data Curation; Writing – Original Draft; Writing – Review & Editing; Visualization; Funding Acquisition; Supervision.

Competing interests

The authors declare no competing interests.

Ethical approval

Ethical approval was not required as the study did not involve human participants.

Informed consent

Informed consent was not applicable as the study did not involve human participants and the raw data is publicly available.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1057/s41599-024-03572-7.

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