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Spatial-temporal heterogeneity of sustainable development goals and their interactions and linkages in the Eurasian continent

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ABSTRACT

Comprehending the complex interactions and linkages among Sustainable Development Goals (SDGs) is fundamental to prioritizing and advancing progress. However, studies on the regional-scale SDGs and their interactions and linkages are limited. Here, an aggregated approach would allow for progress, trade-offs, synergies, modularity, and prioritization to reveal the relationship between different SDGs. And then, homogeneity and heterogeneity were considered from a comparative regional perspective, that means we used homogeneity and heterogeneity to analyze differences between regions. The results highlight that the synergistic effect among the Eurasian SDGs was greater than the trade-offs. The trade-offs were concentrated in SDG12(Responsible Consumption and Production) and SDG13(Climate Action). As for linkages, between 2000 and 2010, the modularity of the Eurasian SDGs increased from 0.2095 to 0.2189, indicating a weakening of inter-module linkages and a strengthening of intra-module linkages. However, it tended to stabilize between 2010 and 2020. SDG3 (Good Health and Well-Being), SDG4 (Quality Education), and SDG1 (No Poverty) were the prioritized SDGs. In addition, there were spatial homogeneity and heterogeneity in the progress, interactions, and linkages of the SDGs. Our study highlights spatial homogeneity and heterogeneity to focus on regions with SDGs progress networks and may help to fix prioritization to achieve as many SDGs as possible by 2030.

1. Introduction

The United Nations has established 17 Sustainable Development Goals (SDGs) to address urgent human challenges, including climate change, poverty, inequality, and education quality (Sachs et al., 2019; Xu et al., 2020). The successful implementation and accomplishment of these SDGs require evaluating the progress in diverse settings and establishing development prioritizations (Kørnøv et al., 2020; Weitz et al., 2018). These 17 SDGs are integrated and indivisible and interact and link in complex ways (Kroll et al., 2019; Liu et al., 2021). Therefore, determining the progress of SDGs and quantifying their interactions, linkages, and prioritizations is essential for uncovering the intricate mechanisms and outcomes of sustainable development (Guenat et al., 2022; Wiedmann and Allen, 2021).

SDGs have diverse intimate and intricate relationships, including spatial-temporal distributions. These relationships include synergistic (changes in the same direction) and trade-off relationships (changes in opposite directions) (Fu et al., 2019). Efforts toward achieving one goal can strengthen or counteract efforts toward achieving another, leading to synergies and trade-offs among the SDGs (Dong et al., 2021). Understanding the complex relationships among SDGs, preventing avoidable trade-offs, and enhancing synergies can facilitate the realization of SDGs (Han et al., 2023; Zhou et al., 2022). Although current research on the relationships among SDGs has become significant, these studies are unevenly distributed regionally; for example, research on the Eurasian continent remains inadequate (Leal Filho et al., 2022), and the characteristics of the interactions among its SDGs remain unclear. Hence, our understanding of SDG interconnections is somewhat restricted (Wei et al., 2022). Employing systemic thinking and analysis to evaluate intricate SDG linkages and prioritizations is the vanguard of

Abbreviations: ASEAN, Association of Southeast Asian Nations; BRI, the Belt and Road Initiative; BSSR, the Baltic Sea sub-region; CASR, the Central Asia sub-region; EESR, the Eastern Europe sub-region; EU, European Union; GDP, Gross Domestic Product; HDI, Human Development Index; MNSR, the Mongolia sub-region; RUSR, the Russian sub-region; SDGs, sustainable development goals; SDG, sustainable development goal; TCSR, the Transcaucasia sub-region; WDC, weighted degree centrality.

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sustainability research (Allen et al., 2019; Guenat et al., 2022; Pradhan et al., 2017). Previous research has recognized SDG interactions, the significance of their objectives at diverse levels, and their variations among regions (Coenen et al., 2022; Gebara et al., 2024). Moreover, comparing different countries has revealed that SDG interconnections differ according to the socioeconomic attributes of a nation, such as income, region, and population makeup (Fu et al., 2019).

Although global and countrywide analyses have emerged for complex SDG networks, regional analyses are overlooked (Allen et al., 2021; Pizzi et al., 2020; Wu et al., 2022). Global targets and initiatives are broad and translating them into specific and feasible actions at the national level is complicated. This is exemplified by the fact that Asian countries are insufficiently progressing in attaining these SDGs by 2030 (Cheng et al., 2023; Huan et al., 2023). Conversely, actions implemented at the national level can be impactful; however, they often fail to consider broader scales. Critical SDG interactions may be overlooked if worldwide efforts are defined merely by aggregating individual actions taken by separate nations. This might additionally diminish the prioritization of certain SDGs and obstruct the global trajectory toward their fulfillment (Del Río Castro et al., 2021; Malagó et al., 2021). Therefore, conducting more refined sustainable development research at the regional level is key to establishing global and national sustainable development research connections (Muhirwa et al., 2023; Ogunmakinde et al., 2022). The absence of this might prompt countries to execute "arbitrary or politically salient" policies without a thorough knowledge of their interdependencies, rendering SDG attainment more arduous (Rashid, 2021).

The Eurasian continent is a densely populated region with a strong economic impact. In addition, the region faces many challenges, such as poverty, inequality, climate change, and environmental damage (Chung et al., 2021; Vanham et al., 2019). The region has a complex geopolitical environment and has recently been a hotspot for geopolitical conflicts (Yousfi et al., 2024). The ongoing war in Ukraine has been the most notable conflict in Europe since the Second World War and affects global sustainable development (Rawtani et al., 2022). In addition, the Eurasian continent is a typical representative of the affected and sensitive areas of global climate change, complex spatial and temporal patterns of the ecological environment, and evident patterns of geographical differentiation (Kilinc-Ata and Likhachev, 2022; Zheng et al., 2022). Therefore, the Eurasian continent is a regional priority and a complex area for realizing global SDGs. Furthermore, ameliorating the uneven advancement of the Eurasian SDGs remains a substantial obstacle (Xu et al., 2020). The Eurasian continent is vast and is homogeneous and heterogeneous regarding the natural environment and socioeconomic development. Therefore, there is homogeneity and heterogeneity in achieving their SDGs (Faridi et al., 2019). Regional homogeneity implies that most Eurasian regions are historically part of the "Post-Soviet Space" and are connected in terms of the geo-environment and ecological environment, indicating consistency and similarity in achieving SDGs (Hartvig et al., 2024). Similarly, influenced by the law of geographical differentiation and the insufficiency and unevenness of development, diverse natural environments, demographic characteristics, and economic development levels exist between different locations. Hence, there lie evident differences in achieving their SDGs (Raihan and Tuspekova, 2022). However, few existing studies have investigated the homogeneity and heterogeneity of realizing SDGs in the Eurasian continent; therefore, the regional imbalance of this realization remains unexplored.

To fill the research gaps, this study considered the Eurasian continent, characterized by regional heterogeneity and homogeneity, as the study area and addressed the following questions: First, how are the Eurasian continent SDGs progressing, and what are their spatial-temporal variations? Second, what are the interactions of the SDGs and their spatial-temporal variations? Third, what are the linkages of the SDGs and the variations in their spatial-temporal distributions? Fourth, what are the prioritizations of the Eurasian continent to achieve SDGs? Compared to existing literature, this study's contributions are primarily manifest in the following aspects. This study intend to develop an integrated evaluation framework grounded in progress, interactions, linkages, and prioritization to apply to the SDGs of the Eurasian continent, making comprehensive evaluation more scientific and in line with the theme of sustainable development. Furthermore, we introduced a new model to quantify the modularity between sustainable development goals, which can quantify the interactions of the SDGs combined with regional status and enrich the research perspective of further quantifying the interactions of SDGs. In addition, this study can provide reference for sustainable development research in regions with similar historical origins and ethnic groups, such as the European Union (EU) and the Association of Southeast Asian Nations (ASEAN), which are regional integration organizations (Varzaru, 2024). These areas also face regional homogeneity and heterogeneity in the process of achieving sustainable development. This study can provide reference for achieving sustainable development in these complex homologous regions. In summary, this study aims to strengthen the comprehension of the sustainable development, provides new insights into the interactions, linkages, and prioritization of SDGs in the homologous region, and provides a promising approach for identifying opportunities for coherence in action, regional collaboration, and national transformation.

2. Material and methods

2.1. Study area

The study area comprises 16 Eurasian countries, the vital regions for constructing "the Belt and Road Initiative"(BRI) (Chen et al., 2020) and a hotspot for global geostrategic conflicts. Regarding geopolitical relevance, most countries in this continent belong to the "Post-Soviet Space. " (Sutyrin, 2022). This region has adopted a differentiated approach to regional development owing to many historical legacies, particularly the redevelopment of the Soviet-era challenges in the new socio-historical context, and there are great difficulties and challenges in achieving the SDGs in this region. Among the 16 countries in the study area, the country with the largest total Gross Domestic Product (GDP) in 2020 was Russia (1488.3 billion dollars), and the country with the least is Tajikistan (7998 million dollars). Among them, three countries - the Russian Federation, Kazakhstan, and Ukraine - have a total GDP of >100 billion dollars. For the international debt ratio, the internationally accepted standard is that the debt ratio should be kept below 20 %, i.e., 20 % is the so-called "alert level". Among the 16 countries in the study area, only 3 countries - Estonia, the Russian Federation and Tajikistan - had debt ratios below 20 % in 2020, while the remaining 13 countries had debt ratios above 20 % and are facing national debt crises.

In addition, the region is sensitive to global climate change. Moreover, it is a typical area with complex spatial-temporal patterns of the ecological environment and follows the law of geographical differentiation (Zhang et al., 2022a). This is reflected in the large topographic relief, with elevations ranging from −260 m to 7306 m. The terrain rises gradually from north to south and from east to west, and the landscape is dominated by plains, plateaus, and mountains. In terms of climatic conditions, the climate in the study area is variable, with low precipitation and large regional differences, and annual precipitation is 20-2000 mm. The ecological pattern in the area is complex and diverse, including alpine glaciers, alpine bare land, mountain forests, meadows and grasslands, typical grasslands, desert grasslands, bare land, sands, deserts and other ecosystems (Allen et al., 2021; Cohen et al., 2021).

Based on the natural conditions, economic level, social development, ethnoreligious and cultural background elements of the Eurasian continent, the study area was divided into six parts: P1: the Russian sub-region (RUSR); P2: the Eastern Europe sub-region (EESR), including Ukraine, Belarus, and Moldova; P3: the Baltic Sea sub-region (BSSR), including Lithuania, Estonia, Latvia; P4: the Transcaucasia sub-region (TCSR), including Georgia, Azerbaijan, and Armenia; P5: the Central

Asia sub-region (CASR), including Kazakhstan, Uzbekistan, Tajikistan, Kyrgyzstan, and Turkmenistan; and P6: the Mongolia sub-region (MNSR) (Fig. 1).

2.2. Research process

The process comprised four steps (Fig. 2). (1) calculation of SDG progress scores for the Eurasian continent and its sub-regions. (2) calculation of the interactions among the Eurasian SDGs using Spearman's correlation coefficient. (3) a linkage study of the Eurasian SDGs through social network analysis, and (4) prioritization of the Eurasian SDGs using social network analysis.

2.3. SDGs progress

(1) Constructing indicator framework and database

According to data availability, 155 indicators were included in the assessment, corresponding to 104 targets and 17 SDGs (Table S1). Indicator sources included the SDG Global Indicator Framework proposed by the United Nations Statistics Division, World Development Indicators provided by the World Bank, Sustainable Development Report 2020, and Our World in Data. To alleviate the impact of absent data, we substituted them with those from nearby or previous years or interpolated them using the mean value of those of the adjacent years. In certain instances, a regression method was employed.

(2) Data processing

Raw data could not be compared owing to dissimilarities in the measurements and unit dimensions of diverse indicators (Zhu et al., 2023). Thus, we used the min-max method to normalize the data (Eq. (1)), which is a normative approach for sustainability assessments (Song and Jang, 2023). However, first, considering the properties of modifications in the indicators, including positive, negative and moderate values was essential. Positive values mean that the higher the value, the better the sustainable development performance, while negative values mean the opposite. Moderate values mean that the closer the indicator is to 50 %, the better the performance is (Xu et al., 2020).

The indicators were standardized by formula (1).

$$y_{ijk} = \begin{cases} \text{positive indicator } \dfrac{x_{ijk} - x_i^{min}}{x_i^{max} - x_i^{min}} \\ \text{negative indicator } \dfrac{x_i^{max} - x_{ijk}}{x_i^{max} - x_i^{min}} \\ \text{moderate indicator } \begin{cases} 1 - \dfrac{x_q - x_{ijk}}{max\left(x_q - x_i^{min}, x_i^{max} - x_q\right)}, x_{ijk} < x_q \\ 1 - \dfrac{x_{ijk} - x_q}{max\left(x_q - x_i^{min}, x_i^{max} - x_q\right)}, x_{ijk} > x_q \\ 1, x_{ij} = x_q \end{cases} \end{cases} \quad (1)$$

In Eq. (1), y_{ijk} is the standardized indicator i for area j in kth year; x_{ijk} is indicator i for area j in kth year; x_i^{max} is the maximum of i, x_i^{min} is the minimum of i and x_q is the moderate of i.

Fig. 1. Location of the Eurasian continent.

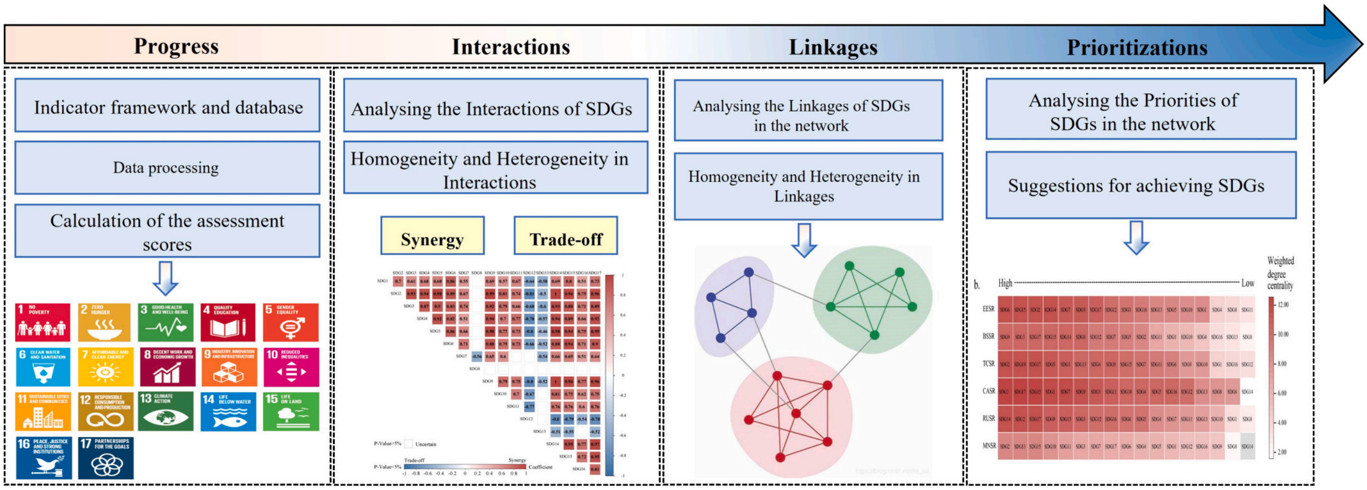


Fig. 2. Flowchart of SDGs and their interactions and linkages in the Eurasian continent.

(3) Calculation of the assessment scores

Because there are no standard methods for assigning weights, equal weights were assigned to each SDG target. Similarly, every indicator within a target was treated equally, implying that each indicator had the same significance and was not subjective. Following this, we employed the arithmetic mean approach to consolidate the individual indicator values into scores matching their respective targets. Thereafter, these target scores were compiled to derive the annual SDG scores for every nation involved. The score for each SDG varied between 0 and 1. Finally, we used these SDG scores as substitutes to map the SDG connections (Zhu et al., 2023).

(4) Calculation of the change in SDG Score

On the national scale, the 17 SDG scores were aggregated separately to obtain an SDG index score for each country. At the regional scale, we aggregated the 17 SDG scores for Eurasia between 2000 and 2020 into a single regional SDG score (Eq. (2)). We separately calculated the temporal changes in SDG scores for the Eurasian continent and the 17 SDGs in the subregion by subtracting the 2000 scores from those of 2020 (Huan et al., 2021). On this basis, we further compared the spatial differences in the progress of the SDGs in the six subregions of Eurasia and summarized the spatial-temporal heterogeneity of the progress of the SDGs in different subregions of the Eurasian continent.

$$s_q = \frac{\sum_{j=1}^{n} s_g}{n} \tag{2}$$

In Eq. (2), s_q is the SDG Score for the qth subregion, s_g is the SDG Score for each country included in the subregion, n the number of countries included in the subregion.

2.4. SDG interactions

In this study, we used synergies and trade-offs to explore SDG interactions. The Spearman's coefficient (P-value) is useful in evaluating the monotonic association between given data pairs (Spearman, 1904). Furthermore, it has the capability to discern non-linear relationships, all while exhibiting reduced susceptibility to outlier effects (Hauke and Kossowski, 2011). Therefore, it serves to evaluate the overarching relationship between variables, not confined solely to linear associations (Chen et al., 2022; Li et al., 2023; Wei et al., 2023; Zhu et al., 2022). Consequently, this research adopted Spearman's rank correlation coefficients to systematically quantify the interdependencies among all feasible pairs of the 17 SDGs in the Eurasian continent and the six subregions between 2000 and 2020. When the significance level was $P < 0.05$ and the correlation coefficient was $R < 0$, there was a trade-off relationship between the SDGs; however, $R > 0$ indicated that the SDGs were synergistic (Zhu et al., 2022).

We performed robustness tests using Pearson's correlation to verify the robustness of the analytical results (Gerecke et al., 2019; Wei et al., 2023; Zhang et al., 2019; Zhu et al., 2022). The SDG correlations were aligned using Spearman's correlation analysis; that is, the direction of correlation (synergy or trade-off) was robust, regardless of whether the relationship was linear or non-linear.

2.5. SDGs modularity

In this study, we constructed a synergy and trade-off network for the Eurasian continent over 21 years (2000–2020) (Weitz et al., 2018). Within this network structure, the 17 SDGs serve as the nodes, while the connections between these nodes signify the interactions, encompassing both synergistic effects and trade-offs (Zhong and Li, 2022). The modularity of the SDGs in the Eurasian continent was selected to capture the features of their interaction networks, and their changes were investigated. Modularity represents the strength of a network partitioned into modules, indicating the degree of network association (Table 1). Modularity was calculated using the 'cluster walktrap' algorithm in R package igraph. This algorithm involves using correlation coefficients as weights and performing random walks to partition densely-connected subgraphs (Wu et al., 2022).

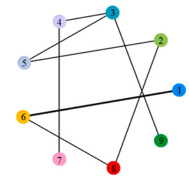
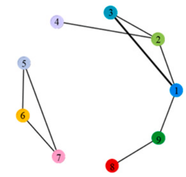
2.6. SDGs prioritizations

We used the weighted degree centrality (WDC) of each SDG to identify more effective prioritizations and accelerate their achievement for Eurasia over 21 years (2000–2020) (Eq. (3)). Conversely, we determined the centrality of an SDG by considering the number of links and the corresponding weights attributed to the SDG (Weitz et al., 2018). For every pairing of SDGs, Spearman's correlation coefficient of its absolute value was used as the weight (Wei et al., 2023).

$$C_D^{w_\alpha}(i) = \sum_{j}^{N} x_{ij} \times \left(\frac{\sum_{j}^{N} w_{ij}}{\sum_{j}^{N} x_{ij}} \right)^{\alpha} \tag{3}$$

In Eq. (3), i signifies a designated SDG, j encompasses the remainder of the SDGs, N denotes the full complement of SDGs, and x represents the adjacency matrix in which the entry x_{ij} equals 1 when SDG i has a direct

Table 1
Module degree definition.

Network	Definition	Meaning in the SDG network	Low value	High value
Modularity	A module is a cluster of nodes that exhibit strong internal connections and weak external connections. Modularity measures the degree to which a network can be divided into cohesive 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.		

linkage with SDG j, otherwise, it is 0; Meanwhile, w denotes the weighted adjacency matrix, where $w_{ij} > 0$ confirms a direct connection between SDG i and SDG j, and the value indicates the weight of the interaction. The notation $C_D^{w_\alpha}$ signifies the WDC of SDG i, with α being a favourable adjustment factor that adjusts to emphasize the comparative significance of the quantities and magnitudes of associations of an SDG. To outline variations more precisely in SDG prioritization spatiotemporally, we established an SDG interaction network. This network facilitated the separate computation of the centrality of each SDG within the six distinct sub-regions, thereby enhancing our understanding of regional dynamics.

3. Results

3.1. Spatial-temporal heterogeneity in the progress of sustainable development in the Eurasian continent

Our results indicate that the Eurasian continent improved its SDG Index score at the regional level over time. The regional scale SDG Index score increased by approximately 18.66 %, from 48.39 in 2000 to 57.42 in 2020. Based on individual SDG scores, the growth of the European SDG scores is primarily attributed to SDG14 (Life Below Water), SDG17 (Partners for the Goals), and SDG2. The increase in SDG14 in the Eurasian continent was primarily owing to increases in SDG14 scores in BSSR and EESR, and the increases in SDG17 and SDG2 scores in Eurasian continent were primarily owing to increase in SDG17 and SDG2 scores in CASR.

Notably, while the overall SDG score for the Eurasian continent trended upward, two SDGs showed decreasing scores over time (Fig. 3). The SDGs with decreasing scores were SDG12 (Responsible Consumption and Production) and SDG13, with decreases of 6.44 % and 4.88 %, respectively, indicating that the Eurasian continent is face significant challenges regarding these two SDGs. Unsustainable production and consumption patterns, inefficient use of resources, increasing industrial waste, solid waste, and air pollution, and growing fertilizer application in agriculture may explain the decreased SDG 12 score. Similarly, the increased regional CO_2 emissions may explain the decrease in SDG 13 scores (Fang et al., 2023; Xu et al., 2020; Zhang et al., 2022b).

The overall Eurasian continent SDGs indicated an increasing tendency; however, there was heterogeneity in their progress, with northern regions having better performance among the SDGs, resulting in a disparity or unevenness among the northern and southern regions (Fig. 4a). At the subregional level, by 2020, the BSSR had the highest average SDG score, and the MNSR was with the lowest score. Although the current progress of the MNSR in achieving SDGs is slow, the increase in the MNSR SDGs scores is greater than its decrease; therefore, the MNSR has more potential to achieve SDGs (Fig. 4a).

Similarly, we found that even across countries with different subregions, the change in SDG scores shows some homogeneity. For the number of changes in SDG scores, the SDGs with increasing scores were greater than those with decreasing scores for all countries (Fig. 4a). For the trend of SDGs scores, SDG2, SDG3, and SDG5 (Gender Equality) showed increasing trends in all 16 Eurasian countries (Fig. 4b). For SDG12, except for Armenia, Mongolia, and Uzbekistan, the remaining countries showed a decreasing trend. For SDG13, except Azerbaijan, Estonia, Ukraine, and Uzbekistan, all countries showed a decreasing trend (Fig. 4c). Hence, the Eurasian SDG12 and SDG13 are declining. Furthermore, the similarity and homogeneity in the progress of the Eurasian continent SDGs reflect regional connectivity. Twelve Eurasian countries belong to the Post-Soviet Space, and these countries chose different development models and policies after the collapse of the Soviet Union; however, they have similar development processes and dilemmas in achieving SDGs.

3.2. Spatial-temporal heterogeneity in interactions among SDGs in the Eurasian continent

The results showed that the synergistic effect between the Eurasian SDGs (66.18 %) was greater than the trade-off effect (19.12 %) over 21 years (2000–2020). This shows that most SDGs are interlinked and mutually reinforcing, a reason for the overall improvement in sustainable development in the continent. Trade-offs were primarily concentrated in SDG12 and SDG13, with more trade-offs than synergies with other SDG objectives (Fig. 5). Among the 17 SDGs, SDG3, SDG5 (Gender Equality), and SDG7 had the greatest synergy. Notably, the Eurasian SDG12 and SDG13 scores declined, and trade-offs may be the primary reason for the declines. In addition, SDG13 was connected to a high fraction of trade-offs with other SDGs (Fig. 5).

We further examined the annual synergies and trade-offs for each Eurasian SDG between 2000 and 2020 (Fig. 6). Over the past 21 years, the synergy share of three SDGs has remained stable despite fluctuations: SDG7, SDG16 (Peace, Justice, and Strong Institutions), and SDG17. The synergy shares of nine SDGs showed an upward trend in fluctuations, and those of the remaining five showed a downward trend (Fig. 6a). The trade-off shares of 12 SDGs showed stability amid fluctuations, with only SDG16 declining (2.21–0.74 %), and SDG1 (No Poverty), SDG8 (Decent Work and Economic Growth), SDG9 (Industry, Innovation, and Infrastructure), and SDG13 showed increased trade-off shares (Fig. 6b).

To comprehend variations in their spatial interactions, we leveraged the individual SDG scores of each subregion to compute the Spearman's rank-order correlations among the SDGs for all six subregions (Fig. 7). For regional homogeneity among the Eurasian sub-regions, their synergies outweighed their trade-offs. For regional heterogeneity, the shares of synergies and trade-offs differed across subregions. The synergies and trade-offs for the EESR were 55.14 % and 10.29 % (Fig. 7a), for the BSSR were 31.62 % and 18.38 % (Fig. 7b), for the TCSR were 49.26 % and 17.45 % (Fig. 7c), for the CASR were 63.97 % and 17.65 % (Fig. 7d), and for the MNSR were 20.59 % and 19.12 %, respectively (Fig. 7f). The predominant proportions of SDG synergies were noted in the CASR (63.97 %), followed by the EESR (55.14 %) and the TCSR (49.26 %), whereas the MNSR had the least (20.59 %) (Fig. 7). However, the highest percentage share of trade-offs between SDGs were identified in the RUSR (27.94 %), followed by the MNSR (19.12 %) and BSSR (18.38 %), and the least were in the EESR (10.29 %) (Fig. 7). Furthermore, in each subregion, the collaborative synergies among SDGs outweighed the competing trade-offs, exhibiting the greatest disparity in the CASR (46.32 %) and the smallest in the MNSR (1.47 %) (Fig. 7).

Fig. 3. SDG scores in the Eurasian continent between 2000 and 2020.

Fig. 4. Spatial characteristics of the SDG scores and their changes between 2000 and 2020 in the Eurasian continent. a. Spatial distribution of SDG scores in 2020; green (red) bars indicate increased SDGs (decreased) between 2000 and 2020. b. Increased SDG scores between 2000 and 2020. c. Declined SDG scores between 2000 and 2020.

Notably, SDG14 was primarily related to the marine ecosystem, while the MNSR constitutes inland countries; therefore, SDG14 was excluded from MNSR.

3.3. Spatial-temporal heterogeneity in linkages of SDGs in the Eurasian continent

Based on the synergies and trade-offs between the SDGs (Fig. 5), we formed a network of the interactions in the Eurasian continent from 2000 to 2020 and assessed the modularity of the SDG network. We found that the modularity of the Eurasian SDGs between 2000 and 2020 reflected the coupling process of the Eurasian SDGs. The 17 SDGs were divided into seven modules in 2000; by 2010, as the level of sustainable development increased, the modules were combined to become four. SDGs 1, 2, 5, 6 (Clean Water and Sanitation); 9 (Industry, Innovation, and Infrastructure); 11 (Sustainable Cities and Communities); 14, 15 (Life on Land); 16 were combined into a specific module, SDGs 3, 7, 8 and 13 were combined into a specific module, SDGs 4 (Quality Education) and 12 are combined into a specific module, SDGs 10 (Reduced Inequality) and 17 were combined into a specific module (Fig. 8b).

There were five modules by 2020, while the individual SDGs were SDG11, SDG12, and SDG17 (Fig. 8a). Between 2000 and 2010, the modularity of the Eurasian SDGs increased from 0.2095 to 0.2189, indicating a weakening of inter-module linkages and a strengthening of

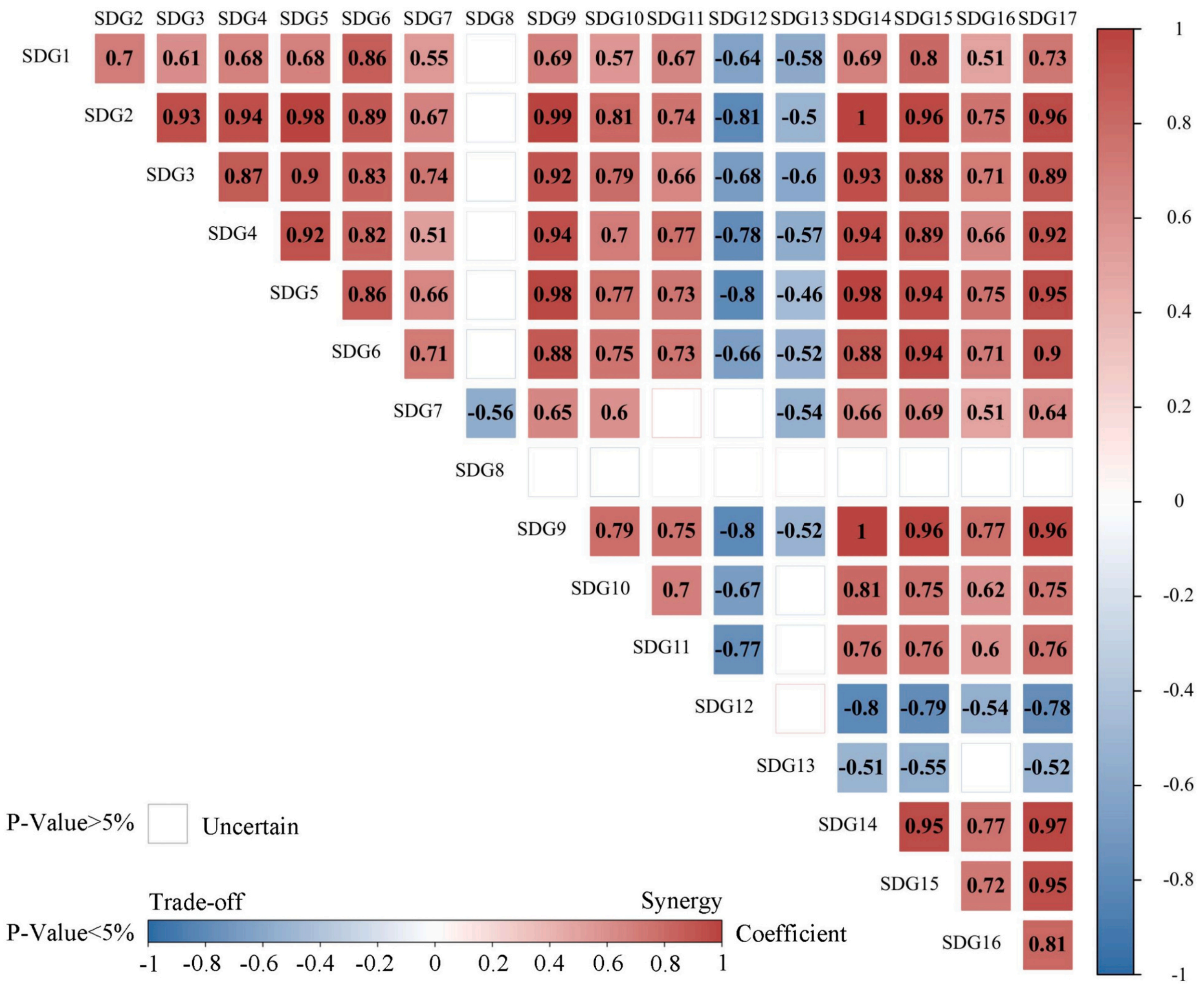


Fig. 5. Synergies and trade-offs among SDGs in the Eurasian continent between 2000 and 2020.

intra-module linkages (Fig. 8a). However, between 2010 and 2020, the modularity of the Eurasian SDGs was stable. This shows that the Eurasian modularity changed drastically during 2000–2010 and tended to stabilize in 2010–2020.

Before 2010, most European countries experienced rapid economic and social progress after the dissolution of the Soviet Union, which required addressing many challenges of imbalanced and unsustainable development. After 2010, most of these countries began to take measures to achieve their SDGs and made some progress, gradually stabilizing modular changes.

We examined the changes in modularity for the six Eurasian subregions in 2020 and found regional homogeneity and heterogeneity. Homogeneity primarily indicated that for each subregion, SDG8 and SDG13 were in the same module (Fig. 9). This shows that a strong link existed between economic growth and climate change in each Eurasian sub-region, as climate change threatened economic stability and sustainability. Failure to reduce the effects of climate change can significantly affect the global economy, resulting in escalated unemployment and potentially debilitating economic growth in several nations. Therefore, considering climate change in efforts to promote SDG8 and taking appropriate measures to address its impacts is essential. Similarly, factoring in economic aspects is imperative for attaining SDG13 and securing sustainable development in the long run.

SDG4 and SDG11 were in the same module (Fig. 9), indicating that there is a strong link between education and sustainable communities in each Eurasian subregion and that sustainable cities need quality education. Individuals with a good education can offer the expertise and understanding needed for the growth and administration of cities, aiding their sustainability. Simultaneously, sustainable cities offer superior educational prospects and resources for inhabitants to begin their complete potential and engage in the progress of their cities. Therefore, achieving SDG4 is crucial for realizing SDG11.

SDG15 and SDG17 were in the same module (Fig. 9), indicating that life on land in each Eurasian subregion is closely linked to regional cooperation and partnerships. In Eurasia, many countries have rich natural resources and ecosystems and face many environmental challenges, such as land degradation, water scarcity, and climate change.

Heterogeneity was primarily manifested in the different modularity of the subregions. The subregion with the highest modularity was the EESR (0.0328), while the CASR had the lowest (0.0041) (Fig. 9), and the modularity of the EESR and BSSR were significantly higher than those of other subregions. This indicates that, compared with other subregions, the EESR and BSSR are strongly connected within each module of the SDGs, whereas the connections between different modules were sparse. Moreover, the EESR and BSSR were divided into three modules, while other subregions were divided into two.

3.4. *Prioritizations of SDGs in the Eurasian continent*

To effectively achieve SDGs, understanding their interactions and linkages and implementing the most impactful goals within their complex network is essential. Therefore, we evaluated the weighted degree

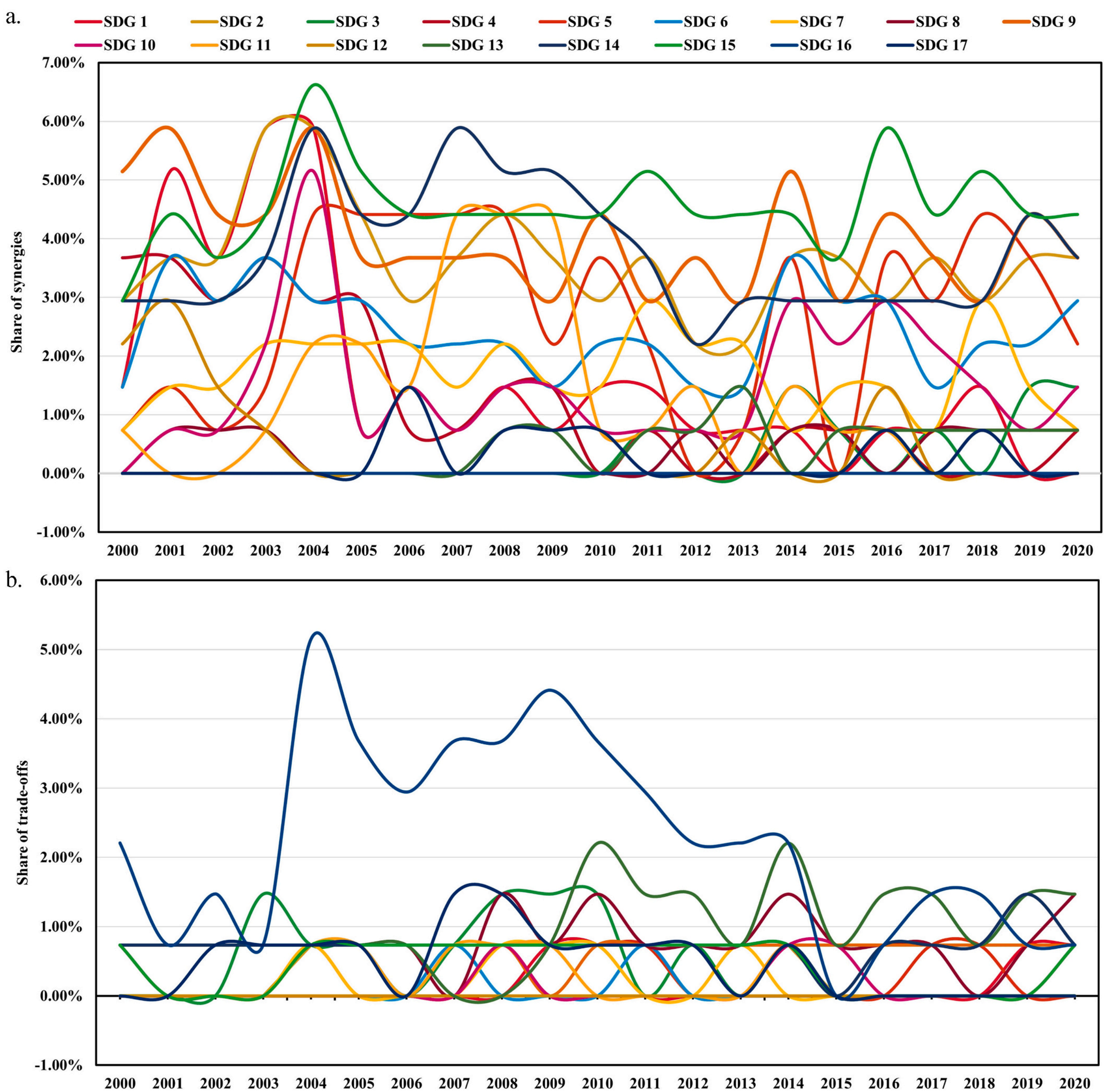


Fig. 6. Shifting dynamics of the synergy and trade-off shares of SDGs in the Eurasian continent between 2000 and 2020. a. Shifting dynamics of the synergy shares of SDGs in the Eurasian continent between 2000 and 2020. b. Shifting dynamics of the trade-off shares of SDGs in the Eurasian continent between 2000 and 2020.

centrality of each SDG to prioritize the 17 SDGs (the large impact indicated a high priority). The results showed that the SDG with the highest weighted centrality ranking among the 17 SDGs were SDG3, SDG4, and SDG1, representing those goals with the greatest network impact (i.e., priority) (Fig. 10a).

SDG3 is a critical developmental outcome where multiple SDGs stand to benefit from advancements in reproductive and respiratory healthcare, as well as the containment of infectious disease spread. Examples include SDG6 and SDG7. In addition, SDG3 can be a major enabler; for example, it can largely contribute to SDG1 and SDG8. SDG4 serves as the primary leverage point for adding new technologies to SDG9, which can improve SDG7 and SDG6, increasing agricultural production and contributing to the realization of SDG2. Poverty is at the root of many other challenges worldwide, such as hunger, inequality, and health and education disparities. Achieving SDG1 ensures that people have adequate food, water, and sanitation; access to good education and health services; and a stable social and economic base. These are the core elements of sustainable development critical to long-term human well-being and global peace in the long term.

Furthermore, prioritization of SDGs differs across subregions. We found that, spatially, the CASR 17 SDGs had the largest differences in network impacts (weighted centrality), from 1.38 of SDG6 to 12.42 of SDG14, whereas the MNSR had the smallest, from 1.92 of SDG8 to 8.46 of SDG2. SDG prioritization varied spatially across the sub-regions. In general, SDG2 consistently received top priority across a majority of subregions, in contrast to SDG8, which frequently garnered the least attention in terms of prioritization (Fig. 10b). SDG2 strives to eradicate hunger, attain food self-sufficiency, enhance dietary quality, and foster

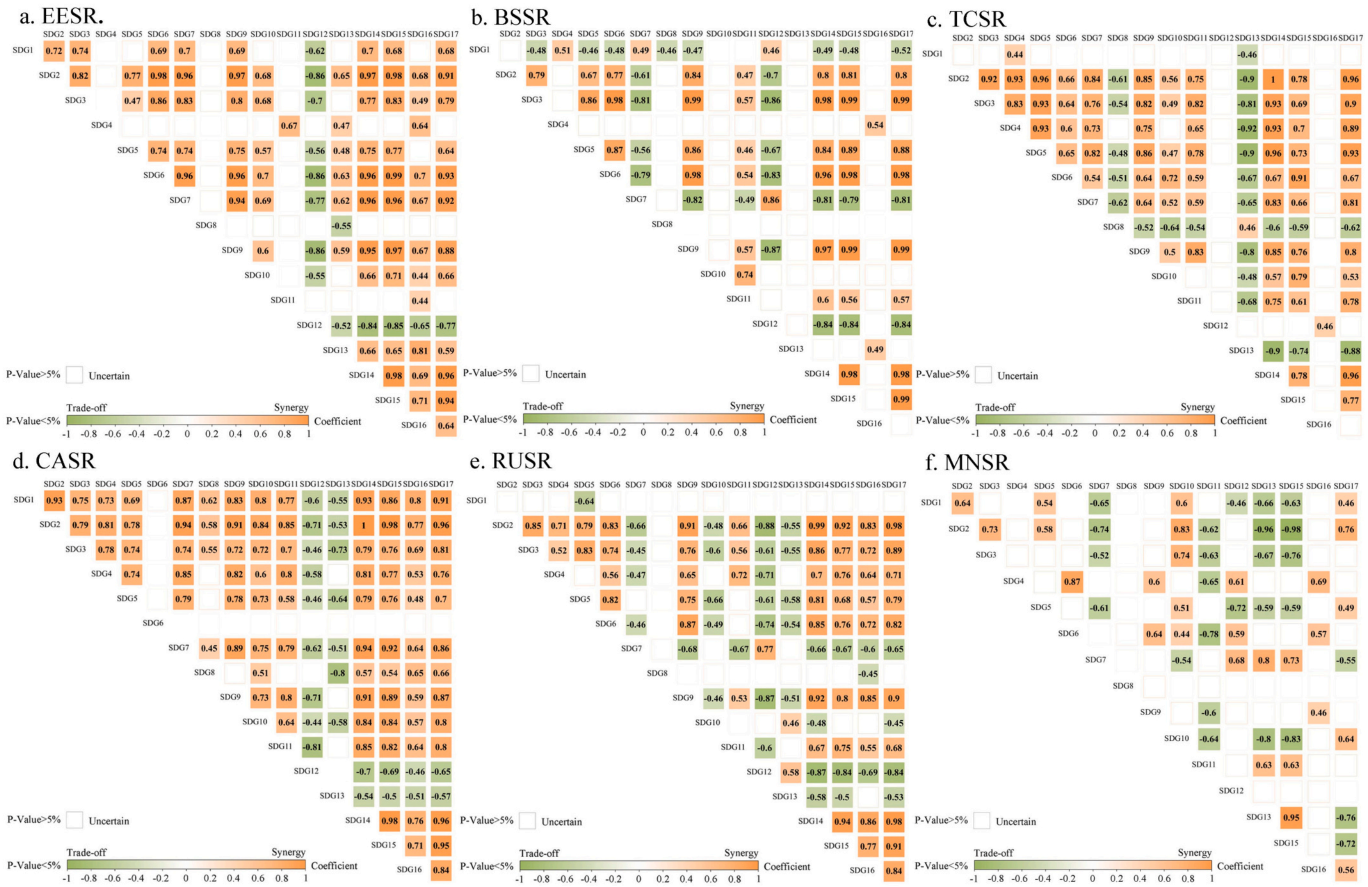


Fig. 7. Interactions among SDGs in the Eurasian continent sub-regions over the period 2000–2020. a. Interactions among SDGs in EESR over the period 2000–2020. b. Interactions among SDGs in BSSR over the period 2000–2020. c. Interactions among SDGs in TCSR over the period 2000–2020. d. Interactions among SDGs in CASR over the period 2000–2020. e. Interactions among SDGs in RUSR over the period 2000–2020. f. Interactions among SDGs in MNSR over the period 2000–2020.

sustainable farming practices. With approximately 2813.90 million poor Eurasians, food security is the most critical and urgent challenge. If SDG2 is blocked, all other SDGs will be affected.

3.5. *Challenges and keys of SDGs in the Eurasian continent*

The Eurasian continent has made some progress toward achieving SDGs between 2000 and 2020; however, challenges in achieving the 2030 SDGs persist (Henderson and Loreau, 2023). First, SDG12 and SDG13 have a decreasing trend in Eurasia (Fig. 3); they were commonly associated with trade-offs, implying that promoting SDG12 and SDG13 may require trade-offs with other SDGs. Maintaining simultaneous growth of other SDGs while promoting SDG12 and SDG13 is a major challenge for the Eurasian continent. Previous studies have found that higher levels of GDP and Human Development Index (HDI) caused improved health and nutrition; however, they also caused greater environmental and physical impacts and amplified greenhouse gas emissions, impeding the achievement of SDG12 and SDG13 (Allen et al., 2021; Hu et al., 2022). Eurasia is a major world economic power and population center, and its economic development and energy consumption profoundly impact global climate change. Unusual climate change has been crucial to natural and livelihood changes in Eurasia for decades. In addition, many Asian and European countries are affected by climate hazards and environmental damage in their internal and border areas, making responding to climate change an urgent task for the region (Zhang et al., 2022a). Prior causal analysis has emphasized that neglecting this issue could weaken the progress of 16 out of 17 SDGs, conversely, addressing it effectively holds the potential to bolster all 17 SDGs (Fuso Nerini et al., 2019). Therefore, Climate Action (SDG13) is vital in the SDG interactive networks. Similarly, this explains the conflict among SDG12, SDG13 and other SDGs (Acuti et al., 2020).

Second, by assessing the progress of the Eurasian SDGs, we found that sustainable progress on the continent varies considerably across regions and changes significantly over time. The northern Eurasian countries are generally progressing faster toward sustainable development than the south. The EESR, BSSR, TCSR, and RUSR are developed sub-regions of Eurasia. Abundant human and social resources and rapid technological advancements are coupled with high GDP, household income, and a large influx of educated people. This accelerated the achievement of the Eurasian SDGs. In contrast, the MNSR and CASR remain challenged and hindered in achieving their SDGs. For Mongolia, the decline in SDG13 illustrates that deforestation and desertification in the country stemming from human activities and climate change (Ren et al., 2022b) pose a considerable hindrance to accomplishing sustainable development objectives, affecting the livelihoods of millions and poverty reduction efforts. Hence, Mongolia has a high poverty rate, and a significant percentage of the population lives below the poverty threshold (Ren et al., 2022a). In addition, the decline in SDG7 and SDG8 illustrates the structure of an economy dominated by the mining sector that lacks diversification and sustainability, making it dependent on global commodity price volatility (Amartuvshin et al., 2021; Zandariya, 2022). All these pose significant challenges for Mongolia in achieving sustainable development (Fig. 4b). As a typical region of water-constrained development (Huan et al., 2023), the decline in SDG6 and SDG12 indicates that the shortage and distribution of water resources in the CASR and the sustainable use and recycling of water resources significantly challenge sustainable development in the region (Fig. 4b) (Qin et al., 2022).

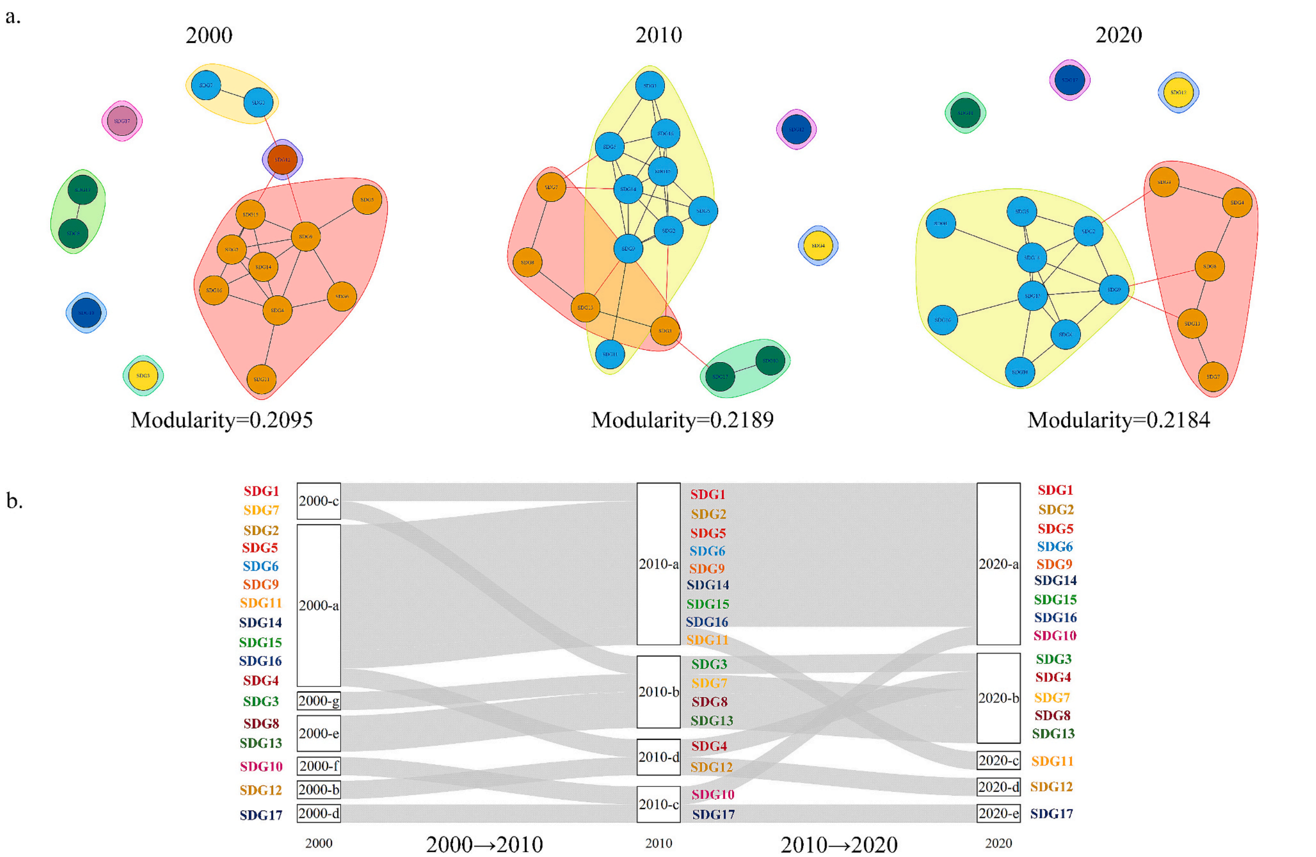


Fig. 8. Modularity of the SDG networks between 2000 and 2020. a. Modules of the SDG networks. Each module is represented by a different background color. Black lines depict SDG interactions within the same module, while those across different modules are depicted by red lines. b. Changes in module composition of the SDG networks. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Third, based on a specific analysis of the SDG progress, the overall progress of the Eurasian continent masks the decline in SDGs in some regions (Fig. 4a) and each SDG (Fig. 4b). For example, the score of SDG1 has been increasing, while decreasing in eight countries (Azerbaijan, Ukraine, Estonia, and Latvia); SDG4 scores have been increasing but declining in five countries (Belarus, Ukraine, and Estonia) (Fig. 4b). Therefore, the key to contributing to the overall achievement of the SDGs at the regional level is to avoid the negative impact of partially deteriorating SDGs, the reason being that these SDGs would counteract the overall SDGs (Bali Swain, 2017). Similarly, considering whether declining scores in certain regions are concealed by progress in others is essential (Ike et al., 2019). Furthermore, according to the interaction of the Eurasian SDGs, their shares of synergy and trade-offs increased, whereas the shares of uncertainty decreased, indicating an increasing interaction between the SDGs (Fig. 5). However, we found that most of the trade-offs between the Eurasian SDGs were connected to unsustainable development, a model that emphasizes the importance of increasing economic prosperity to produce human well-being at the cost of ecological sustainability. Thus, a crucial way to achieve the SDGs is to minimize the trade-offs between different goals while maximizing synergies (de Oliveira and Oliveira, 2023; Senadjki et al., 2022; Vanham et al., 2019).

3.6. Development patterns and strategies of SDGs in the Eurasian continent

The homogeneity and heterogeneity of the Eurasian continent determine the complexity of achieving their SDGs, which require countries to cooperate and take collaborative measures to achieve the SDGs (Van Niekerk, 2020). This includes building partnerships between the governments, non-governmental organizations, and the private sectors to share best practices, technologies, and experiences and to jointly integrate resources, including human, material, and financial assets, to facilitate SDG implementation (Shaofeng et al., 2019; Xiong et al., 2021). However, each country has unique cultural, political, economic, and social contexts. These differences should be considered when developing SDG governance strategies to ensure that governance measures are adapted to the circumstances of different countries (Bose and Khan, 2022; Cuiyun and Chazhong, 2020; Fang et al., 2021; Gao and Bryan, 2017).

First, regarding the economic development level, the EESR, BSSR, TCSR, and RUSR have achieved relatively stable economic growth and a high level of per capita income. In contrast, the MNSR and CASR economies are smaller, in the development stage, and challenged with poverty, unemployment, and inequality. Therefore, the regions should promote sustainable economic growth, reduce poverty, and increase employment to achieve SDGs (Zhan et al., 2022). Second, concerning environmental protection, Mongolia experiences grassland degradation and desertification. The vast expansion of sandy areas is significantly threatening and associated with preventing and controlling dust storms, and land degradation should be combined with the support of green technology and policy regulations (Zandariya, 2022). To achieve the 2030 SDGs, identifying rational land use patterns and implementing related policies are crucial for promoting sustainable development in the MNSR (Zhang et al., 2022a). As the RUSR is a large emitter of greenhouse gases, improving energy efficiency and strengthening restrictions and regulations on pollutant emissions will help solve Russian environmental challenges and facilitate accomplishing the SDGs (Kilinc-Ata and Likhachev, 2022; Sutyrin, 2022). The BSSR, TCSR, and CASR should focus on water management and environmental pollution control (Zhan

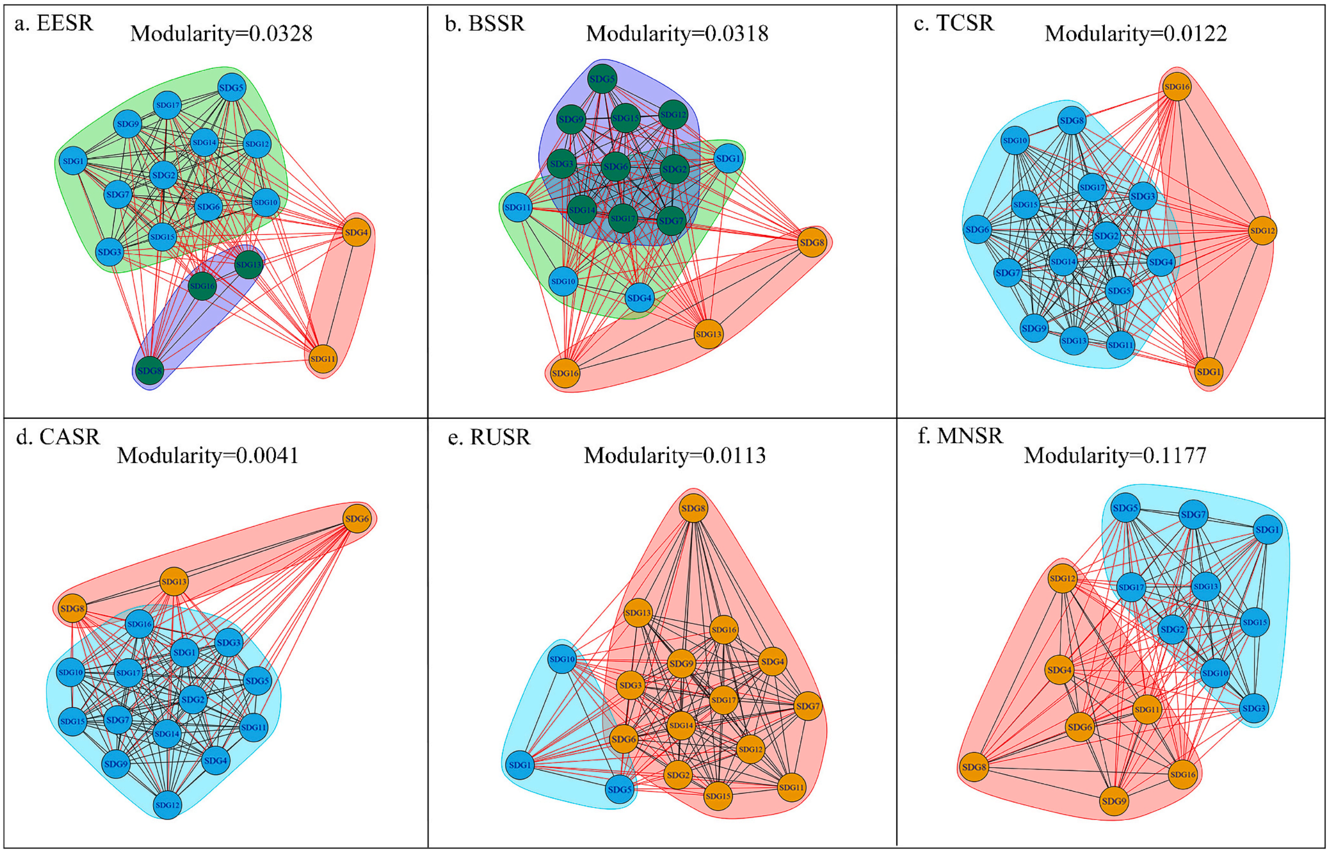


Fig. 9. Modularity of the SDG networks in different regions.SDG14 was excluded from the MNSR.

et al., 2022). Finally, in the social sphere, the EESR and RUSR relations are complex and contradictory (Saiu et al., 2022), and the war in Ukraine caused severe social devastation and humanitarian crises requiring reconstruction and recovery efforts (Rawtani et al., 2022). The MNSR, on the other hand, should focus more on infrastructure development, education, and healthcare access to improve living standards and social welfare (Amartuvshin et al., 2021).

Between 2000 and 2020, the trade-offs and synergies among the Eurasian SDGs gradually became clearer, uncertainty gradually decreased, and the share of synergies among the SDGs gradually increased (Fig. 6a). However, the trade-off shares also gradually increased (Fig. 6b), particularly, that of SDG13. Decades-long peculiar shifts in climate have notably steered both environmental transformations and adjustments in human sustenance across the Eurasian continent (Zhan et al., 2022). Past studies on causation have demonstrated that it can be detrimental to the 16 SDGs, even if countering it can strengthen 17 SDGs (Filho et al., 2023). Therefore, recognizing synergistic pathways for SDG13 and socioeconomic development is essential to address the barriers to a shift in the interaction of the Eurasian SDGs (Yin et al., 2023). In addition, system analysis is critical for managing trade-offs, identifying leverage points, and achieving sustainability goals (Huan et al., 2021). Foremost among these is the need for strong, cross-scale, cross-sectoral regulatory regimes that recognize complex interactions between the components of sustainable development (Pradhan et al., 2017). Decision-makers cannot continue working in isolation and should manage to broaden participation, create collective benefits, and build a consensus (Weitz et al., 2018).

4. Conclusions

Determining the progress of SDGs and quantifying their interactions, linkages, and prioritizations is essential for uncovering the intricate mechanisms and outcomes of sustainable development. Thus, this study constructed a research framework for regional SDGs and quantified the progress of SDGs in the Eurasian Continent from 2000 to 2020. In addition, we used the Spearman coefficient to study the interactions between SDGs and used social network analysis to explore linkages and prioritizations.

The findings of this paper are as follows: (1) The SDGs in Eurasian Continent had an overall upward trend; however, SDG12 and SDG13 showed a downward trend. The northern region generally had a better performance than the south. Furthermore, for all 16 countries, SDG2, SDG3, and SDG5 showed an increasing trend. (2) Moreover, the synergies between the Eurasian SDGs were greater than the trade-offs, and there was regional heterogeneity in the ratio of synergies to trade-offs across the subregions. Similarly, between 2000 and 2010, the Eurasian modularity changed drastically; in 2010–2020, the modularity changed steadily. SDG3, SDG4, and SDG1 were the prioritized SDGs. (3) In addition, this research highlights the significance of investigating spatial variations and temporal fluctuations in the interactions and prioritization of regional SDGs. This can be fundamental to conducting similar analyses in other regions. Overall, attaining complete SDG implementation continuously poses a significant global challenge.

Accordingly, the study furnishes policymakers, scholars, and relevant stakeholders with a suite of recommendations for both regional and national levels, encompassing initiatives such as cross-jurisdictional collaboration and multidisciplinary studies. In conclusion, this study outlines a comprehensive methodology for understanding the dynamics of sustainable development and the intricate web of SDG interactions, connections, and prioritization strategies – a roadmap meriting sustained investigative focus beyond the 2030 horizon.

Several limitations and challenges require attention in future studies. (1) From the data availability of the Eurasian continent assessment indicators, data availability varies considerably between regions, years,

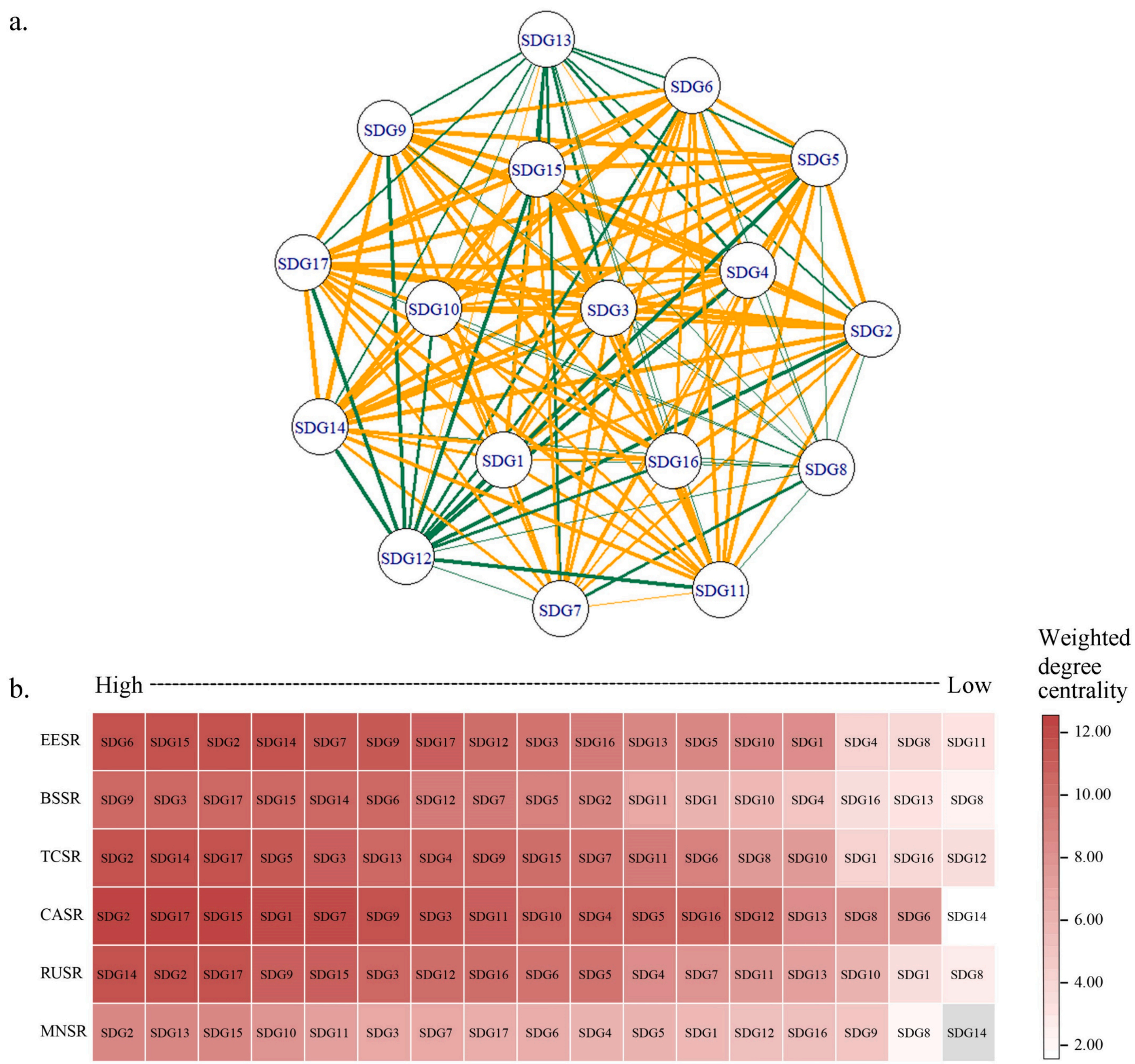


Fig. 10. SDG prioritizations in the Eurasian continent. a. SDG prioritizations (network impacts) in the Eurasian continent. b. SDG prioritizations (network impacts) in each subregion. SDG14 was excluded from the MNSR.

and indicators, with more missing data for Turkmenistan and Mongolia (Table S2). There is more missing data before 2005 (Table S3), and SDG17 has missing data. Therefore, it is complicated and challenging to build an SDG indicator system with complete time series and national data and indicators. In the future, big Earth data can be used to provide more accurate and real-time data sources. (2) Complex causal feedback among different SDGs and their cross-scale effects significantly influences the overall implementation of SDGs; studying these gaps is outside the scope of this study.

Despite these limitations, our analytical framework and results provide perspectives for future sustainability policies and establish a foundation for subsequent studies. In the future, with improved data methods, we will shift from correlation to causality analysis and analyze the dynamic changes in the interactions among SDGs, further revealing the complex mechanisms behind their synergistic and balancing effects and finding solutions to sustainable development conflicts. Moreover, the development and linkages of SDGs are dynamic and susceptible to various influences, such as resource accessibility, financial motivations, and unforeseen occurrences, which may influence the progress, interactions, and prioritizations of regional SDGs. The Eurasian continent is a hotspot of geopolitical conflict, particularly the war in Ukraine, which has had significant impacts and spillover effects on the economic, social, and environmental development of the Eurasian continent. The war in Ukraine has increased uncertainty in global oil, gas, and food markets; exacerbated the spike in energy prices and the global food crisis since 2021; and complicated achieving SDGs such as SDG7 and SDG2. Therefore, acquiring additional data to compare the Eurasian SDG process before and after the war in Ukraine is essential to explore the impact of black swan events such as the Ukrainian war on the Eurasian SDG network.

CRediT authorship contribution statement

Qian Liu: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft. **Fujia Li:** Funding acquisition, Supervision, Validation, Writing – review & editing. **Suocheng Dong:** Funding acquisition, Supervision, Validation, Writing – review & editing. **Hao Cheng:** Resources, Software, Visualization. **Longwu Liang:** Supervision. **Bing Xia:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2024.06.007.

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