



# A Method of Evaluating Safe Operating Space: Focus on Geographic Regions, Income Levels and Developing Pathway

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## Abstract

Safe and Just Space (SJS) is a framework for determining the range where the use of natural resources within the Earth's carrying capacity can maintain human well-being. However, there has been no systematic monitoring and evaluation of their sustainability across time and space. Here we developed and applied a model and a sustainable development human safe operation space (SDHSOS) index to assess the sustainability capacity and development path of 149 countries from 2000 to 2018. The results demonstrate that (1) The overall sustainable development capacity of all countries is at the middle or lower level and that it has increased over time. (2) The sustainability of natural and socio-economic dimensions and their degree of change show obvious geographic differences and income differences. (3) The national development path divided by income is characterized by a decline in natural environment dimensions and an increase in socio-economic dimensions, which mainly reflects a traditional development path model that promotes social welfare at the expense of the natural environment. This study suggests that nations can accurately identify development characteristics, expand their comparative advantages is the key to improving sustainable development capabilities.

**Keywords** Safe and just space · Carrying capacity · Sustainable development · Development path · Sustainable development capabilities

## Introduction

This planet's relatively stable environmental state has endured for 11,700 years, a period defined as the "Holocene" (Steffen et al. 2015, 2007; Syvitski et al. 2020). Unfortunately, since the Industrial Revolution, this stable state has been threatened, and the scale and intensity of key planetary system processes of human activities have gradually deviated from the Holocene stable state (Steffen et al.

2005). The rapid increase in the intensity of human activities at an unprecedented speed has raised the growing alarm about the stability of the earth system (Rockström et al. 2009a; Steffen et al. 2015). Further pressure placed upon the earth system may undermine the stability of its key biophysical systems, inevitably harming human well-being and risking disasters, perhaps even leading to sudden or irreversible environmental changes (Almond et al. 2020; Rockström et al. 2009a, b; Lenton et al. 2008; 2019).

In 2015, the Sustainable Development Goals (SDGs) became the baton of the Millennium Development Goals, for guiding global sustainable development from 2015 to 2030. The SDGs consist of 17 goals and 169 targets and should provide an aspirational agenda for society (Allen et al. 2016a). The aim is to solve social, economic, and environmental development issues in an integrated manner, and embark upon a path of sustainable development in a globalized society.

To achieve these ambitious SDGs, the UN Statistical Commission (UN Statistics Commission) has proposed a hybrid, which is a combination of a more comprehensive approach (covering human and environmental issues) and a more isolated (only environmental) approach. There are 232 global indicators to measure their achievement, but many

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observers suggest these indicators lack comprehensiveness (TWI2050 - The World in 2050 2020). In parallel, several relatively mature frameworks and indicator systems have been formulated, such as the planetary boundary framework (Rockström et al. 2009a, b; Steffen et al. 2015), the Safe and Just Space (O'Neill et al. 2018; Raworth. 2017), the environmental sustainability index (Babcicky 2013; Whitford and Wong 2009), and the ecosystem health index (Xu et al. 2005), and so on. There are also many comprehensive indexes based on different perspectives and purposes, such as the Living Planet Index (WWF 2020; Almond et al. 2020), Ocean Health Index (Halpern et al. 2012), Human Development Index (Dervis and Klugman 2011), and Sustainable Development Goal Index (Sachs et al. 2018), and so forth. However, most approaches to comprehensively evaluate sustainable development focus on socio-economic aspects, with fewer focusing on environmental sustainability. Conversely, an environmental sustainability evaluation index (Esty et al. 2005; Hsu et al. 2016) tends to focus on more environmental systems and less on social sustainability. Raworth (2017) proposed a 'Safe and Just Space' (SJS) framework that combines planetary boundaries with SDGs, to form a doughnut-shaped space encompassing the sustainable development of humanity. This can satisfy the basic well-being of society at large without crossing the earth's boundaries so that the planet can be maintained in a safe state in the Anthropocene. This SJS framework consists of 11 social goals and 7 biophysical indicators. However, the lack of an effective comprehensive evaluation system makes it impossible to make intuitive comparisons between different countries. Consequently, it is difficult to monitor and measure the scope of the human operational space for sustainable development.

To achieve the SDGs agreed upon in 2015 and implement the commitment of the Paris Agreement, developed and developing countries alike will need to transform all aspects of society. These transformations will also require data calculation methods and monitoring frameworks that link planetary boundaries to SDGs objectives (Häyhä et al. 2016; Steffen et al. 2015). We also need to design innovative solutions and cultivate integrated approaches to achieve synergistic sustainability of natural and social health, taking into account the trade-offs and synergies between various goals and indicators (Nilsson et al. 2016; Schmidt-Traub et al. 2017; Fanning et al. 2022).

To guide research that can better inform policy and practice, here we systematically synthesized knowledge gaps from recent assessments of planetary boundaries and SDGs, established an evaluation system, and explored the temporal and spatial dynamics of the sustainable development of a human-environment system. Our objectives were to assist countries in measuring their SDG baselines and to gauge their future progress.

To do this, we explore differences in countries' performance, using a proposed sustainable development human safe operation space (SDHSOS) index to indicate the Country's level sustainable development capabilities from 2000 to 2018, and discuss differences in income, geographic location, and development paths.

## Material and Methods

### Definition and Analytic Framework

The sustainable development human safe operation space (SDHSOS) index is intended to convey which drastic anthropogenic activities and environmental changes ought to be avoided to not exceed the ecological thresholds of the earth system, thereby ensuring human life, when assessing each country's sustainable development capabilities.

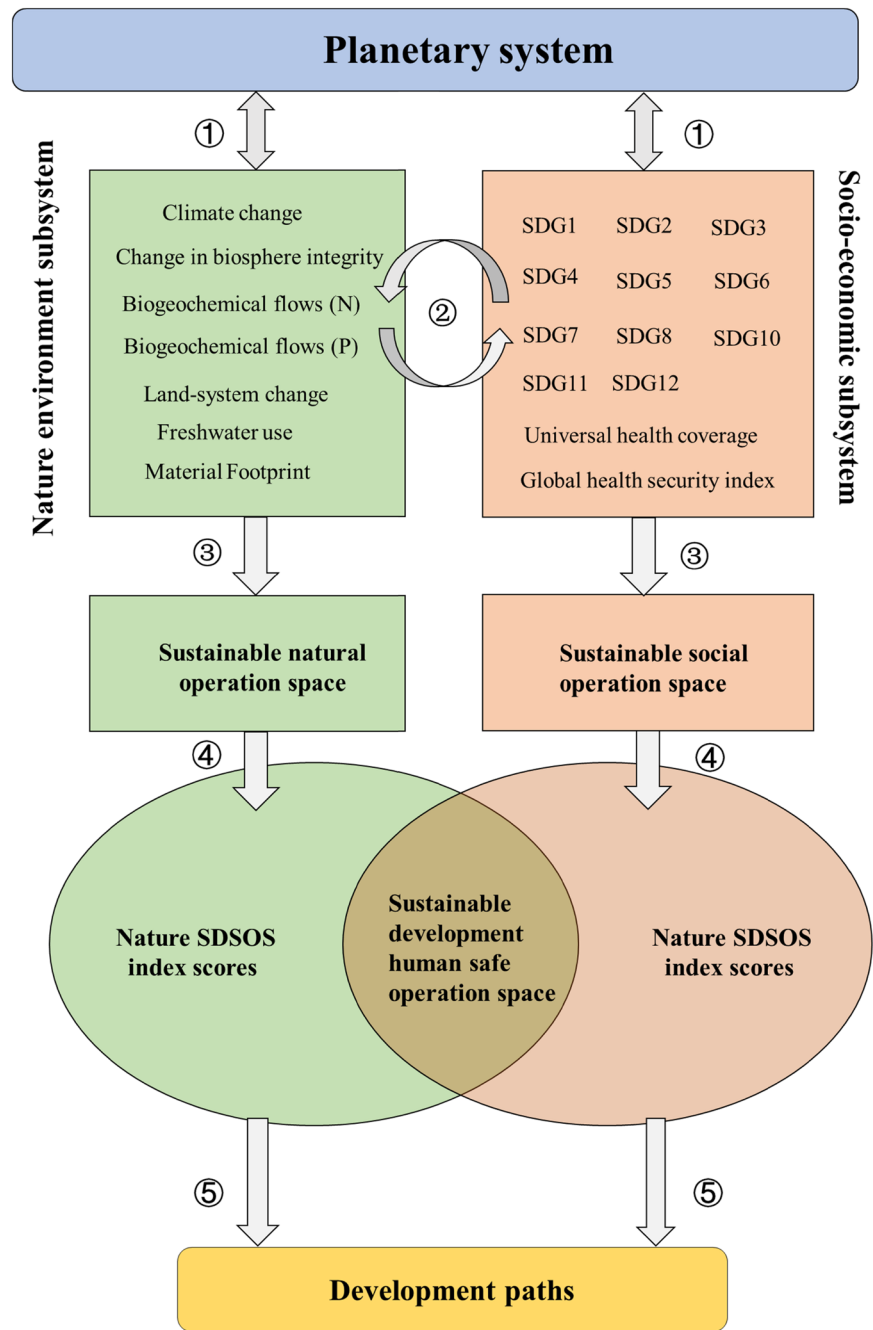
For Fig. 1, we illustrate the analytical framework is composed of two dimensions: the natural environment and a socio-economic, which is a variation of a Safe and Just Space (SJS) elaborated by O'Neil et al. (2018) in 2018. The boundaries of the socio-economic dimension are based on the 2012 UN SDGs, and the natural boundaries are based on the nine planetary boundaries proposed by Rockström et al. (2009a, b) in 2009. These natural environments and socio-economic dimensions have feedbacks that can operate in both directions. The natural environment system is the foundation for providing broad social well-being; accordingly, the socio-economic dimension depends on the natural environment and the resources provided by its complete and healthy ecosystem services (O'Neill et al. 2018).

Society may slow the planetary boundaries' transgression, thereby improving the relationship between humans and the environment. The purpose of this framework is not to assess the absolute value of sustainable development, but rather to assess the capacity for sustainable development. Based on the SDGs Index (Sachs et al. 2018), we extend the SJS framework, combining the planetary boundaries and SDG indexes, to provide indications of current possibilities of future development paths. To do this, we ensure that selected indicators meet established criteria, such as measurability, methodological soundness, target relevancy, comparability, and ease of communication and access (Horan 2020; Schmidt-Traub et al. 2017).

### Data and Indicator Sources

To ensure the reliability of the results, the indicators are selected based on the relevant results of authoritative research and the indicators with the most empirical data publicly available. Meanwhile, the countries selected for inclusion were those with a population of more than 1

**Fig. 1** SDHSOS characteristics and analytic framework. The blue outer box represents the earth system, and the green and orange inner boxes represent the natural environment subsystem and the socio-economic subsystem, respectively. The green and orange circles represent sustainable natural operation space and sustainable social operation space respectively, and their overlapping area corresponds to the sustainable development human safe operation space (SDHSOS). Arrow ① denotes the interaction between the subsystems and the earth system, while ② indicated the interaction between subsystems. Arrow ③ indicates the safe operating space of the natural and social systems, and ④ indicators of natural and social systems that constitute the natural sustainable development human safety operation index, and the social sustainable development human safety operation space index. Arrow ⑤ indicates that the development path is composed of natural and social SDSOS index scores



million. Based on the social threshold of SJS, and following the SDGs, we added 7 indicators to the socio-economic subsystem to ensure the integrity and integrity of the indicators.

The 13 SDHSOS indicators of the socio-economic dimension were mainly collected from the SDSNs Sustainable Development Report for 2020 (or that most recently available). Due to the limitation of the availability and validity of the data, this paper selects 14 socio-economic dimension indicators. Data came from the World Bank’s Open Data initiative (<https://data.worldbank.org.cn/>), the World Inequality

Database (<https://wid.world/>); the Institute for Health Metric and Evaluation (IHME) (<http://vizhub.healthdata.org/sdg/>); the FAOSTAT database (<http://www.fao.org/faolex/zh/>), the Inter-Parliamentary Union (<https://www.ipu.org/>); UN-HABITAT, retrieved from the United Nation’s Millennium Development Goals database (<http://mdgs.un.org/>); the UNESCO Institute for Statistics (<http://uis.unesco.org/>); the Global Footprint Network (<https://www.footprintnetwork.org/>); and UNAIDS (<https://www.unaids.org/en/topic/UHC>).

The SDHSOS indicator for the natural environment dimension was collected from the planetary boundary

framework (according to the precautionary principle). The latter defines the human interference of the earth's biophysical limitations, proposes boundaries for nine interaction processes, to maintain the Holocene environmental conditions similar to that of human beings. Due to the limitation of the availability and validity of the data, this paper selects 6 natural environment dimension indicators and adds material footprint. At the same time, pertinent data were collected from the FAOSTAT database (<http://www.fao.org/faolex/zh/>), the Water Footprint Network (Mekonnen and Hoekstra 2017), the global map of the Biodiversity Intactness Index (Newbold et al. 2016), World Bank open data (<https://data.worldbank.org.cn/>), Our Planet's CO<sub>2</sub> (<https://www.co2.earth/>), the material flows database (<http://www.materialflows.net/>), and other reputable literature sources (Liu et al. 2020a). See details in supplementary material, Table A.1 "Nature and social thresholds" for the SDHSOS indicators.

### Downscaling Planetary Boundaries and Establishing Social Thresholds

Based on the planetary boundaries framework constructed by Steffen et al. (2015) and Rockström et al. (2009a, b), we narrowed the five boundaries—climate change, biodiversity, land system change, freshwater use, biogeochemical flow, and material footprint—on a per capita basis (O'Neill et al. 2018; Springmann et al. 2018; Bringezu 2015), and compared them with each other.

The control variable threshold of atmospheric CO<sub>2</sub> draws on the method of O'Neil et al. (2018) and sets 1.5 °C and 2 °C targets according to the climate warming target ceilings of the Paris Agreement. As a measure of biodiversity, it is difficult to convert species extinction rates into meaningful countries and borders, so we selected the Biodiversity Integrity Index (BII) as the control variable (Newbold et al. 2016; O'Neill et al. 2018; Rockström et al. 2009a, b). The maintenance of ecosystem functions depends on the functional diversity, range, and abundance of functional traits of existing species (Newbold et al. 2016). Therefore, BII (defined as the abundance of undisturbed habitats relative to the average abundance of originally existing species in a wide range of species) is recommended as the best measure (Newbold et al. 2016). Material footprint also known as raw material consumption (RMC), measures the amount of used material extraction (minerals, fossil fuels, and biomass) associated with the final demand for goods and services (Wiedmann et al. 2015; O'Neil et al. 2018; Fanning et al. 2022). Following O'Neil et al. (2018) and Fanning et al. (2022), we incorporate it into our analysis, as material use is an important indicator of environmental pressures imposed by socio-economic activities and an important bridge between

society and the environment. We adopt analysis by Bringezu (2015), which uses higher population growth projections, suggests a per capita target value of 5 t for the year 2050, with a range of 3–6 t.

To evaluate the sustainable development capacity of society, we adopted aspects of the SJS framework constructed by Raworth (2017) and Dearing et al. (2014) and the United Nations Sustainable Development Goals framework (Sachs et al. 2018). Within our framework, these include 11 indicators of needs' satisfaction (i.e., nutrition, health, income, access to energy, education, social support, equality, quality of democracy, and employment) and two previously unused indicators of public health safety (i.e., universal health coverage and the ability to respond to public health events). Each indicator is given equal weight, and the threshold setting corresponds to what is needed to attain the minimum level of social well-being (O'Neill et al. 2018; Raworth 2017). The SDG3-good health and well-being control variable was selected as health-related SDGs to gauge health-related sustainable development (Allen et al. 2016b). Using this indicator, progress made by countries and regions in terms of 41 health-related SDG indicators can be explored, such as road injury mortality, the prevalence of intimate partner violence against women, maternal mortality, and the incidence of new HIV infections.

The sudden emergence of COVID-19 was designated a global public health emergency in 2020, obliterating most of the sustainable development achievements of countries around the world. The number of hungry people is twice as high as before the pandemic and the world economy has shrunk by more than 4% (International Monetary Fund 2020; Pallanch 2020). This is an unprecedented decline, one not seen for several generations. This requires us to strengthen and improve the public health safety governance system, increase the speed of emergency public health emergency response, establish global and regional epidemic prevention materials reserve centers, and build a "firewall" for the global public health system. Therefore, it is necessary to integrate universal health coverage and the ability to respond to public health incidents into the sustainability framework, to ensure that everyone has access to the health services they need without having to experience financial difficulties when paying for them.

### Normalization of Indicator Values

To compare the degree of transgression between boundaries, we use the following formula to define the normalized control variables in the range 0–100 (Sachs et al. 2018; Xu et al. 2020; Lade et al. 2019). Lower-case symbols hereafter denote normalized control variables, and upper-case symbols denote un-normalized control variables.

a. **Natural control variables** (Lade et al. 2019):

$$n = \frac{N - X_o}{X_{PB} - X_o} \tag{1}$$

where

$$\begin{cases} \frac{X_{PB}-n}{X_{PB}} \times 100, X_{PB} - n > 0 \\ \frac{X_{PB}-n}{X_w - X_{PB}} \times 100, X_{PB} - n \leq 0 \text{ and } X_w - n > 0 \\ \frac{X_{PB}-n}{X_w} \times 0, X_{PB} - n \leq 0 \text{ and } X_w - n \leq 0 \end{cases} \tag{2}$$

where  $n$  is the natural normalized value above 1 that is possible, indicating that the safety threshold is exceeded;  $N$  is the planetary boundary unnormalized control variable;  $X_o$  is the pre-industrial value;  $X_{PB}$  is the safe boundary-value;  $X_w$  is the high-risk boundary-value. For an indicator with two control variables, the normalized values are averaged. To define the boundary value, we use the safety threshold set by the planetary boundary framework method (Rockström et al. 2009a, b; Steffen et al. 2015).

b. **Social control variables** (Xu et al. 2020):

$$s = \frac{S - X_{min}}{X_{max} - X_{min}} \tag{3}$$

where

$$\begin{cases} 100, & \frac{X_{SE}-S}{X_{SE}} > 0 \\ 100 + \frac{X_{SE}-S}{X_{SE}}, & X_{SE} - S \leq 0 \end{cases} \tag{4}$$

where  $s$  is the social normalized value;  $s$  is the current value of the social boundary;  $X_{min}$  is the minimum value, this set to 0;  $X_{max}$  is the maximum value, this set to 0;  $X_{SE}$  is the threshold is set to 0.95. For an indicator with two control variables, the normalized value is averaged.

**2.5 Calculating the Sustainable Development Human Safe Operation Space (SDHSOS) Index**

Within the framework of sustainable development human safe operation space, any crossing of boundaries can be catastrophic, and all goals are considered irreplaceable. While previous studies using arithmetic means to calculate scores have given us insights into the efficiency and achievement of states in terms of biophysical processes and social outcomes (Fu et al. 2019; Nilsson et al. 2016; Pradhan et al. 2017; O’Neil et al. 2018). But it does not fit the logic of planetary boundaries and sustainability frameworks, as it allows good performance to compensate for poor performance in other metrics (Pradhan 2019; Hickel 2019; Fanning et al. 2022).

To reduce substitution and compensatory effects between indicators, reduce uncertainty in scoring, Liu et al. (2020b) introduced the evenness of biology into the SDG indicators’ calculation. Following Liu et al. (2020b), we optimized the uniformity measurement method to quantify the uniformity score of Spatio-temporal SDHSOS. We chose the standard deviation—it is most commonly used in probability statistics to objectively quantify the dispersion of statistical distribution—in statistics as the measurement standard. Because the indicator score range is [0, 100] (from the worst to best performance), the standard deviation range is also [0, 100]. That is, the evenness score (the natural/social standard deviation) is 100.

Nevertheless, we also believe that the capacity for the sustainable development of society and nature are equally important on the planet, so we averaged their respective scores when calculating the total score,  $W = 1/2$ .

For the SDHSOS composed of natural and socio-economic dimensions, standardized indicators are aggregated into a unique score with the same weighted arithmetic mean score and evenness score.

$$SDHSOS = \frac{1}{w} S_{nature} + \frac{1}{1-w} S_{social} \tag{5}$$

where  $S_{nature}$  is the natural score, and  $S_{social}$  is the social score.

$$S_{nature} = \frac{1}{z} \left( \sum_{i=1}^n AM_{nature} \cdot ES_{nature} \right) \tag{6}$$

where  $AM_{nature}$  is the arithmetic mean score of the natural environment dimension,  $ES_{nature}$  is the evenness score of the natural environment dimension, and  $z$  is the number of indicators in the component.

$$S_{social} = \frac{1}{p} \left( \sum_{i=1}^p AM_{social} \cdot ES_{social} \right) \tag{7}$$

where  $AM_{social}$  is the arithmetic mean score of the socio-economic dimension,  $ES_{social}$  is the evenness score of the socio-economic dimension, and  $p$  is the number of indicators in the component.

**Sensitivity Analysis of the SDHSOS Index**

To explore the uncertainty introduced by the number of SDG indicators, we ran uncertainty analyses. We adopted a widely used sensitivity index to measure the degree of SDHSOS sensitivity (Liu and Ashton 1998; Xu et al. 2020):

$$P_x = (\Delta X/X)/(\Delta P/P) \tag{8}$$

where  $X$  is the SDHSOS score under the original condition, and  $\Delta X$  is the difference in the SDHSOS score between the original and modified condition. The  $P$  is the value of the SDHSOS index under the original condition, and  $\Delta P$  is the difference between the SDHSOS index data value under the original and modified condition.  $P_x$  refers to the change in the SDHSOS score due to the change in the data value of the SDHSOS indicator.

The sample size  $n$  for each presented figure is 20 indicators. The sensitivity index  $P_x$  of SDHSOS scores is depicted for cases when each SDHSOS indicator's original data value had decreased by 10% or increased by 10%, for four example countries (United States of America, China, Angola, and Mali) at four income levels (high, middle-high, middle-low, and low) based on the country-specific average SDHSOS scores in 2000, 2005, 2010, and 2018. We found that, generally, the SDHSOS framework is only marginally sensitive to changes in the data values (see details in Supplementary Material, Supplementary Fig. A.1 “Sensitivity of SDG scores to changes in each indicator”).

## Results and Discussion

### Assessment of the Relative Developing Status of 149 Countries in 2000–2018

We use annual time-series data relevant to the 18 benchmarks of SDHSOS from 2000 to 2018 at the national level and calculated an SDHSOS index score (0–100) per country. We standardize and quantitatively, transparently, and comprehensively evaluate the overall performance of 149 countries in terms of their SDHSOS. The latter concept synthesizes 11 SDGs indicators and 6 indicators for planetary boundary into an overall assessment of SDHSOS performance and ranks the countries according to their starting points on the 18 benchmarks of SDHSOS (see details in supplementary material, Supplementary Table A.1. “SDHSOS Index for 2000, 2005, 2010, 2015, and 2018 scores and rankings”). Going further, we determined the Spatio-temporal changes in SDHSOS index scores across the 149 countries at the national level for the 2000–2018 period. We compared the SDHSOS index scores and development paths of different income countries and regions over the same period during the 2000–2018 period. Finally, the annual SDHSOS dashboard (see details in Supplementary Table A.2. “Nature and social thresholds”) presents changes to the SDHSOS which can be useful for determining the implementation priorities for each country. By comparing scores for the individual SDHSOS, we then examined the range of human operating spaces toward achieving

unique targets. On that basis, we can explain the development pathways at both national and regional levels and the current challenges facing different countries and regions.

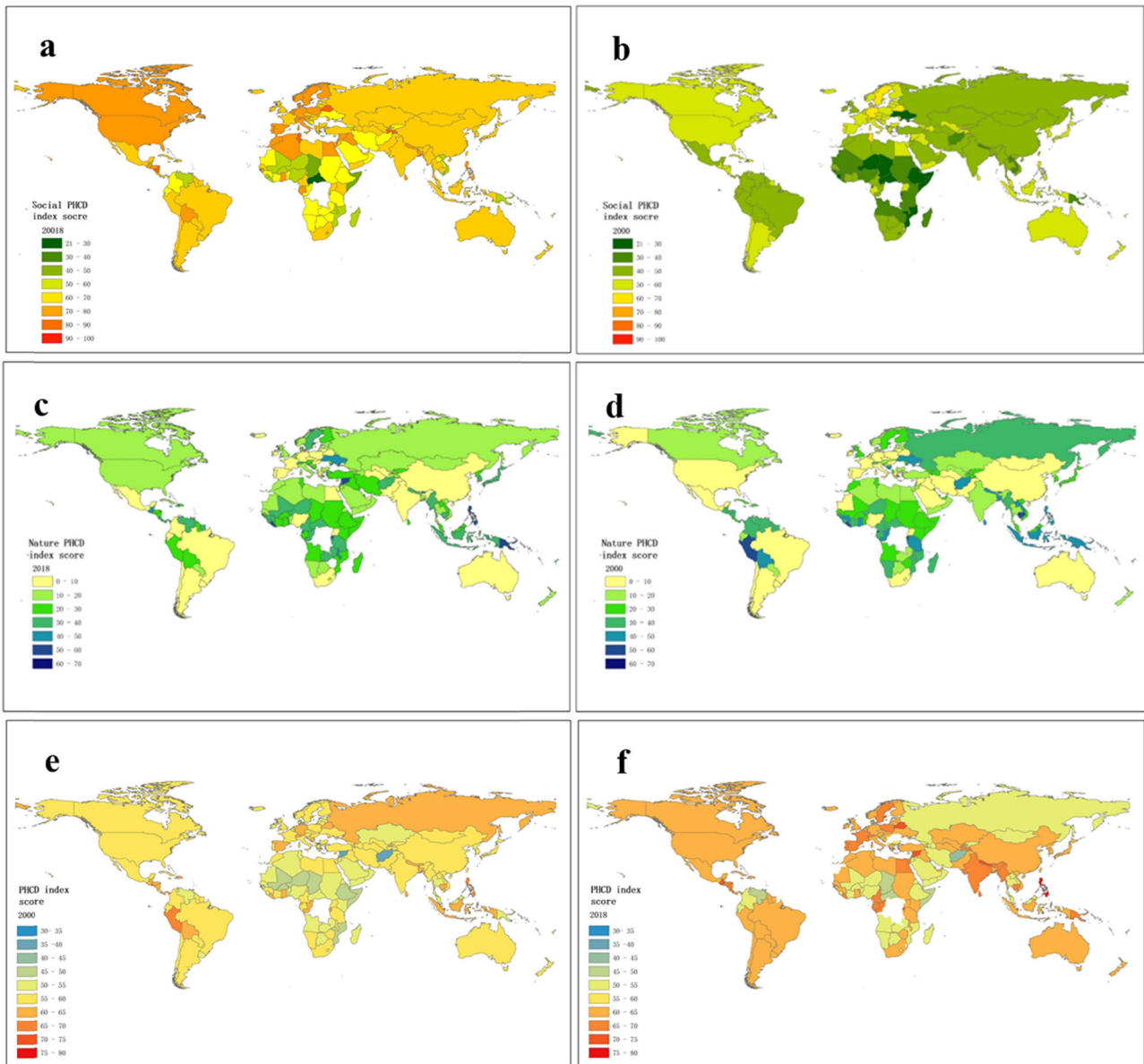
The results show that the SDHSOS index score at the national level ranged from 33.42 to 73.05 in 2000, having a mean value of 60.24. Over time, however, the average SDHSOS index score of each country increased by 2.89%, attaining a mean value of 61.98 in 2018. The evenness index score at the nation level ranged from 65.12 to 90.48 with a mean value of 68.38 in 2000; it increased by 2.07% over time, to reach a mean value of 69.14 in 2018 (Fig. 2). Supplementary material Table A.1 lists the SDHSOS index ranking for a selection of countries. The Philippines, Dominican Republic, Nicaragua, The Democratic Republic of the Congo, Rwanda, Trinidad and Tobago, Timor-Leste, Indonesia, Belarus, and Nepal emerged as the top 10 countries.

Yet the performance of the top 10 countries in terms of their natural environment dimension is quite different. Except for Belarus, the rest of the natural scores are above the arithmetic average. Five of them entered the top 10%, having scores that ranged from 11.38 to 93.997. At the same time, their social scores are relatively high (i.e., in the top 25%), except for the Democratic Republic of Congo (whose natural score is in the top 10%).

In the rankings, Afghanistan, Niger, Ethiopia, Somalia, Chad, Lebanon, Central African Republic, Mozambique, Mali, and Madagascar have identified as the bottom 10 countries. When classified according to their national economic levels, there is only one low-middle-income country with the rest being low-income countries. In their geographical location classification, except for Afghanistan and Lebanon in Asia, all the other countries are in Africa. The reason for this result is that the natural score is at a medium level, but the social score is extremely low (in the bottom 10%), which severely constrains the space available for sustainable human operations and safety, and reduces the overall capacity for sustainable development. Compared with other high-ranking countries, these comprising the bottom 10 face major challenges in implementing sustainable development.

### Implications of Different Geographic Regions

The SDHSOS index differs relatively little between continents (mean value: 59.68–63.33), and the natural and socio-economic dimensional scores and their degree of change display clear geographic differences (Table 1). The two-dimensional scores and rate of changes in North America and Europe have inverse characteristics, that is high social scores and low natural scores, along with a high natural score growth rate of changes (Europe has a low



**Fig. 2** Spatial patterns of the SDHSOS index score, nature index score, and social index score in 2000 and 2018. **a, b** Social SDHSOS index scores for all countries. **c, d** Nature SDHSOS index score for all

countries. **e, f** SDHSOS index scores for all countries; these were calculated as the average value of nature and social SDHSOS index scores in each country from 2000 to 2018

**Table 1** Two-dimensional scores and change characteristics of the six geographic regions

Geographic regions	Natural score	Social score	Natural score change rate	Social score change rate
Africa	No.1 High	No. 6 Low	No. 5 Negative low growth rate	No. 1 High
Asia	No. 4 Medium	No. 4 Medium	No. 4 Negative low growth rate	No. 2 High
Latin America and the Caribbean	No. 2 High	No. 3 Medium	No. 6 Negative high growth rate	No. 3 Medium
Oceania	No. 3 Medium	No. 5 Low	No. 2 Positive high growth rate	No. 4 Medium
North America	No. 6 Low	No. 1 High	No. 1 Positive high growth rate	No. 6 Low
Europe	No. 5 Low	No. 2 High	No. 3 Positive low growth rate	No. 5 Low

natural score growth rate of changes), and low social score growth rate of changes.

For Africa, its characteristics consist of “one low, two highs, and one negative”; that is, it is currently in a state distinguished by high natural scores and low social scores, though the natural scores are beginning to decline, while the social scores are rapidly increasing.

Asia is a typical middle group, with the characteristics of “two mediums, one negative and one high”. The natural and social two-dimensional scores are in the fourth middle level, but the change rates of the two are opposite, that is: the natural change rate shows a low level of negative growth, and the social change rate shows a rapid positive growth state.

The Latin America and the Caribbean and Asian groups are both in the middle group, and there are still slight differences. It has the characteristics of “one high, two middle, one negative”, the natural score is at a high level, and the social score is at a medium level. Similar to the Asian group, the natural score change rate shows a rapid negative growth state, and the social score change rate shows a medium positive growth level.

North America and Europe have different characteristics from the other four countries, with the characteristics of “two lows and two highs”. The natural score is in the bottom two, but the social score is far ahead. At the same time, the natural score showed rapid positive growth, and the social score increased slowly.

For Oceania, its characteristics are “two middles, one low, and one high”: medium natural and social scores alongside a high natural score growth rate and low social score growth rate of change.

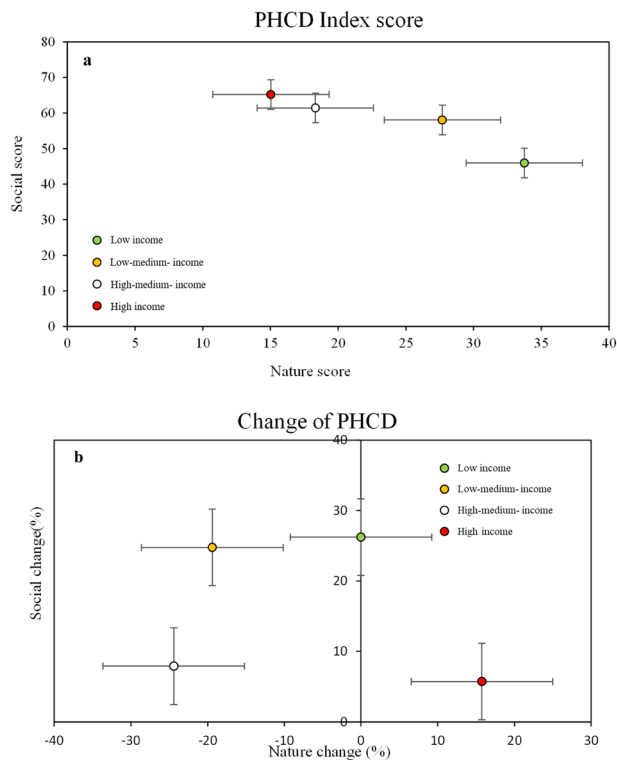
The SDHSOS index shows that different regions have different sustainable development capabilities. North America and Europe have a high capacity for socially sustainable development, a goal on the cusp of being achieved. Although their historical natural losses are large and their natural scores are low, their positive growth rates are very high and their sustainability is gradually strengthening. The reason for this feature is mainly the industrial transfer caused by the social division of labor. In the 1950s, the United States made major adjustments to their domestic industrial structure with the aid of the third industrial revolution, transferring traditional industries, such as steel and textiles, to Europe, Japan, and other places abroad. These countries are now mainly dedicated to integrated circuits, precision machinery, and other forms of capital, along with fostering progress in technology-intensive industries (He and Xin 2015). It has also altered the development path and stage of its development, by consuming less domestic natural resources in exchange for a large amount of economic growth, while improving the capacity for

socially sustainable development, which also enhances that of natural sustainable development, thereby expanding its sustainable development human safe operation space.

Africa is a natural and sustainable space for human safety and has a great capacity for sustainable development. Although the sustainable development capacity of society there has increased rapidly with rising economic income, a high-productivity production system (especially in the manufacturing sector) has yet to be implemented. On the contrary, the export of unprocessed agricultural commodities/minerals with lower productivity appears prevalent in Africa (Cramer et al. 2020). By consuming substantial natural resources in exchange for sustainable economic and social development capabilities, the SDHSOS for natural sustainable development has begun to shrink, the SDSO index has grown slowly, and the lowest level minimum requirements of human well-being is are still far off.

### Implications of Different Income Levels

The degree of change in the natural and social SDHSOS of different income groups has obvious characteristics of income disparity (Fig. 3). From the point of view of score



**Fig. 3** SDHSOS score and change characteristics under different country income levels. **a** SDHSOS index score (the abscissa is the natural score, the ordinate is the social score). **b** SDHSOS index changes score (the abscissa is the natural score change, the ordinate is the social score change)



composition (Fig. 3a), natural scores and income levels show opposite trends; that is, low-income groups score high for nature (the average values are 35.76%), and high-income groups score low for nature (the average values are 13.06%). However, from the perspective of social SDHSOS scores, low-income societies have low scores (the average values are 46.72%) and high-income societies have high scores (the average values are 65.53%). To better achieve the goals of sustainable development, low-income countries urgently need to increase the space for sustainable social operations, and high-income countries need to increase their respective sustainable space for natural operations.

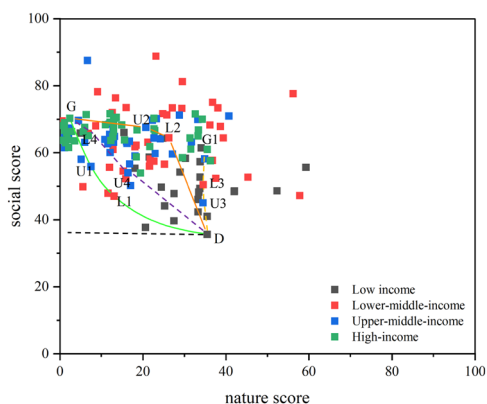
In terms of the rate of changes (Fig. 3b), there is a relatively large difference between the natural and social SDHSOS indexes. The high-income and low-income countries for the natural SDHSOS index feature positive growth (the average values are 15.77 and 0.01%), while the low-middle-income, and upper-middle-income countries all have negative growth, whose declines vary in magnitude (the average values are  $-19.37$  and  $-24.39\%$ , respectively). The social SDHSOS index also has a positive growth in the four income groups, but similarly, their growth rate differs. In this respect, low-income countries have increased the greatest, followed by low- and middle-income and upper-middle-income countries, with the increase in high-income countries being the least (the average values are 26.23, 24.77, 7.90% and 5.71, respectively).

Middle-income countries have the characteristics of “two middle, one negative, and one high” scores. The main reason is that they are in the midst of a rapid development stage with an increasing demand for human well-being, usually at the expense of natural sustainable development capabilities. Although this will contribute greatly to progress towards the sustainable development of society, the cost of resource overdraft will be incurred. However, blindly consuming natural resources, even at the cost of exceeding the threshold, will reduce the scope of SDHSOS, cause steady-state transformation of the planetary system, and endanger the sustainable development of the planet. This development path can be confirmed by the environmental Kuznets curve hypothesis, which posits an inverted U-shaped relationship between economic growth and environmental pollution (Isik et al. 2018; 2021). Piao and Tsai (Pao and Tsai 2011) used panel co-integration technology to analyze the relationship between carbon dioxide emissions and GDP, energy consumption, and Fixed asset investment (FAI) in the BRIC countries, finding evidence in those four countries that support the ECK hypothesis.

The high-income group has the characteristics of “one low, one high, and two positives” scores. Typically, these countries have already passed through a stage of rapid development, and are currently in a post-development stage

of a stable state, paying more attention to balanced and high-quality development. While improving the sustainable development capacity of its society, it also focuses on improving natural sustainability. It is an effective way for humans and nature to live in harmony, realize humanity’s common future, and fully attain the SDGs. To mitigate global warming and keep it under  $1.5^{\circ}\text{C}$ , the major economies responsible for 65% of global carbon emissions have begun to aim for and implement a “carbon neutrality” target. For example, high-income economies, such as the United Kingdom, China, Germany, and the European Union, have taken the lead in responding to this “carbon neutrality” initiative. This will not only help achieve the goals of the Paris Climate Agreement and actively respond to climate change, but it will also promote the global economy’s shift into a more sustainable, inclusive, and resilient stage. Therefore, all efforts must be made to transform the development mode, improve the quality of development, reduce the pressure on the natural environment, and carve out a new trajectory for the sustainable development of humanity and nature.

By studying the geographic distribution of income groups, it can be seen that the scoring characteristics of geographic regions closely match those of income groups, and the development patterns and stages are somewhat similar within the same region. Low-income and low-middle-income countries are mostly concentrated in Africa, low-middle and high-middle-income countries are mainly found in Asia and Latin America, and high-income countries are mainly in Europe, America, and Oceania. The reasons for this are twofold: (1) Spillover effect: The actions of one country can have an impact on other countries, be it good or bad; for example, in terms of  $\text{CO}_2$  emissions, climate change, wars, etc. The SDGs formulated in 2015 emphasized the sustainability of environmental protection and economic development. However, the “Emission Gap Report 2019” (United Nations Environment Programme 2020) issued by the United Nations Environment Program (UNEP) noted the glaring gap between the current countries’ emission reduction ambitions and the requirement to limit global warming within  $1.5^{\circ}\text{C}$ . The “Paris Agreement” has now entered its full implementation phase. We must now coordinate the relationship between economic development and the reduction of carbon dioxide emissions, strive to control carbon emissions, achieve carbon neutrality, and protect the planet while also promoting economic prosperity. Interestingly, the transition from middle- and high-income countries to high-income countries have continued to improve social sustainability, as well as the sustainable use of natural resources (natural and social scores are gradually increasing). (2) Regional economic unions provide guarantees for the free flow of elements among the member states of the union. Currently, there are



**Fig. 4** Natural and socially sustainable human safe operating space conditions of countries in the different income groups within 19 years (average values, from 2000 to 2018). D stands for low-income countries; G, G1 stands for high-income countries; L1, L2, L3, L4 stands for low- and middle-income countries, and U1, U2, U3, U4 stands for upper-middle-income countries. D-L1-U1-G is the development path Z1, D-L2-U2-G is the development path Z2, D-L3-U3-G1 is the development path Z3, D-L4-U4-G is the development path Z4, the dotted line from D to the left is Z5. The solid line represents the path mainly discussed in this article, and the dashed line represents the path not discussed for the time being

economic alliances on all continents, but the economic strength of each alliance is not the same (Africa: African Union; Europe: EU, etc.). Humans have only one earth on which to live and call home, and all countries coexist in this same world. China has proposed a new perspective, that of a community with a shared future for humans in 2012, aiming to pursue its interests while taking into account the legitimate concerns of other countries, and to promote the common development of all countries in the pursuit of sustainable development.

### Sustainable Developing Pathway Model and Implications

To achieve the ambitious SDGs, based on the SDHSOS index and the evenness score, we next explored the characteristics of the development path at the national scale. As Fig. 4 shows, most low-income countries share the same “high natural, low social” score characteristics, and likewise, most high-income countries have the same “low natural, high society” score characteristics, whereas the middle-income countries diverge in their characteristics.

Next, we conducted a specific analysis of the development path at different stages. In Fig. 4, the black, red, blue, and green points represent low-income, low-middle-income, middle-high-income, and high-income countries. Different points represent different states of the country. Increasing the national income level is one of the main goals of sustainable development. The national development path (regardless of leapfrogging and temporary

retrogressive development) will inevitably undergo a gradual development dominated by income increase. The initial stage of the country may be different (for example different resource endowments, etc.), but the development trend must be the continuous increase in income levels. Therefore, studying the development path of a country can be transformed into a stage of development from a low-income country to a high-income country.

Connecting the red, blue, and green points by any black point in this way indicates a possible development path. We use point D in low-income countries as the starting point of the analysis, and G and H in high-income countries as the endpoints. As shown in Fig. 4, the development path probably presents 5 trends, namely: “U”-shaped curve: Z1 (D-L1-U1-G); inverted “U”-shaped curve Z2 (D-L2-U2-G); straight-line Z3 (D-L3-U3-G1); diagonal line Z4 (D-L4-U4-G) and horizontal line Z5 (black dotted line). Straight-line Z3 shows that in the entire development stage, the social economy is rapidly upgraded at the expense of destroying natural sustainability, and thus transformed into a high-income country. This situation may exist, but it is at the cost of consuming the natural resources of other countries. Therefore, it is not discussed as a typical path. The diagonal line Z4 indicates that a consistent development rate is maintained at all stages of development. However, in actual situations, this state is very rare, so it is not discussed as a typical development path. The horizontal line Z5 indicates that the social development status of low-income countries at this stage is at a low-middle level. Attempts to consume natural resources in exchange for the development of the country and society, but the results are very small. This situation is relatively special and will not be discussed as a universal development path for the time being. Therefore, two representative routes need to be considered, Z1 (D-L1-U1-G) and Z2 (D-L2-U2-G), which are reasonable first and second path trajectories, respectively.

For the Z1 path, the early stage of a country’s development is characterized by a rapid decrease in natural scores and a slow increase in social scores, and the later stage of development is characterized by a slow decline in natural scores and a rapid increase in social scores. The overall path takes on a “U-shaped” pattern. In countries on this path, their industrial infrastructure is in the early stage of development, wherein low-value-added industry types are predominant and mainly based on raw exports (i.e., the industrial structure is dominated by primary industries), so they play the role of resource providers in the global industrial chain. Concurrently, substantial amounts of natural resources are depleted, resource utilization is low, social welfare is hindered and only slowly improving, and the space for safe operation is on verge of being exited. To return to the safe operating space, the advancement of science and technology and adjustments of industrial

**Fig. 5** Comparison of SDHSOS with other comprehensive indexes. The leftmost column is the names of comparison indexes, while across the top are the characteristic factors of each index. “○” means that the index satisfies this feature, with that cell highlighted in green; “-” indicate that the index does not meet this feature or it does not exist, with the cell highlighted in white

Characteristic Index and framework	Characteristics 1 Evenness between indicators	Characteristics 2 Composite index	Characteristics 3 Cross-dimension	Characteristics 4 Relevance to earth's key process	Characteristics 5 Relevance to SDGs goals framework
Sustainable Development Human Safe Operation Space Index	○	○	○	○	○
Sustainable Development Goals Index	-	○	○	-	○
Sustainable development score	○	○	○	-	○
Living Planet Index	-	○	-	-	○
Human footprint Index	-	○	○	-	○
Planetary boundaries	-	-	-	○	○
Human Development Index	-	○	-	-	○
Safe and Just Space	-	-	○	○	○
Life expectancy index	-	-	-	-	○
Poverty index	-	-	-	-	○
Income index	-	-	-	-	○

infrastructure is needed to fuel high economic value-added industries, to serve as production factors and technology providers, so the consumption of natural resources is markedly reduced while the utilization rate of resources is increased, with social welfare then quickly improved. This development path is called the *traditional development path*, which is suitable for countries with a small space for the safe operation of natural resources (i.e., located on the edge of the safe operating space or about to break through the horizon), such as the case of China.

The Z2 path is characterized by a slower decrease in natural scores and a rapid increase in social scores in the early stages of development, and a faster decrease in natural scores and slower increases in social scores in later stages of a country’s development. The overall path follows an “inverted U-shaped” pattern. Consumption in the safe space of natural resources does not reduce the natural score, but it can swiftly improve social well-being. In later stages of development, with the exhaustion of natural resources and exiting the safe operating space, the natural score rapidly decreases; but at this time, due to long-term dependence on natural resource consumption, the industrial infrastructure fails to get upgraded and transformed accordingly, so a resource-exporting low-value-added industry persists. The consumption of natural resources continues to increase, and the efficiency of resource utilization is low, thus leading to a slowdown in the improvement of social well-being. This development path is called a *special development path*. A country on this trajectory may be a country with a large space for the safe operation of natural resources (perhaps a certain kind

of resource endowment is unusually rich), such as the case of Saudi Arabia.

Therefore, countries need to seize upon their comparative advantages, accelerate industrial upgrading and transformation, and at the same time improve their resource utilization efficiency and reduce network resource consumption, without breaking through the safe operating space in the development process in achieving the goals of sustainable development.

## Discussion

### Comparison of SDHSOS with other comprehensive indexes

As shown in Fig. 5, the SDHSOS index addresses various shortcomings in sustainability research, namely the lack of evenness within and among other indexes, use of a truly comprehensive index, the cross-dimension aspects, relevance to the key processes of the earth, and the inexplicit coupling to sustainable development indicators. The evenness here is not to equalize the values and characteristics of various earth system functions and social indicators, but rather is a way of assessing indicators in the calculation of which the common indicator for assessing sustainable development progress is a composite score using the arithmetic mean of all target scores (Xu et al. 2020; Sachs et al. 2018). However, when the target score difference is large, choosing this method will make up for the high score and the low score target, which will cause the actual index score to be falsely high. Therefore, the balance of variance is introduced into the calculation method of the index, and

the deviation is calibrated so that the final result is close to reality.

### Limitations and future research

There remain some limitations to be addressed in future studies. Through the collection of the required data indicators in this article, it can be seen that the data sources and time series are missing to varying degrees, which may challenge the selection of indicators and further restrict subsequent evaluation and analysis. For example: two sub-indicators in the national health indicators: universal health coverage and global health security. Global health security was evaluated for the first time in 2019. Due to the large difference from the currently selected study period, it has not been calculated yet. However, it is indispensable in the entire sustainable development. Therefore, it is included in the analysis framework. The remaining missing indicators are handled by the requirements of the SDGs, and the data sources are official and authoritative. A top-down downscaling method is adopted in the planetary boundary to assess the natural sustainability of countries. However, there is a lot of controversy in the scientific community about this downscaling method. We use the same downscaling method as most studies, the average per capita method. If the bottom-up and top-down approaches are combined to better deal with the downscaling of planetary boundaries, it will help advance the framework and the development of planetary boundaries and even geography.

### Conclusions

As a retrospective study, this evaluation system integrates the planetary boundary framework and the sustainable development goal framework, providing a new method for assessing sustainable development capabilities and development pathways. This article comprehensively assessed the natural and socially sustainable development capacity of 149 countries. The SDHSOS index score at the national level is between 33.42 to 73.05 in 2000, having a mean value of 60.24. Over time, however, the average SDHSOS index score increased by 2.89%, attaining a mean value of 61.98 in 2018. The sustainability of natural and socio-economic dimensions shows obvious regional differentiation and income grouping differences. The scoring characteristics of geographic regions closely match those of income groups, and the development patterns and stages in the same region are also somewhat similar. The social and natural environment dimensions show that the development path presents the characteristics of decreasing natural sustainable development capacity and increasing social sustainable development capacity.

Future research needs to measure the impact of spillover effects on the sustainable development capacity of other countries, and the degree of influence on the sustainable development capacity of a certain regional event or area. By better addressing such spillover effects, as well as sustainable consumption and production patterns in the SDHSOS index, the ranking of some high-income countries may significantly change. Also, given the unprecedented effects of the ongoing COVID-19 pandemic, all sectors ought to consider the risks of unexpected external shocks. Lastly, exploring the coupling effect and cascade effect between the natural planetary boundary and the sustainable development of society could prove instrumental for revealing the key driving mechanisms and factors influencing the human–land system.

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### Compliance with Ethical Standards

**Conflict of interest** The author declares no competing interests.

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