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Decoupling of SDGs followed by re-coupling as sustainable development progresses

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Understanding the complex interactions among the Sustainable Development Goals (SDGs) is key to achieving all of the SDGs and 'leaving no one behind'. However, research about dynamic changes of SDG interactions is limited, and how they change as sustainable development progresses remains elusive. Here, we used a correlational network approach and a global SDG database of 166 countries to analyse the evolution of SDG interactions along a progression of sustainable development measured by the SDG Index. SDG interactions showed nonlinear changes as the SDG Index increased: SDGs were both more positively and more negatively connected at low and high sustainable development levels, but they were clustered into more isolated positive connection groups at middle levels. The identification of a process of decoupling followed by re-coupling along the SDG Index strengthens our understanding of sustainable development and may help to suggest action priorities to achieve as many SDGs as possible by 2030.

To tackle the most pressing issues facing humanity, such as climate change, poverty, inequality and quality education, the United Nations adopted 17 ambitious Sustainable Development Goals (SDGs) to stimulate actions in critically important areas for people, the planet and prosperity[1]. The 17 SDGs are integrated and indivisible, balancing the economic, social and environmental dimensions of sustainable development[1]. They cover all aspects of human life and interact in complex ways[2]. Actions for one goal may reinforce or offset the actions for another[3,4], resulting in synergies and trade-offs among the SDGs. For example, using coal to improve energy access (SDG 7) will accelerate climate change (SDG 13) and disrupt health (SDG 3) through air pollution[3]. Given the 'leave no one behind' objective of the 2030 agenda[3,4], understanding interactions among the SDGs is crucial when designing appropriate and efficient policies to implement them[5,6].

Using systems thinking and analysis to assess the complex SDG interactions is at the forefront of sustainability research[7]. Multiple studies qualitatively scored and assessed SDG interactions by expert expertise[3,8,9] or text mining applied to official documents and the wording of SDG targets[10,11], while other studies used pairwise correlations between the official indicator data for each SDG to quantitively analyse relationships between SDGs[4,5,12]. Network analysis, which has been widely used in studies of complex systems (for example, health[13], ecosystems[14] and societies[15,16]), is a holistic approach to explore the characteristics of SDG interactions[17] and their changes[18]. It provides clear visualization and conceptualization of interactions between variables and well-developed notions to characterize those interactions[7]. An array of network centrality measures (for example, degree centrality, betweenness centrality, eigenvector centrality and closeness centrality) can measure the importance of SDG goals or targets in the interaction network[2,7,12,19], while network community detection can reveal the strongly connected groups of SDG goals or targets in the interaction network[5,7,20]. By characterizing the synergies and trade-offs between SDGs, previous studies have identified the frequency of SDG interactions and the importance of individual SDG goals or targets at different scales[4,5,21,22], as well as their differences across regions[7,12]. Comparisons among different groups of countries have shown that SDG interactions vary with a country's socioeconomic characteristics, such as income, region and population composition[2,9,17].

Although previous studies have helped policymakers and analysts grasp the complex and systemic nature of SDGs[23], research about dynamic changes of SDG interactions, that is, how SDG interactions change as sustainable development progresses, is limited. By revealing dynamic changes of SDG interactions along sustainable development levels, we can determine the critical transformative stages of sustainable development, identify the hurdles and opportunities of sustainable development for countries at different levels and find specific action priorities for countries at different levels based on a better understanding of the sustainable development process. To fill this knowledge gap, this study addressed three major questions with a correlational network approach (Fig. 1a). First, did SDG interactions change along sustainable development levels and, if so, how? Second, which SDGs were more related to others, and how did the connections change along sustainable development levels? Third, which groups of SDGs tended to be achieved together, and how did the compositions of these groups change along sustainable development levels?

To address these questions, we used SDG data of 166 countries (Fig. 1b and Supplementary Table 1) from the *Sustainable Development Report 2020* prepared by the Sustainable Development Solutions Network and the Bertelsmann Stiftung[24], which calculated scores for each of the 17 goals and the SDG Index (reflecting the overall sustainable development level) for each country, to build correlational networks along an SDG Index gradient. SDG interactions can be analysed at both goal and target levels[2,12,19,21,22].

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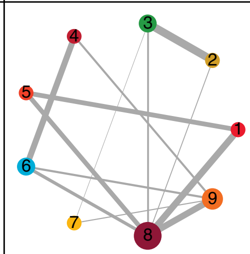
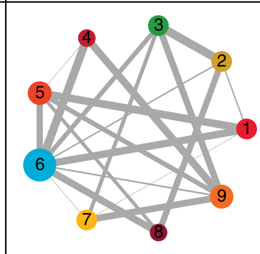
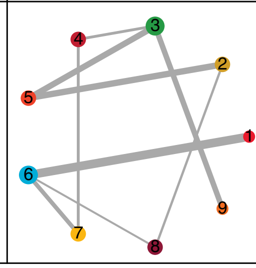
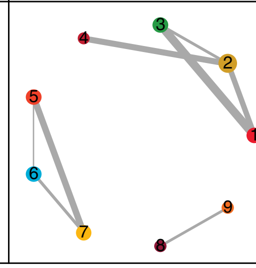
Network metric	Definition	Meaning in the SDG network	Low value	High value
Connectivity	Proportion of positive or negative links to all possible links in the network, weighted by the strength of the links.	High connectivity of synergy networks indicates that more SDGs can be achieved simultaneously. High connectivity of trade-off networks indicates that more SDGs cannot be achieved simultaneously		
Modularity	A module represents a group of nodes that are highly connected among them and loosely connected to others. Modularity represents the strength of the partition of a network into modules.	In a highly modular network, SDGs can be divided into isolated groups according to their connections, while in a less modular network, the interactions of all SDGs are closer.		

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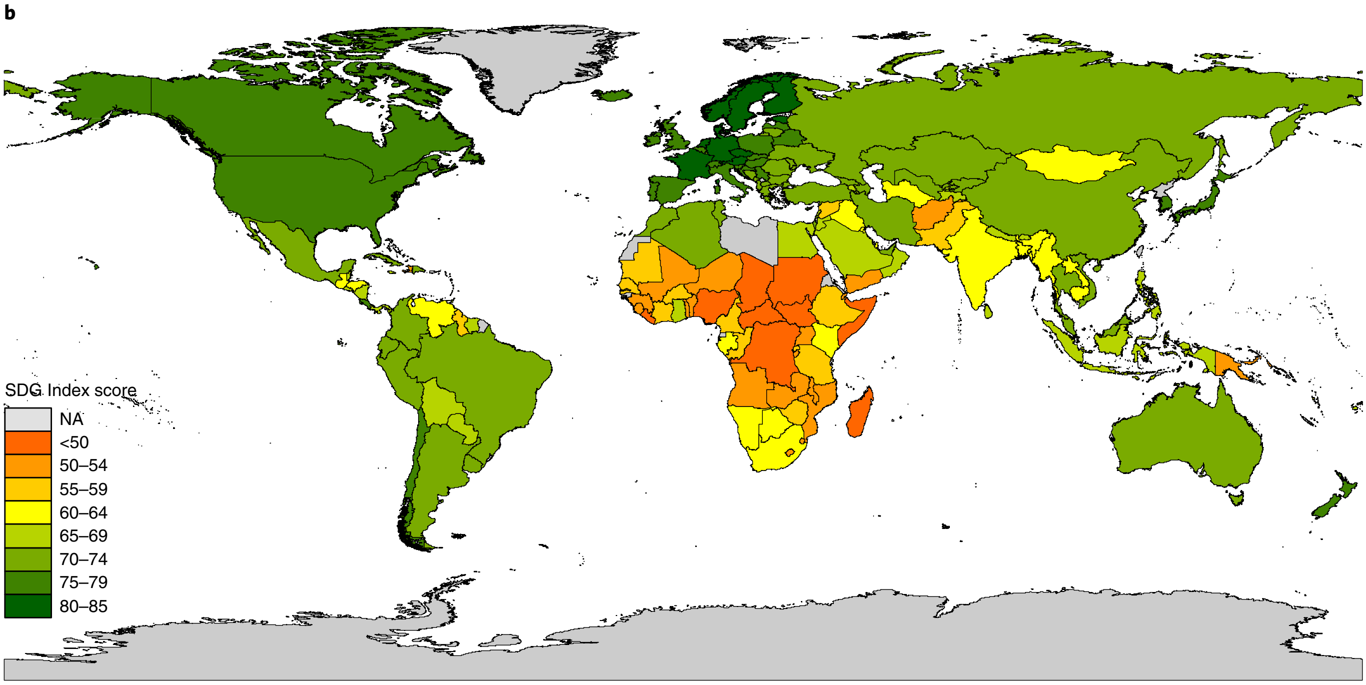

Fig. 1 | Metrics and countries used in the network analysis. a, Network metrics used in this study. **b**, SDG Index score of 166 countries from *Sustainable Development Report 2020*[24]. The index score signifies a country's position between the worst (0) and the best or target (100) outcomes across the 17 SDGs.

As previous studies suggested that maintaining flexibility on targets while remaining focused on goals may offer more opportunities to avoid SDG conflicts and achieve overall sustainability[2], we chose the goal level for analysis. Causal relationships of SDGs have been explored qualitatively or quantitively in previous studies[8,12,22,25]; however, due to data constraints, interactions between pairwise SDGs were represented as correlations between advancements towards each SDG in this study. We sorted the 166 countries along the Sustainable Development Solutions Network's SDG Index gradient from the minimum to the maximum score and used a moving-window approach[18] to analyse the effect of an increasing SDG Index on interactions among the SDGs. The moving-window size was set at 50 (Methods), resulting in a total of 117 windows (that is, countries 1–50, 2–51, …, 117–166) and 117 correlational networks (Supplementary Fig. 1). In the networks, each node represented an individual SDG, and pairwise SDGs that were significantly ($P < 0.05$) correlated were connected by a link, where the strength of each link indicates the Pearson correlation coefficient. The obtained networks with 17 nodes were weighted and undirected (directionality can be estimated only if the direction of causality is known[2,12,22]). Because correlations can be positive or negative, we built separate networks for synergies (positive correlations, meaning a pair of SDGs improve or deteriorate together) and trade-offs (negative correlations, meaning one SDG improves while the other deteriorates).

Two key network metrics, connectivity and modularity, were selected to reflect the characteristics of the SDG interaction networks and analyse their changes (Fig. 1a). Connectivity is the proportion of present links to all possible links in the network weighted by the strengths of the links, reflecting the number and strength of the correlations[18]. A module represents a group of nodes that are highly connected among themselves and loosely connected to others, and modularity represents the strength of the partition of a network into modules, indicating the degree of network compartmentalization[18]. To determine whether and how SDG interactions changed along the SDG Index, we fitted generalized additive models to analyse the effect of the SDG Index and other possible variables on the network metrics (Methods). After evaluating the changes of these metrics along the SDG Index at the network level, we further calculated the weighted node degree (that is, the average strength of connection to other nodes[18]) of each node in each network to examine changes in connections of individual SDGs and identified the module composition of synergy networks to examine changes of groups of SDGs tending to be achieved together (Methods). On the basis of the findings, this study provides new insights about dynamic changes of SDG interactions along sustainable development levels, which will be useful for identifying action priorities for countries at different levels of sustainable development.

Results

Nonlinear changes of SDG interactions. All the metrics of the SDG interaction networks changed significantly along the SDG Index (Fig. 2, Supplementary Fig. 2 and Supplementary Table 2) while controlling for the effects of other factors such as gross national income (GNI) per capita, population density and precipitation (Methods). The nonlinear changes in the SDG interactions suggested a process of decoupling of SDGs followed by re-coupling along sustainable development levels. Connectivity of both synergy and trade-off networks showed an overall trend from decreasing to increasing as sustainable development progressed: SDGs became less connected when sustainable development levels increased from low to middle (a decoupling of SDGs), but they became more connected than the initial state when sustainable development reached high levels (a re-coupling of SDGs). The overall trend of the synergy networks' modularity was the opposite to that of connectivity; it increased at first but then decreased along the SDG Index, reaching a peak when the SDG Index was about 69. This indicates that the 17 SDGs divided into more isolated positive connection groups at the mid-level of sustainable development. However, the trend of the trade-off networks' modularity depended on the selection of moving-window size (Supplementary Fig. 6 and Supplementary Table 3) and was not considered in our study.

Highly connected SDGs in the sustainable development process. The connectivity of most SDGs first declined then increased to a value higher than the original value along the SDG Index in the synergy networks (Fig. 3a and Supplementary Fig. 3a). SDG 3 (good health and well-being), SDG 9 (industry, innovation and infrastructure), SDG 16 (peace, justice and strong institutions) and SDG 6 (clean water and sanitation) were the relatively dominant SDGs along the index, meaning that many other SDGs will be disproportionately improved as progress is made towards these four goals (and vice versa). SDG 4 (quality education) was a dominant SDG when the SDG Index was low but became less important in the synergy networks when the SDG Index was high, and SDG 1 (no poverty) and SDG 7 (affordable and clean energy) showed similar trends. SDG 8 (decent work and economic growth) was less important when the SDG Index was low but became one of the top five dominant nodes when the SDG Index was high. A similar trend was observed for SDG 5 (gender equality).

The connectivity of most SDGs was relatively low in the trade-off networks, but SDG 12 (responsible consumption and production) and SDG 13 (climate action) played dominant roles in the negative interactions among SDGs (Fig. 3b and Supplementary Fig. 3b). This means that actions to meet these goals impair the ability to address many other SDGs (and vice versa). Connectivity of these two SDGs declined at first but then increased to a higher value as the SDG Index increased. SDG 15 (life on land) and SDG 14 (life below water) were also relatively dominant SDGs (the connectivity of SDG 15 exceeded that of SDG 13 at one point) when the SDG Index was low, but they became less important in the trade-off networks when the SDG Index was high. On the contrary, connectivity of SDG 17 (partnerships for the goals) remained low when the SDG Index was low but was in the top three when the SDG Index was high.

Disruption then reunion of SDG synergy modules. Changes in the module composition of SDG synergy networks along the SDG Index (Fig. 4 and Supplementary Fig. 4) also reflected a process of decoupling followed by re-coupling of SDGs. According to their positive interactions, the 17 SDGs clustered into 3 modules at a low SDG Index (score = 54), mainly reflecting the social and economic SDGs (L1: SDGs 1–9, 11 and 16), environmental SDGs (L2: SDGs 12–15 and 10) and partnerships for the goals (L3: SDG 17). As the level of sustainable development improved, these modules were disrupted, and the number of modules increased as the modules became smaller, and the modularity increased. There were five modules at the middle SDG Index level (score = 66): module L1 broke up into two modules and SDG 10 (M4) became isolated from module L2. These modules reunited when the SDG Index was high (score = 78): modules M1, M2 and M4 and SDG 15 from module M3 made up a module of 13 SDGs (H1), leaving only SDG 14, SDG 17 and a pair of SDGs (12 and 13) isolated from these connected SDGs.

Discussion

Understanding dynamic changes in SDG interactions as sustainable development progresses is crucial for developing appropriate and integrative policies for countries at different development stages. Our study provided new insights into the sustainable development process and identified an interesting pattern. The 17 SDGs first experienced a decoupling followed by a re-coupling process as sustainable development level increased: SDGs were both more positively and negatively connected at low and high sustainable development levels but clustered into more isolated positive connection groups at middle levels.

The observed nonlinear changes of SDG interactions along sustainable development levels partially coincide with the findings of other studies from distinct perspectives but unify them into the general context of sustainable development. Previous studies employing concepts such as the Kuznets curve, environmental Kuznets curve, and gender Kuznets curve empirically proved that the relationships between economic development and income inequality[26], between economic development and environmental degradation[27] (for example, CO_2 emission[28], air pollution[29], water pollution[30] and deforestation[31]) and between economic development and gender inequality[32] form inverted U-shaped curves. These studies indicate that improvements in economic SDGs would impair social and environmental SDGs in the initial stages of economic development but then would improve simultaneously with these other SDGs after a turning point. These studies explained the observed decoupling followed by re-coupling of SDGs in synergy networks and the disruption followed by reunion of the SDG synergy modules. They also explained why SDGs 10, 14 and 15 were highly negatively connected goals at low SDG Index levels and SDGs 5 and 8 became more positively connected goals at high SDG Index levels. As for the trade-off networks, the total number of negative interactions first increased

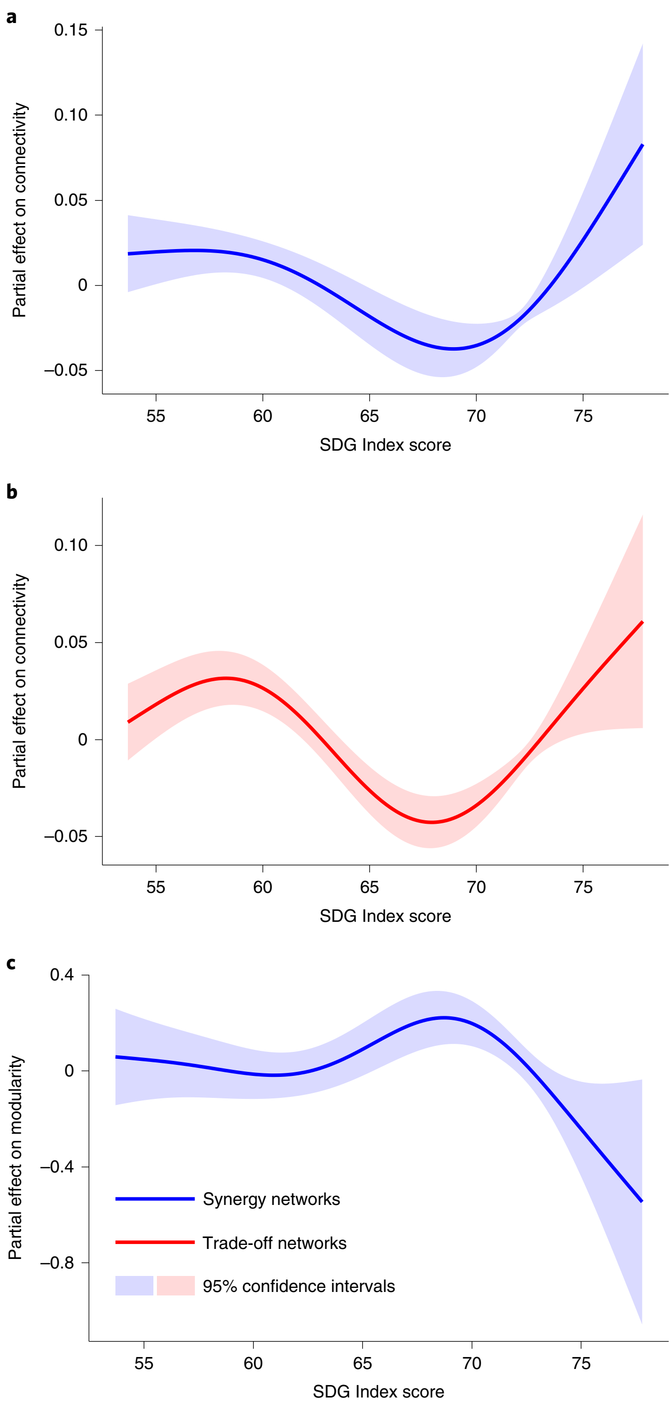

Fig. 2 | Effects of SDG Index score on the structure of both positive and negative correlation networks of SDGs. a,**c**, Synergy networks (blue). **b**, Trade-off networks (red). The graphs show the partial effects of the SDG Index score on connectivity (**a**,**b**) and modularity (**c**) while controlling for the other variables listed in Supplementary Table 2. Shaded areas represent the 95% confidence intervals of the fitted generalized additive models. All effects are significant ($P < 0.001$).

before decreasing along the SDG Index (Supplementary Fig. 8, network density, that is, the proportion of present links to all possible links in the network), but because we excluded non-significant correlations with low correlation coefficients, the connectivity showed a first declining then rising trend.

Revealing the highly connected SDGs can help to identify the hurdles and opportunities facing policymakers when trying to implement successful SDG policies[2]. Our results showed that SDGs 3, 6, 9 and 16 remained highly positively connected while SDGs 12 and 13 remained highly negatively connected throughout the SDG Index progression. Some studies combining expert judgement and scientific literature reviews or using causal analysis have explored the causal relations of these and other SDGs[8,12,22]. Health (SDG 3) is both a key enabler and a critical outcome of sustainable development[8]: progress on gender equality (SDG 5), clean water (SDG 6), clean energy (SDG 7) and many other goals are likely to support it by improving reproductive health[33], reducing the spread of infectious disease[34] and improving respiratory health[35]; good health is also a strong enabling factor for effective poverty reduction (SDG 1) and a prerequisite for economic growth (SDG 8)[8]. In addition to health, progress on SDG 6 will also enable and drive progress on other SDGs, such as hunger (SDG 2), education (SDG 4), gender equality (SDG 5) and environmental protection (SDG 15)[36]. Reliable and sustainable infrastructure (SDG 9) enhances resilient rural and urban livelihoods (SDG 11), agricultural productivity (SDG 2) and water availability (SDG 6); moreover, science, technology and innovation are essential for health (SDG 3), renewable energy (SDG 7) and climate action (SDG 13)[37]. Having effective governance systems and institutions is key to an effective, efficient and coherent approach to implementation of many, if not all, SDGs[8], which explains the dominant role of SDG 16 in the synergy networks. Most trade-offs among SDGs can be linked to the unsustainable development paradigm that focuses on economic growth to generate human welfare at the expense of environmental sustainability[4]. Previous studies found that higher levels of gross domestic product and human development index contributed to the improvement of health and nutritional status but also caused larger environmental and material footprints and higher greenhouse gas emissions[4,38,39], which are barriers to achieving responsible consumption and production (SDG 12) and climate action (SDG 13)[2]. This relationship explains the increasing level of conflicts between these two SDGs and other goals at a high SDG Index level.

Our study deepens the understanding of the sustainable development process and provides new insights into achieving as many SDGs as possible by 2030. Learning from the changes in relationships among economic, social and environmental SDGs, we found that sustainable transformation that minimizes trade-offs and facilitates new synergies is necessary, especially for the countries that are currently at the middle sustainable development level, near the turning point of SDG interactions. This transformation calls for the collaboration of scientists, policymakers, non-governmental organizations and other actors and the pursuit of broader policy mixes[40–42]. All countries should pay more attention to the SDGs that dominate the synergy and trade-off networks throughout the sustainable development progression. Our results indicate that actions taken to ensure healthy lives and promote well-being, ensure availability and sustainable management of water and sanitation, promote inclusive and sustainable industrialization and foster innovation, and build effective, accountable and inclusive institutions will have simultaneous compounded positive effects on other SDGs. However, simply promoting sustainable consumption and production and climate actions might hinder the overall progress towards the 2030 agenda. In addition to focusing on SDGs that are dominant throughout the process of sustainable development, we need to contextualize and prioritize SDGs by different sustainable development levels. For countries with a low SDG Index (for example, most African countries), alleviating poverty and ensuring inclusive and equitable quality education and access to affordable and clean energy should be considered as high priorities because they can positively affect other SDGs. But care must be taken that these goals are achieved without compromising marine and terrestrial

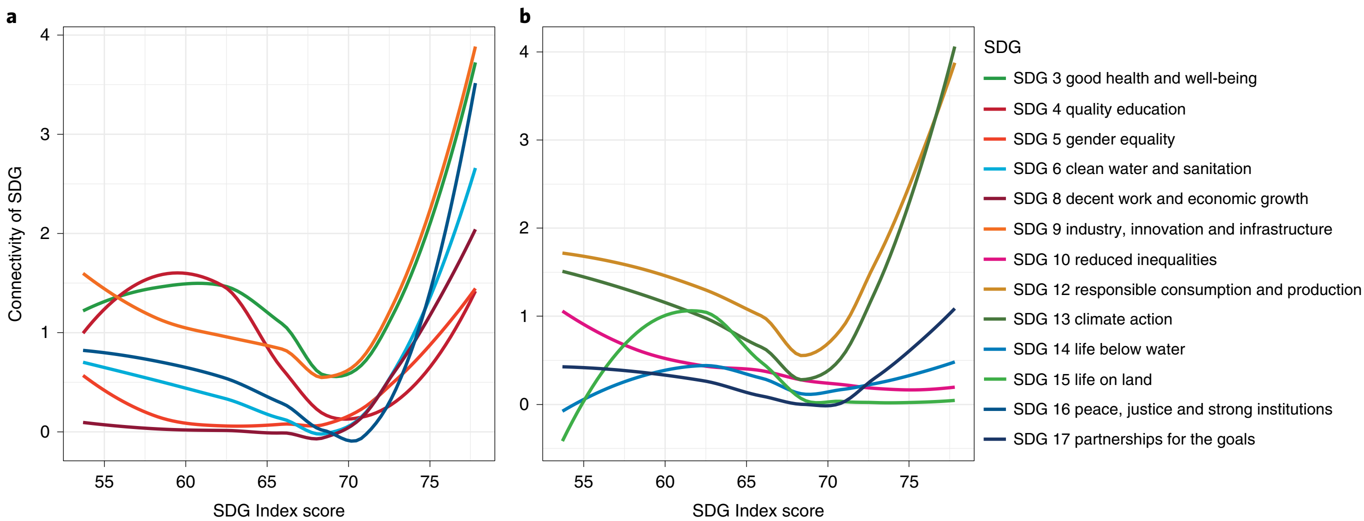

Fig. 3 | Connectivity of individual SDGs along the SDG Index. a, Synergy networks. **b**, Trade-off networks. Only SDGs with a maximum weighted node degree >1.5 in synergy networks and SDGs with a maximum weighted node degree >1.0 in trade-off networks are shown in the panels.

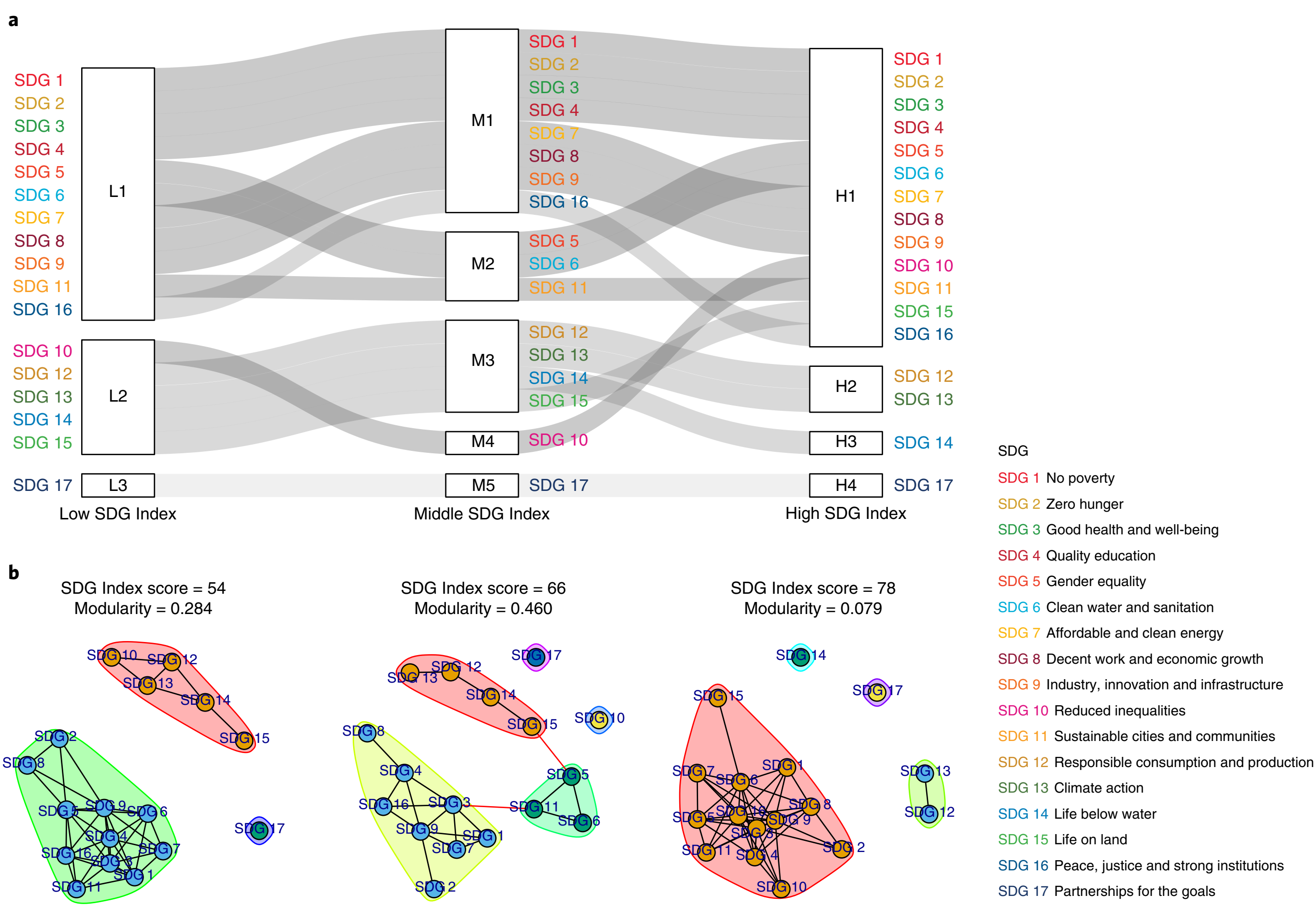

Fig. 4 | Module composition of synergy networks and their changes at different SDG Index score levels. a, Changes in module composition of the synergy networks at different SDG Index score levels. **b**, Modules of the synergy networks at different SDG Index score levels. Different background colours represent different modules. Black lines represent SDG interactions in the same module; red lines represent SDG interactions in different modules.

ecosystems because SDGs 14 and 15 are highly negatively connected at this development level. Payments for ecosystem services, which directly incentivize landowners and other resource stewards to adopt environmentally friendly practices for better environmental outcomes, human welfare and social equality, provide an innovative economic intervention to mitigate trade-offs between environmental and development goals[43,44]. For countries with a high SDG Index (for example, most Organisation for Economic Co-operation and Development (OECD) countries), progress in achieving gender equality, promoting sustainable economic growth and reducing inequality can also promote other SDGs. These countries should especially focus on developing new governance and technologies to increase resilience to climate change and decrease emissions to mitigate the negative connections between SDGs 12 and 13 and the other SDGs. Policies in the European Union, such as the EU Emissions Trading System (ETS), the Effort Sharing Regulation for non-ETS sectors, the land-use, land-use change and forestry regulation, and the Renewable Energy Directive, are good examples for the development of such policy mixes[45,46].

Although this study provides important and interesting findings, there are some limitations in the data and methodology. First, the identified synergies and trade-offs were based on data from *Sustainable Development Report 2020*, which used only 115 of the United Nations' 231 indicators, primarily because most of the other indicators are either hard to quantify or lack data[24]. As more data become available in the future, our approach can easily be applied to an updated SDG goals or targets database to provide a more comprehensive and detailed picture. Second, the SDG interactions were analysed by using correlation coefficients as proxies, but they do not imply causality[10]. The observed synergies between two SDGs could be independently related to another process linked with SDGs[4]. Nevertheless, the causal relations of some SDGs were explained in our discussion on the basis of existing studies that used expert knowledge or causal analysis. Several studies have started to explicitly address causation in SDG interaction networks by using approaches such as Granger causality analysis[23,25]. Additional data and the development of methods of analysis will enable us to move from correlation to causality and build directed and weighted networks to analyse dynamic changes of SDG interactions[2,23,25]. Future research can further investigate the complex mechanisms behind the trade-offs and synergies among SDGs[47] and find solutions to address conflicts among them[9].

In conclusion, this study revealed changes in SDG interactions as sustainable development progresses. The identification of a process of decoupling followed by re-coupling along the SDG Index strengthens our understanding of sustainable development and may help to suggest specific action priorities to achieve as many SDGs as possible by 2030. This study proves the necessity of research about dynamic changes in SDG interactions and may also begin to lay a foundation for analysing such dynamic changes at different scales.

Methods

Data sources. The overall SDG Index scores and scores on the individual SDGs of 166 countries were collected from *Sustainable Development Report 2020*[24], which describes each country's progress towards achieving the SDGs. The report is available for each year from 2017 to 2021, and each report provides the scores of each country for that year. However, due to changes in the indicators as well as some refinements in the methodology, SDG scores cannot be compared among the different years[24]. Because the trends of network metrics along the SDG Index are similar when calculated using data from the different years (Supplementary Fig. 5) and the number of countries is greatest in *Sustainable Development Report 2020*, we selected that report for use as our dataset.

The scores can be interpreted as a percentage of optimal performance. To generate comparable scores and rankings, the same basket of indicators is used for all countries. A total of 115 indicators, 85 global indicators and 30 indicators added specifically for OECD countries was used (Supplementary Table 4). Most of the data used in this report come from international organizations such as the World Bank, the Food and Agriculture Organization, the World Health Organization, the United Nations Children's Fund, OECD and others, which have extensive and rigorous data-validation processes. To calculate the SDG Index, this report first censored extreme values from the distribution of each indicator, then rescaled the data to ensure comparability across indicators and finally aggregated the indicators within and across SDGs.

Interactions among SDGs. We used Pearson correlation coefficients to represent the interactions among SDGs: a positive value represents a synergy whereas a negative value represents a trade-off, and the absolute value of the correlation coefficient represents the strength of the interaction. To analyse the effect of an increasing SDG Index on interactions among the SDGs, we used a moving-window approach[18]. In total, 166 countries were sorted along the SDG Index gradient from the minimum to the maximum SDG Index score. To examine the influences of moving-window size, we tried using different moving-window sizes (from 30 to 80) to compare the trends and turning points of the network metrics, which were the main focuses of this study. Under all moving-window sizes, the connectivity of both the synergy and trade-off networks showed an overall trend of declining then rising while the modularity of the synergy networks showed an overall trend of rising then declining. The turning points of the trends of these metrics fell within an SDG Index range of 67.9–71.2 (Supplementary Fig. 6 and Supplementary Table 3). However, the modularity trend of the trade-off networks depended on the selection of the moving-window size and thus was excluded from this study. The relative ranges of the three network metrics (calculated as the proportion of the range of the network metric under one moving-window size to the maximum range of the network metric under all moving-window sizes) all exceeded 60% when the moving-window size was 50 (Supplementary Table 3). Compared with other moving-window sizes, the size 50 can avoid an overemphasis of the change of one network metric (Supplementary Table 3). Therefore, we set the moving-window size at 50, resulting in a total of 117 windows, each containing 50 countries. We calculated the mean SDG Index score for each window, resulting in an SDG Index gradient ranging from 53.7 to 77.8.

For each window, we calculated the Pearson correlation between each pair of SDGs and used the significant correlation coefficients ($P < 0.05$) for additional analyses. To examine the influences of different selection criteria of correlation coefficients, we also built networks using correlations with an absolute coefficient >0.5 and correlations with an absolute coefficient >0.3. We then repeated the analyses of network metrics for comparison. The network metrics showed similar trends under different selection criteria of correlation coefficients (Supplementary Fig. 7), which reinforced our conclusion. Some SDGs (for example, SDG 14) were missing for some countries because of a lack of indicators. The missing SDGs were dropped individually for each pairwise correlation by using the 'pairwise.complete.observation' mode[18]. To facilitate the interpretation of the results, the networks for positive (synergies) and negative (trade-offs) correlations were calculated separately, while network modules were calculated only for synergy networks.

Network analyses. The Pearson correlations for each window were converted to a network graph object and analysed by the R package igraph[48]. In the network, the nodes represent the 17 interactive SDGs, and links between nodes represent positive/negative correlations between two nodes and their weights (Supplementary Fig. 1). We calculated connectivity and modularity (Fig. 1) for the synergy and trade-off networks, respectively. Connectivity was calculated as the proportion of present links to all possible links in the network, weighted by the absolute value of the correlation coefficient[18]. Modularity was calculated by the 'cluster walktrap' algorithm in igraph, which separates densely connected subgraphs via random walks using correlation coefficients as weights[18].

Previous studies have found that SDG interactions vary with a country's income and region, along with the gender, age and location of its population[2,17]. To determine whether and how the SDG Index affects SDG interactions, we also collected the GNI per capita, precipitation, urbanization, population density, percentage of females in the population and percentage of the population aged 0 to 14 years from the World Bank's World Development Indicators. For each of these variables, we used the average value of all the countries in each window. To avoid multicollinearity, we then calculated each variable's variance inflation factor and excluded variables for which it was >10. Only SDG Index, GNI per capita, population density and precipitation remained after this exclusion process. We fitted generalized additive models to analyse the effect of these four variables on the network metrics using the mgcv package[49] and smoothed the fitted response by setting the k attribute of the generalized additive models to avoid unexpected wiggliness of the curve[18] (Supplementary Table 2).

To test whether the effect of SDG Index on network metrics differed from random expectations, we compared our results with the network metrics for 100 randomizations of the dataset along the SDG Index gradient. In the randomizations, the individual SDG scores of each country were maintained, but the overall SDG Index scores assigned to each country were randomized[18]. This procedure allowed us to test whether the observed changes are related to the SDG Index or occur by chance. Through the comparison, we found clear differences in the trends of the observed network versus the 100 randomizations (Supplementary Fig. 8). To assess the effect of excluding non-significant correlations, we repeated the analyses of network metrics for synergy and trade-off networks with the raw correlations. There were no major differences between the approaches except for an opposite trend of density (the proportion of present links to all possible links in the network) in trade-off networks when using the raw correlations (Supplementary Fig. 7).

Besides the network metrics, we used the weighted node degree (the average strength of connection to other nodes, calculated as the product of the degree of a node and the mean of the absolute correlation coefficients of all connections[18]) to calculate the connectivity of individual SDGs in the interaction networks. We calculated this value for each node in the networks to identify the most connected node and the change in connectivity of each node along the SDG Index. To compare the module composition of the synergy networks at different levels of the SDG Index, we used the cluster walktrap algorithm in igraph to identify the module composition of each network (Supplementary Fig. 4). We compared the composition of the network modules at the low (SDG Index score = 54), middle (SDG Index score = 66) and high (SDG Index score = 78) SDG Index levels. Note that the existence and composition of the modules in a network is independent from the network's modularity value, which means that modules can be identified even if the modularity value is low[18].

Data availability

All of the data used in this paper can be obtained from the *Sustainable Development Report* (https://www.sustainabledevelopment.report/) and the World Bank World Development Indicators (https://databank.worldbank.org/reports.aspx?source=world-development-indicators).

Code availability

All computer code used in conducting the analyses summarized in this paper is available from the corresponding author upon reasonable request.

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B.F. and X.W. designed the research. X.W., S.W. and S.S. performed the data analysis. X.W., B.F., S.W., S.S., Y.L., Z.X., Y.W. and J.L. contributed to the interpretation and writing.

Competing interests
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