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Unveiling complementarities between mangrove restoration and global sustainable development goals

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ABSTRACT

Indonesia, renowned as the most mangrove-rich nation, has committed to extensive mangrove restoration policies, but the effects of these policies have yet to be systematically evaluated. Our study conducts a comprehensive network analysis to investigate the synergies between mangrove restoration policy and global Sustainable Development Goals (SDGs) achievements by exploring their interactions. This investigation follows the 'product space' method in economics and creates the 'Mangrove-SDG space' to assess each metric pair's co-occurrence and comparative advantages with validated stability. Our analysis unveils a tripartite structure, encompassing socio-economic and environmental clusters, each significantly contributing to global sustainability and a distinctive mangrove cluster tied to land attributes. At the Goal level, mangrove loss showcases robust synergies with SDGs 12 (Responsible Consumption and Production) and 13 (Climate Change), and mangrove metrics such as tropical storm frequency and mangrove change, indicating strong interdependences between mangrove forests and SDGs. The result indicates that improved performance of climate change and responsible consumption can greatly enhance mangrove forests' performance in alleviating mangrove loss and reducing tropical storms. Moreover, our analysis underscores the central roles played by 'bridge' Goals. Indicator-level space details how they warrant prioritization because of their cascade synergistic enhancements across widely interconnected indicators, triggering systematic positive improvements. Turning to Indonesia, we advocate a strategic shift from solely expanding mangrove extent to focusing on four critical policy priorities: effective nitrogen management, enhancing Ramsar site efficiency, optimizing logistic performance, and addressing urban population conditions. These priorities are pivotal to seeking complementarities between Indonesia's international sustainability commitment and fostering mangrove restoration success.

1. Introduction

Mangrove forests play a vital role in sustaining ecosystems at both local and global scales. This salt-tolerant ecosystem found in the intertidal regions of tropical and subtropical coastlines provides a habitat for wildlife, traps nutrients within dense root systems, nourishes marine wildlife, and serves as a carbon sink that contributes significantly to global climate regulation (Friess et al., 2019a). Healthy marine ecosystems can support local livelihoods and assist in eradicating poverty. Consequently, prior studies have found that mangrove forests broadly influence various socio-economic aspects of society, including substantial economic and ecological benefits (Himes-Cornell et al., 2018; Siikamaki et al., 2012; Ricke et al., 2018). For example, preventing further mangrove loss could potentially avoid nearly 424 $MtCO_2e$ by 2030 globally, which equates to 6% of the emissions generated by land use change in 2019 (Sasmito et al., 2023).

However, conserving the world's mangrove forests is a complex issue with various challenges. As the human population increases, especially in coastal communities, mangrove forests have experienced a net loss in recent decades (Alban et al., 2020; Goldberg et al., 2022; Thomas et al., 2017). Studies have indicated that as high as 35% of the world's mangrove areas in the 1980s–1990s had already been deforested, and

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the yearly mangrove deforestation rate is from 1% to 8% between 1980 and 2012 (Friess et al., 2019a). On the other hand, the natural condition of mangrove forests and their complex root system make it challenging to allocate property rights efficiently for proper management. Privatizing mangrove areas has resulted in negative socio-ecological impacts (Adger and Luttrell, 2000), such as worsening the loss of ecosystem services from mangroves and increasing socioeconomic inequality in local communities by favoring inefficient and unsustainable allocation of resources (Ferreira et al., 2022). Therefore, conserving mangroves is hard to achieve as it is closely linked with the efficiency of mangrove management and the quality of mangrove governance.

Moreover, identifying mangrove forests and the extent of their underlying drivers has long presented challenges due to a combination of natural and human-induced factors. Mangrove forests thrive exclusively in the intertidal zone, bridging the gap between coastal and terrestrial landscapes. Their existence is intricately intertwined with the landscapes' natural ebb and flow. It is inherently susceptible to shifts induced by increased temperatures, rising sea levels and the erosive forces of large-scale disturbances such as stronger storms and ocean acidification. Furthermore, the spatial distribution of mangroves exhibits considerable variation due to divergent abiotic environments, forest structures, species diversity, and more, each varying within and across nations (Worthington et al., 2020). This high geographical variability serves as a fundamental driver of mangrove deforestation, consequently leading to the loss of crucial ecosystem services, such as carbon sequestration, on a global scale (Sasmito et al., 2023).

Conversely, the successful efforts to expand mangrove extent and the concurrent enhancement of ecosystem services through restoration projects have spurred the emergence of national and regional policies geared toward mangrove conservation and rehabilitation. Mangrove forests are widely mentioned by at least 45 countries in their national plans to tackle climate change (Deng et al., 2022), 28 countries in their restoration pledges, and 62 countries in their national biodiversity plan (Landgap Report - Homepage; International Day for the Conservation) for global sustainability. For example, Indonesia proposed a mangrove rehabilitation target to restore 600,000 ha by 2024, in line with the UN Decade of Ecosystem Restoration (2021-2030), highlighting a strong commitment made by the global conservation community to increase mangrove cover by 20% by 2030 (Sasmito et al., 2023). Similarly, China's national mangrove action plan aims for restoration of 18,800 ha before the year 2025 to support the livelihoods of coastal communities and absorb carbon dioxide (The State Concil, 2020).

The intricate dynamics in mangrove forest habitats encompass an array of factors, including ongoing rehabilitation and conservation initiatives, juxtaposed against mangrove degradation and deforestation resulting from natural climatic fluctuations and anthropogenic logging activities. This complexity introduces significant uncertainties in quantifying mangrove forest extent and its proximate drivers, directly impacting the assessment of how effective mangrove conservation policies are. Notably, compared to the large quantity of global-scale data available for mangrove forest coverage and change, the field lacks robust, time-sensitive, and consistent datasets capable of addressing the geographical variations in mangroves, encompassing different geomorphic settings, species types, and drivers essential for tailoring conservation and restoration strategies for effective policy interventions (Worthington et al., 2020; Slobodian et al., 2018; Maynard et al., 2019). This extends to unanswered questions regarding how macro-scale mangrove conservation policies influence global sustainability.

Nations and organizations have invested efforts in estimating how mangrove forests can contribute to international sustainable development. For example, The United Nations' Sustainable Development Goals (SDGs) proposed in 2015 represent an ambition to foster intergovernmental efforts to achieve sustainable development by 2030. This comprehensive framework includes 17 interlinked Goals and over 200 indicators, including those related to mangrove forests. Moreover, the United Nations (UNRIC, 2022), along with many international and regional non-profit initiatives (Asia; NASA Applied Sciences Program; INSIGHTSIAS; Seymour and Busch, 2017), have listed many ecosystem services that mangroves can provide in achieving specific SDGs, including the discussion on how potential loss could impede SDG achievement (Krause and Tilker, 2022) and how mangrove restoration may facilitate progress (IUCN). Studies have also addressed the mechanisms of how mangrove forests affect certain SDGs, such as Goal 14 (life underwater) in coastal management (Friess et al., 2019b) or in specific regions such as Kenya (Obiene et al., 2022) and Indonesia (Sasmito et al., 2023). These efforts help document the unique interlinkages between mangroves and SDGs in certain areas. However, these understandings of the interactions between mangrove conservation and SDG achievement remain qualitative and unilateral. Governance structure, environmental contexts, and socio-economic conditions can influence their complex interactions, and not including them and their interconnectedness in the policy evaluation system may lead to biased policymaking and distort the overall achievement of the SDGs, along with mangrove conservation.

This paper investigates the complementarities between SDGs and mangrove conservation by comprehensively and systematically connecting mangrove metrics with SDGs at coarse and fine levels by expanding the application of the 'product space' concept in economics. The product space approach, derived from the revealed comparative advantages (RCA) of products, can be used to compare the economic specialization pattern in economics. By measuring the shared production capability between products' economic activities, named as 'proximity,' 'product space' can illustrate the similarity of the productive ability of products (such as infrastructure, labor, capital, etc.). This indicates which products share similar production capabilities and are more likely to be efficiently produced simultaneously representing the complementarities of products. This concept has been applied in constructing 'SDG spaces' (Gong et al., 2024a, 2024b; Yu et al., 2025), measuring the complementarities between SDGs and indicators at global and national levels with a more stable structure and a substitute understanding of SDG pairs' synergies compared to the traditional interpretation. Furthermore, to explore the application of 'product space' and its implications for conservation policy implications, especially in mangrove conservation, we apply the concept to understand the complementarities and structures between mangrove-related indicators and SDGs. The complementarity measurement of the performances of mangrove conservation outcomes and SDGs can provide science-based knowledge on what metrics have similar requirements to work together synergistically, considering efficiency and overall outcomes. The high synergetic proximity between the pairs of SDGs and mangrove metrics displaying a robust network connection is more likely to exhibit synergies: enhancing one goal can positively improve another. Moreover, this integrated approach to quantitatively discussing the structure and relationship between mangroves and the SDGs provides a powerful tool for systematically assessing their interactions by identifying co-benefits and synergies. These synergies can help establish actionable priorities for nations to achieve mangrove-sustainable development, and provide more robust policymaking than focusing solely on specific aspects of SDGs. The concept clarificationn between 'product space' and 'Mangrove-SDG space' is provided in Table 1.

Table 1
Concept clarifications between 'Product Space' and 'Mangrove-SDG Space'.

	Product Space	Mangrove-SDG Space
Network	the relatedness or proximity between products traded in the regional market	The complementarities or proximity between measurements of two policies (mangrove-related metrics and SDGs) in a given regional level
Nodes	Products	SDGs + mangrove metrics
Edges	the similarity of productive ability required to produce two products within a given region	the complementarities between each node pair, reflecting the environment similarity to incubate the performance of each node.

In the Mangrove-SDG space, a well-connected goal, target, or indicator is central to developing numerous other goals or indicators. A less connected goal may need more synergies to avoid slow progress. The study will answer the following questions: (1) What is the global Mangrove-SDG space at goal and indicator levels? (2) Compared to existing methods, is the Mangrove-SDG space stable for long-term policymaking? (3) How do countries prioritize essential goals/indicators for effective policies based on the space? To address these questions, we construct three distinct tiers within the Mangrove-SDG space employing diverse datasets. The initial two tiers of these spaces amalgamate SDG data at the goal level with two sets of mangrove data: one emanating from two sources of mangrove loss data and the other encompassing various metrics of mangrove socio-ecological system. The third tier of the Mangrove-SDG space encompasses SDG data at the indicator level, intricately interwoven with the metrics related to the mangrove socio-ecological system. By constructing three tiers of space, we can test the stability of spaces with different datasets and understand the complementarities in mangrove sustainability at multiple resolutions. Subsequently, we visually represent these intricate network structures and undertake an in-depth network analysis to identify and delineate clusters and ascertain the core-periphery dynamics. We also embark on comparative analysis to discern and quantify the relative stability levels exhibited by the Mangrove-SDG spaces in contrast to correlation coefficient networks. Through these processes, our study can provide policymakers with quantitative tools and insights into achieving sustainable mangrove development and advancing the broader SDGs. It will also enhance understanding of the interconnections between mangrove forests and sustainable development, paving the way for more effective and efficient policymaking.

2. Methods

The methodology includes the construction and network analysis of 'Mangrove-SDG spaces' while emphasizing validating their stability. The subsections discuss them in detail.

2.1. Mangrove-SDG space

Mangrove-SDG space assesses the complementarities among SDGs and mangrove governance metrics from the 'product space' concept (Hidalgo et al., 2007; Alabdulkareem et al., 2018) and its application in measuring SDG interactions (Gong et al., 2024a, 2024b; Yu et al., 2025). We construct three levels of Mangrove-SDG space using different datasets. The first two levels of spaces incorporate SDG goal-level data with two sets of mangrove data: 1) two sources of mangrove loss data and 2) full mangrove socio-ecological system metrics. The third level of mangrove-SDG space covers SDG indicator-level data with full mangrove SES metrics. All levels of SDG spaces are constructed and analyzed following the method below.

We define the 'Mangrove-SDG space' as a network framework encompassing inter- and intra-connections (edges) among SDG indicators and mangrove-related data (nodes). The concept of 'proximity,' signifying the degree of closeness between nodes in this analytical space, serves as the primary metric for identifying synergies within the network. Interactions marked by higher proximity values, closer to 1, denote pronounced synergies within the space. We delineate a proximity threshold by utilizing the mean from the network proximity distribution, setting aside low-proximity interactions to focus on complementarities with high intensity (Gong et al., 2024a, 2024b).

Mathematically, proximity is a quantifiable measure of the co-occurrence of comparative advantages in pursuing different objectives. It is succinctly expressed as the conditional probability that a specific region can achieve one goal more effectively when it demonstrates superior performance in accomplishing another goal. This proximity, denoted as θ (g, g'), is formally defined as:

$$\theta(g,g') = \min\{P(RCA(i,g)>1)|RCA(i,g')>1), P(RCA(i,g')>1)|RCA(i,g)>1)\} = \frac{\sum_i I(RCA(i,g)>1)|I(RCA(i,g')>1)}{\max\left\{\sum_j I(RCA(i,g)>1), \sum_j I(RCA(i,g')>1)\right\}} \quad (1)$$

Here, RCA(i, g) represents the revealed comparative advantage of country i in achieving mangrove metrics/SDG goal/indicator: g. The variables i' and g' encapsulate all countries and metrics/goals/indicators. The indicator function, I(·), yields 1 when the specified condition is met and 0 otherwise.

$$RCA(i,g) = \frac{\frac{x(i,g)}{\sum_{g'} x(i,g')}}{\frac{\sum_{i'} x(i',g)}{\sum_{i',g'} x(i',g')}} \quad (2)$$

RCA represents the revealed comparative advantage in region i in achieving metric/goal/indicator g. x(i, g) signifies the developmental status of metric/goal/indicator g in country i. The symbol $\sum$ represents summation across various indices. For example, $\sum_{g'} x(i,g')$ represents the sum of the development level of all metrics/goals/indicators in country *i*, $\sum_{i'} x(i',g)$ is the sum of the development level of *g* in all countries. *RCA (i,g)* > 1 indicates that region *i* has a revealed comparative advantage in *g* compared to its other capabilities.

The culmination of this rigorous calculation results in a matrix for the Mangrove-SDG spaces, encompassing dimensions of 19x19, 38x38, and 116x116, corresponding to the goal-level space with two mangrove loss data, with all mangrove metrics and indicator-level space, respectively. Notably, the non-diagonal elements within this matrix effectively encapsulate the essence of complementarity between pairs of goals and indicators.

2.2. Network analysis

Our analytical approach encompasses the calculation of community partition and betweenness centrality to unveil the network's aggregation tendencies and delineate the core-periphery structure. A robust community structure manifests as dense connections within groups and relatively sparser connections bridging distinct groups. To quantify this structure, we rely on modularity, a parameter measuring the deviation between the number of edges within a group and the anticipated count in randomly generated equivalent networks (Newman, 2006). Modularity assumes a constant value within the −1 to 1 range, with higher values signifying a more pronounced community structure.

The Louvain algorithm, an unsupervised heuristic technique, facilitates the identification of optimal community partitions. This algorithm operates iteratively, cycling through two phases until convergence is achieved. In the initial phase, nodes are reallocated between communities to maximize the modularity value within each group. The subsequent step involves forming and amalgamating communities into super-nodes to establish an interconnected network. Within communities, nodes exhibit a high degree of complementarity, fostering synergistic interactions. In contrast, inter-community nodes showcase diminished synergy within the space (Blondel et al., 2008).

To delve into the core-periphery dynamics, we employ Ulrik Brandes' algorithm to compute the betweenness centrality of both goals and indicators (Brandes, 2001). The results are then visualized within the network, with node size reflecting their betweenness centrality. In Mangrove-SDG networks, nodes characterized by higher betweenness centrality wield more substantial influence, as they serve as vital connectors facilitating synergistic interactions across many nodes. Those nodes with the highest betweenness centrality values are 'bridge' goals/indicators discussed with further details for policy implications.

The SDG space is subsequently visualized, where network nodes represent goals and indicators, while edges symbolize pairwise proximity links. To create these visualizations, we employ the Force Atlas and Fruchterman-Reingold layouts. Both layouts are underpinned by force-directed algorithms, simulating the behavior of physical systems to attain a stable configuration. In this analogy, graph nodes represent particles, while the edges connecting them act as springs or electrical charges. Consequently, nodes with extensive connections gravitate towards the central regions of the graph, while those with fewer linkages find placement towards the periphery. All these network analysis techniques are executed using Gephi 0.10.0, a robust tool designed explicitly for network analysis, either directly or through Gephi plugins (Bastian et al., 2009).

2.3. Stability validation

Our study compares stability levels between Mangrove-SDG spaces and correlation networks across two distinct time spans: 1996–2006 and 2007–2016. Correlation networks gauge similarity in performance between nodes based on changes in data, influencing the overall network structure via alterations in correlation coefficients between nodes. In contrast, Mangrove-SDG spaces measure similarities in the external environment fostering node performance, which may exhibit less variability with minor changes in node values. For instance, increasing nitrogen efficiency could promptly alter food production enhancements in the correlation network. In contrast, such efficiency improvements might not substantially impact Mangrove-SDG spaces due to their construction based on shared external factors like technology, resources, and capital that nurture efficiency improvements. Mathematically, stability comparison involves quantifying disparities in network structures between the two time spans using matrix norms. Matrix norms serve as mathematical tools to measure matrix structures' "magnitude" or "size", facilitating comparison of network structures. Networks with similar matrix norm values indicate comparable structures. The resultant differences between network structures across periods are assessed relative to a reference network established during 1996–2006, expressed as a proportion. Specifically, this equation is formulated for goal-level comparisons to highlight the extent of network variations between the specified time intervals.

$$\Delta Norm = \frac{((Norm(N_{0716}) - Norm(N_{9606})) \times 100}{Norm(N_{9606})} \tag{3}$$

Here, N represents either the correlation network or Mangrove-SDG space concerning goal-level mangrove metrics and SDG goals. A smaller ΔNorm signifies a lesser disparity in network structures, while an elevated value denotes a more substantial divergence. This analytical process is executed within the Matlab Version R2021a.

3. Results

3.1. Unveiling the Mangrove-SDG nexus: a multi-dimensional exploration

The goal-level 'Mangrove-SDG space' (Fig. 1) encompasses 17 SDG goals and two pivotal mangrove loss indicators, namely GMW_loss and Gold_loss, to represent Global Mangrove Watch (GMW) and Goldenberg (Gold), aggregating to 19 nodes, intertwined by a web of 183 synergetic interactions. These two datasets are well-acknowledged sources of global mangrove forest cover data, with one having an overestimate and the other having an underestimate of the real-world mangrove loss (Goldberg et al., 2022; Bunting et al., 2022).

Employing an unsupervised classification algorithm, we partition this space into two clusters, discernibly categorized as socio-economic development-related goals, denoted as the 'pink group,' and environmental progress-related objectives, represented by the 'green group.' The division is effective because the modularity value of the division is 0.361. This value is used to measure partition quality and falls within a range of 0.3–0.7, which is empirically recognized as an effective partition. The relatively modest modularity value means that all nodes within this space, encompassing the two mangrove loss indicators and the 17 SDGs, are closely interlinked, emphasizing the intricate interplay among elements spanning society, the economy, and the environment.

The proximity between the two mangrove loss indicators is the highest, denoted as 0.94, reflecting the level of similarity of the two datasets in the space regardless of sources and the stability of the space. They are within the environmental-related cluster, underscoring their extensive synergies with environmental-related SDGs. Specifically, they exhibit the highest intense synergies in the space with 12 (Responsible Consumption and Production) and 13 (Climate change) (Fig. 1-b), which are strongly synergized with SDG 14 (Life Below Water). These nodes have the most substantial synergies in the environmental cluster and are the core nodes in the cluster (yellow edges in Fig. 1-a).

Furthermore, enhancing these two mangrove loss indicators can result in synergies with SDGs 2 (Zero Hunger), 8 (Decent Work and Economic Growth), 10 (Reduced Inequalities), and 15 (Life on Land), as they merge within the same cluster, forming a network of robust synergies. SDG 15 (Life on Land) sits at the periphery, with a few tenuous synergistic connections to the core nodes. In contrast, SDGs 2 (Zero Hunger), 8 (Decent Work and Economic Growth), and 10 (Reduced Inequalities) are similarly equidistant from the core of the environmental-related cluster. However, these nodes are in the center of the space with significant betweenness centrality values. These SDGs assume the role of 'bridges' within this space, serving as conduits linking nodes in both clusters. Enhancing these two goals can profoundly augment overall sustainability performance, given their extensive synergistic interactions across the space.

Fig. 1. Goal-level 'Mangrove-SDG' space: (a). 'Mangrove-SDG space,' shaped by two mangrove loss data sources. (b). Synergies between mangrove loss and the associated SDGs.

3.2. Augmenting insight through goal-level 'Mangrove-SDG space'

The goal-level Mangrove-SDG space enriched with a comprehensive array of mangrove metrics constitutes an expansion of prior efforts to categorize interactions to explore more nuanced insights into mangrove sustainability (Fig. 2). As depicted in Fig. 2-a, the space encompasses 20 metrics specific to mangroves and 17 SDGs comprising 37 nodes with 690 synergistic connections. This analysis is an amplified version of the prior goal-level space because the nodes from the preceding space, encompassing SDGs and mangrove loss indicators, are located similarly in this space, with similar classification results. For instance, m-3 (GMW mangrove loss), housed within the environmental-related cluster, clusters with SDGs 12 (Responsible Consumption and Production), 13 (Climate Change), 14 (Life Below Water), and 15 (Life on Land)—mirroring the configuration of the goal-level realm, with their interconnected synergies reinforced by significant proximity (≥0.7).

Our analysis introduces a more intricate web of details concerning mangrove metrics. For example, the core of the environmental cluster embraces mangrove loss and other mangrove metrics, including m-7 (Marine Protected Area (MPA) staff capacity), m-10 (Nationally Determined Contributions (NDC) commitments), alongside m-2 (mangrove change) and m-19 (tropical storm frequency). These mangrove-specific indicators converge with mangrove loss, accentuating their potential to drive transformative improvements in mangrove conservation and the performance of related SDGs within the environmental cluster. Notably, mangrove loss exhibits its most robust synergies with

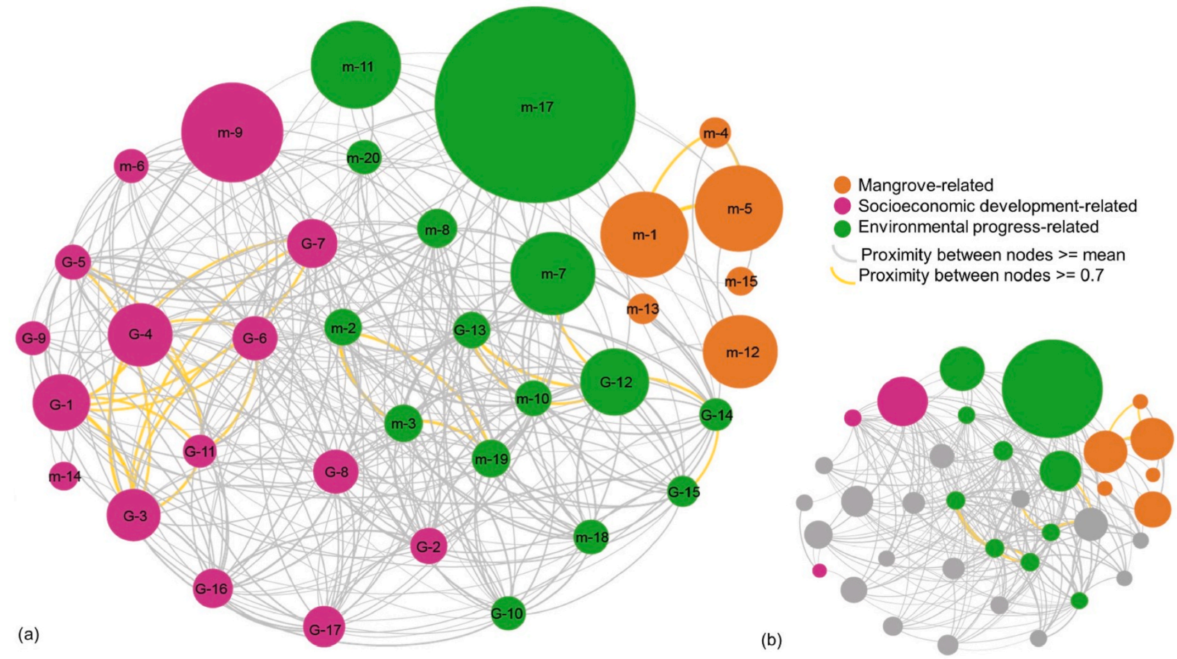

Fig. 2. Augmentation of goal-level 'Mangrove-SDG space': (a). Extending the 'Mangrove-SDG space,' with all mangrove metrics. (b). Synergic interactions between mangrove metrics and their SDGs.

mangrove change and tropical storm frequency, signifying that lower storm occurrences and increasing mangrove areas can significantly mitigate mangrove loss. Additionally, NDC commitments exhibit strong synergies with SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Change), suggesting that international cooperation to encourage countries to reduce emissions can substantially improve climate change mitigation and prompt responsible consumption in industries.

Nevertheless, differences are also discernible. First, an additional cluster takes shape, comprising six mangrove-related metrics. The unsupervised clustering technique indicates the elusive nature of these indicators, rendering them challenging to align with either of the

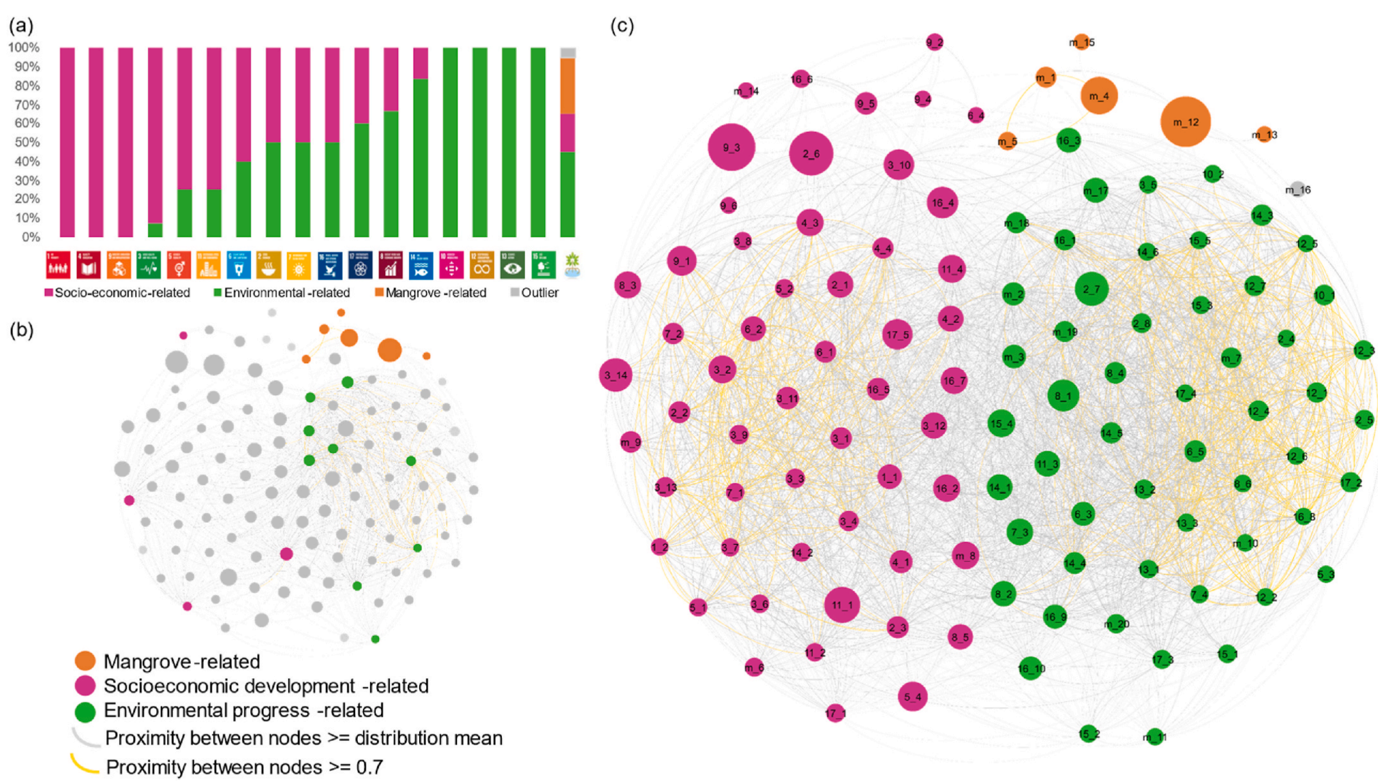

Fig. 3. (a). Percentage chart depicting cluster distribution of SDG indicators and mangrove metrics. (b). Graphical portrayal of synergies binding mangrove metrics and their associated SDG indicators. (c). Indicator-level Mangrove-SDG space with the entirety of mangrove metrics.

primary clusters within the Mangrove-SDG space. These metrics include m-1 (mangrove area in 2016), m-4 (mangrove gain), m-5 (country area in 2016), m-12 and 13 (total number and area of Ramsar sites), and m-15 (the cumulative sum of night light growth). Given their real-world implications, these metrics are intrinsically tied to land areas, diverging from global sustainability metrics rooted in socio-economic and environmental considerations. Furthermore, within the socio-economic cluster, three mangrove indicators find their niche: m-14 (night lights growth), m-6 (varieties of Democracy), and m-9 (the economic complexity index). Notably, m-6 and m-14 occupy the periphery of the socio-economic cluster, characterized by modest betweenness values. Conversely, m-9 stays close to both environmental-related and mangrove-related clusters. It has a high betweenness centrality value of 31.54 with synergies connected in three clusters and suggesting that it is a the 'bridge' indicator.

The significance of these 'bridge' indicators lies in their potential to bolster the growth of their associated indicators, which has a profound influence over the entire network. Consequently, these indicators merit prioritization in future policy considerations. In addition to m-9 (the economic complexity index), m-17 (historical sea level rise) and m-11 (indigenous property tenure) emerge as prominent 'bridge' metrics, underpinned by the highest betweenness centrality values—76.02 and 27.05, respectively. Sea level rise, with an extensive nexus encompassing indicators from three distinct clusters, emerges as a quintessential bridge uniting 11 mangrove metrics with 15 SDGs. This pivotal role accentuates its potential to catalyze broader transformations. Similarly, Indigenous property tenure, straddling the boundary between the mangrove metric cluster and the environmental-related domain, forges a network of connections encompassing nine mangrove metrics and six SDGs. The 15 connections underscore that enhancing Indigenous property tenure relative to other land types within a nation can profoundly influence mangrove sustainability, invigorating environmental and overall sustainability clusters.

3.3. Consistency and complexity in indicator-level Mangrove-SDG space

The similar network structure of the indicator-level Mangrove-SDG space echoes the stability observed in goal-level spaces, laying the groundwork for pinpointing pivotal indicators for future policy implications concerning SDG and mangrove sustainability achievements. This space materializes through the discernment of synergies amid its distribution mean (0.45), encompassing 115 nodes that comprise 20 mangrove-related metrics and 95 SDG indicators. Impressively, the intricate interplay engenders a staggering 6580 interconnecting edges (Fig. 3). Much akin to goal-level spaces, the architecture of this indicator-level realm bears semblances yet discernibly elevates the complexity scale owing to its granular metric inclusions. The parallelisms manifest across three dimensions.

First, indicator-level space can be subdivided into three distinct clusters. The first cluster encompasses all six mangrove indicators, while the remaining two are delineated as socio-economic-oriented and environmentally focused clusters. The socio-economic cluster comprises a relatively smaller subset of mangrove indicators (4), whereas the environmental-related cluster encompasses most of these indicators (10). Second, Fig. 2-b and Fig. 3-b demonstrate the consistency of all mangrove metrics vis-à-vis the goal-level expanse. These metrics assume their designated positions, creating significant synergies and relationships. For example, the interaction of three specific measures related to m-1, the area of mangroves in 2016, m-4, the increase in mangrove area from 2007 to 2016, and m-5, the country area in 1996 shows strong connections and synergies that help achieve specific goals and indicators in the mangrove sector. Finally, the quintessential core-periphery dynamics persist for the bulk of SDG and mangrove indicators. Consider the four socio-economic clustered mangrove-related indicators, distant from the core, primarily positioned as a bridge connecting the socio-economic and environmental enclaves or close to the mangrove cluster.

Table 2
Mangrove-related network similarity comparison at goal-level and indicator-level between 1996-2007 and 2007–2016.

Norm difference	Goal-level space	Indicator-level space
Correlation network (in percentage)	12.26	12.57
SDG space network (in percentage)	6.93	8.4

Moreover, the indicator-level space embraces intricacies, unraveling the strategy for prioritizing SDG and mangrove indicators toward sustainable accomplishments. On a more detailed level, the interaction between m-2 and m-3, changes and loss in mangrove areas during 2007–2016 shows significant connections with various SDG indicators, which are central in linking economic and environmental aspects. These indicators include Sustainable Nitrogen Management, Adjusted GDP Growth, Satisfaction with Public Transport, Property Rights, and Statistical Performance. The connection between mangrove loss and these central SDG indicators shows that tracking mangrove loss is key to monitoring global sustainability. The connection between mangrove loss and these 'bridge' SDG indicators indicates that mangrove loss can be a representative indicator of global sustainability monitoring. Reducing mangrove loss can improve these SDG indicators. These central indicators can also trigger positive ripple effects, leading to improvements across a network of interconnected indicators, which in turn helps in achieving overall sustainability goals.

Furthermore, the dynamic of mangrove changes and loss is encapsulated by m-19 (Tropical storm frequency). Consistent with the goal-level space, the proximity unravels the essence of drivers governing mangrove loss and change during 2007–2016. This demonstrates that natural storm disturbances can unleash cataclysmic impacts on mangroves. This interdependence indicates a pressing need for informed policymaking by emphasizing climate change mitigation, given its potential to directly influence mangrove loss and change, thus paving the way for resilient mangrove sustainable development.

3.4. SDG-Mangrove spaces across scales are more stable than correlation coefficient networks

The consistency of goal- and indicator-level spaces with different mangrove metrics has proven the stability of 'Mangrove-SDG space' regardless of data sources, quality, quantity, and resolution in the above analysis. We also embark on a comprehensive comparison by constructing both the correlation coefficient structure and the space utilizing goal-level and indicator-level data encompassing mangrove and SDG data from 1996 to 2007 and 2007 to 2016. Our objective is to scrutinize their network stability, shedding light on the reliability of our constructed space compared to the most common way to measure synergies between variables (correlation coefficient). To gauge the stability of the networks, we employ matrix norms and calculate the discrepancies in norms between the most recent network structures and their respective earlier counterparts. The results, as delineated in Table 2, reveal the stability of the space. The goal-level SDG space of 1996–2007 differs by a mere 6.93%, and the indicator-level SDG space shows an 8.4% divergence from its 2007–2016 equivalents. In stark contrast, the correlation structure confronts more substantial changes, with the goal-level coefficient network of 1996–2007 displaying a 12.26% disparity from the 2007–2016 network. Similarly, the indicator-level coefficient networks exhibit a 12.57% difference across the two temporal periods.

4. Discussion

4.1. The enduring stability observed in the structure of SDG-mangrove spaces across scales can systematically monitor long-term mangrove sustainability progress and provide countries with case-by-case pathways

The complexities surrounding the conservation of global mangrove forests, compounded by the absence of reliable, timely, and uniform data on mangrove extent and influencing factors, pose significant obstacles to the systematic, long-term monitoring of these ecosystems and their contributions to global sustainability. The stable 'Mangrove-SDG space,' spanning both coarse and fine resolutions and across time, emerges as a potent tool for policymakers, offering solutions to the challenges above, irrespective of data quality and quantity constraints.

First, the stability of our crafted space is significant in the long-term policy planning for mangrove sustainability efforts (e.g., in response to climate change). These policies emphasize the importance of feedback, where policy actions have a lagged performance to the system. A network structure that maintains stability over time is critical, offering tools to visualize, monitor, evaluate, and interpret the dynamics of real-world policy responses and problems. In this regard, it holds the potential to act as a cornerstone for facilitating efficient, sustainable development strategies and robust mangrove conservation efforts with sound science-driven solutions to complex decision-making processes.

Second, the stability elucidates that not all goals, indicators, or mangrove metrics share equal prospects for improvement. For instance, two nodes with high proximity are more likely to require similar external resources because the proximity metric quantifies the similarity in external resources required for attaining two distinct nodes, such as capital investment, technological innovation, and organizational governance. This convergence in resource requirements facilitates efficient resource utilization. Thus, when a country excels in achieving one goal, it is inclined to extend its efforts to pursue its connected nodes in the Mangrove-SDG space with a high-intensity edge to foster sustainability on a broader scale.

Moreover, specific indicators at the peripheral positions encounter more challenges to improve because they are connected with few synergies in the space and may need to navigate through the 'bridge' goals as they occupy peripheral positions. Hence, 'bridge' nodes are of paramount importance. These 'bridge' metrics establish connections among different clusters characterized by numerous weak synergies with other nodes and lay the groundwork for a comprehensive and systematic approach to measuring and evaluating policies to achieve overall sustainability progress and mangrove conservation success. These 'bridge' elements can address and elucidate various dynamics, including (1) the mechanisms by which countries attain comparative advantages in specific goals relative to others, and (2) how countries make determinations regarding the development of goals or metrics, and whether other goals or metrics can be aligned synergistically to advance overall sustainability within the realm of SDGs and mangroves. Consequently, the intricate network topology of the space acts as a 'dictionary' for understanding the synergy of metrics, enabling policymakers to set priorities and initiate constructive dynamics for future development. Using Indonesia as a case study, we illustrate how the goal-level and indicator-level space with mangrove metrics can effectively inform targeted policy-making processes in the nation (Sasmito et al., 2023).

4.2. The massive mangrove loss and the effects of restoration projects in Indonesia can be reflected in the Mangrove-SDG spaces

Indonesia, renowned as the most mangrove-rich nation globally, boasts the largest expanse of mangrove forests, covering 22% of the total global mangrove area (Giri et al., 2011). Notably, it ranks among the trio of countries, alongside Australia and the United States, with the most substantial annual carbon sequestration potential and extensive coverage of coastal ecosystems (Bertram et al., 2021). These mangrove ecosystems are crucial connecting points between Indonesia's people and its natural environment. However, a concerning trend emerges as approximately 800,000 ha of these vital ecosystems have been cleared and converted over the past three decades (Worthington et al., 2020). This concerning trajectory is depicted in Fig. 3-a, illustrating the goal-level Mangrove-SDG space with Indonesia's sustainability performance color-coded. Within this space, we observe the central placement of critical metrics—m-2, m-3, and m-19—representing mangrove loss, mangrove change, and tropical storm frequency spanning 2007 to 2016. These nodes are situated in the heart of the global sustainability clusters, as indicated by the pink-shaded circle, reflecting their suboptimal performance within Indonesia during the same period.

Table 3
The robust synergies directly and indirectly related to mangrove restoration projects in Indonesia.

Source	Target	Link intensity (Proximity)	Target's betweenness centrality
m-4 (mangrove gain in 2007–2016)	m-5 (country's administrative area in 1996)	0.8	9.43
	m-1(mangrove coverage in 2016)	0.77	24.18
	m-13 (Area of Ramsar listed Wetlands)	0.48	183.68
m-1(mangrove coverage in 2016)	m-13 (Area of Ramsar listed Wetlands)	0.54	183.68
	9-3 (Logistics Performance Index: Quality of trade and transport-related infrastructure (worst 1–5 best))	0.48	167.32
	11-1 (Urban Population Living in the Slums)	0.47	105.46
	m-17 (Historical sea level rise)	0.47	45.97
	2-7 (Sustainable Nitrogen Management Index)	0.46	94.50
m-5 (country's administrative area in 1996)	m-13 (Area of Ramsar listed Wetlands)	0.52	183.68
	11-1 (Urban Population Living in the Slums)	0.47	105.46
	9-3 (Logistics Performance Index: Quality of trade and transport-related infrastructure (worst 1–5 best))	0.48	167.32

In response to this loss of a precious ecosystem, policymakers and various non-governmental stakeholders have voiced the urgent need for mangrove conservation and restoration. In collaboration with Eurasia, Brazil, the US, Canada, and India, Indonesia has emerged as a global leader in implementing restoration solutions. Together, they are working towards restoring 15 million hectares of peatlands by 2030 and a staggering 350 million hectares of forests and wetlands by 2050. This concerted effort is projected to reduce nearly five gigatons in emissions annually, marking 30% of the natural climate solution mitigation opportunity by 2030 (Wolosin, 2022). This significant endeavor could benefit a substantial coastal population of 74 million people and contribute to national emissions reductions of up to 16% (Worthington et al., 2020; Wolosin, 2022). We identify the progress in Fig. 3-a and b through the above-average performance of Indonesia in m-4: mangrove gain, which can reflect the direct mangrove extent success of Indonesia's leading restoration projects worldwide. However, neither graph shows the direct synergetic connections with SDG goals or indicators, and its connections with strong synergies are discussed in 3.2.2. Moreover, despite these noble and ambitious efforts, it is essential to acknowledge that many large-scale restoration initiatives have faced challenges and encountered low success rates. The reasons behind these hurdles are multifaceted, including limited ecological understanding, inadequate representation of subnational governments in mangrove governance, and ineffective monitoring and evaluation mechanisms. These factors collectively underscore the complex landscape of mangrove conservation and the pressing need for holistic and well-informed strategies to succeed in these critical endeavors.

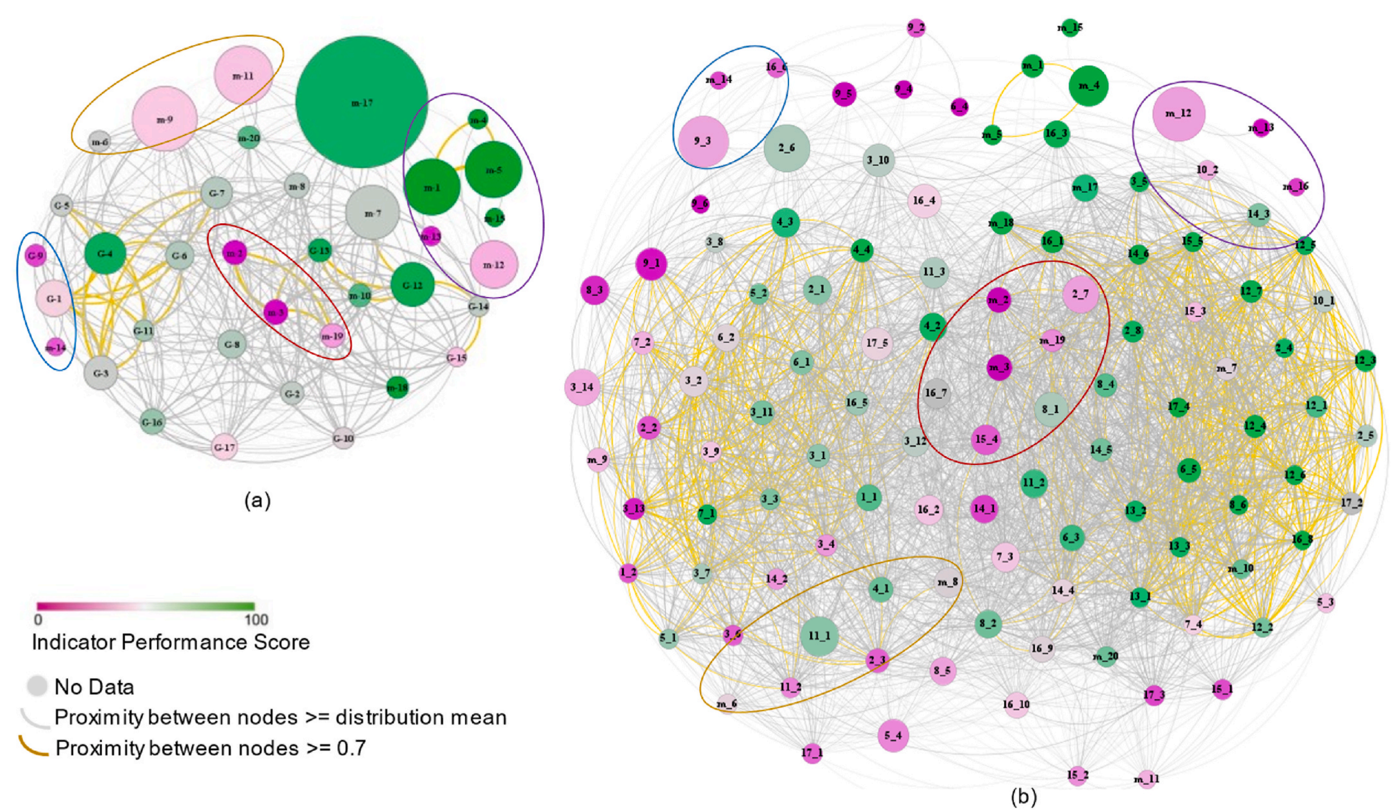

Fig. 4. a. Goal-level space projected to Indonesia's sustainability performance score as the node color. b. Indicator-level space projected to Indonesia's sustainability performance score as the node color. The node color is to visualize the sustainability performance in Indonesia between 2007 and 2016, and node size is scaled by each node's centrality betweenness value in its spaces. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

4.3. The Mangrove-SDG spaces indicate a policy priority transformation from mere mangrove extent gain to its synergized 'bridge' indicators

Our analysis explores different perspectives to explain the failure of mangrove restoration projects in consideration of Indonesia's overall sustainability performance. As shown in Fig. 3-a, m-4, representing mangrove gain between 2007 and 2016, which usually increases due to rehabilitation and restoration projects, is strongly synergized with m-1 and m-5, representing the original natural habitat of mangrove forests and the country's administrative area. They have reached a proper performance (green dots). Moreover, the two land-based metrics are relatively independent in the goal-level and indicator-level spaces (Fig. 3-a and b) and relate to merely a few goals or indicators.

However, when we dig into their synergized nodes with solid connections (proximity >0.45), shown in Table 3, they are 2–7(Sustainable Nitrogen Management Index), m-12 (Ramsar Sites' Area), m-17 (Historic Sea Level Rise), 11-1 (Urban Population Living in the Slums), and 9-3 (Logistics Performance Index). These indicators are the most significant 'bridge' indicators in the spaces, either in goal- or indicator-level spaces, with the highest betweenness centrality values. The performance of these indicators can have the most potent influence in the space, indicating that mangrove forest gain can be affected by the poor performance of these 'bridge' indicators from a broader perspective considering the overall sustainability. However, it has not reached a proper performance now.

These 'bridge' indicators are still poorly performed (pink dots) in Indonesia, which indicates their potential to impede the performance of mangrove forest gain and impact the efficacy of mangrove conservation projects. Except for the urban population living in the slums, the other 'bridge' indicators are below average. In one way, the improvements of mangrove forests have their limits, which are strongly strained and synergized by the natural habitat of mangrove forests and the country's administrative areas. Policies focusing merely on the increase in mangrove extent have limits because natural conditions set the natural habitat of mangrove forests. Too many resources poured into increasing the mangrove forest extent may result in lower resource efficiency. In another way, mangrove forest gain can be weakly influenced or impacted by those weak synergized 'bridge indicators. The policy should prioritize those 'bridge' indicators more, especially poorly performed ones. These 'bridge' indicators' improvements can directly be synergized with mangrove gain performance. Moreover, they have deciding roles to the overall sustainability with positive cascading effects for many other sustainability-related indicators, including mangrove conservation success.

4.3.1. Priority 1: Sustainable Nitrogen Management Index

As shown in Fig. 4-b, indicator 2–7 (Sustainable Nitrogen Management Index) is in the middle of global sustainability-related clusters (red circle with dashed line), between the environmental-related cluster and the socio-economic cluster. Moreover, it is placed close to m-2 (Mangrove change), m-3 (Mangrove loss), and m-19 (Tropical storm frequency) in 2007–2016, along with two SDG indicators: 15-4 (Permanent deforestation percentage) and 8-1 (Adjusted GDP growth), which were poorly performed in Indonesia in 2007–2016. Nitrogen management improvement indicates land efficiency for agriculture and other crops with high economic values, alleviating fierce land conflicts and protecting mangrove forests. Moreover, the improvement of nitrogen management reflects the enhancement of technology, which accompanies economic growth.

These indicators have a high potential to decide Indonesia's future sustainability because of their location, which can act as the 'bridge' between socio-economic and environmental clusters, contributing to the overall achievement of sustainable development. Firstly, they are close in the space, indicating their improvements require similar external incentives, such as policy, institutions, resources, etc. Policy priorities on improving any of these indicators can bring enhancements of their related 'bridge' indicators because of similar policy stigma and external environment requirements. Secondly, these indicators have a broad range of coverage of synergies and can potentially bring positive cascading effects to the whole system. For example, 2–7 is synergized with 78 indicators, including ten mangrove metrics and 68 SDG indicators. The broad coverage of synergy indicates that its improvement can help enhance these indicators, consisting of about half of all indicators (135). Moreover, these 78 indicators include 'bridge indicators, and their improvements can generate broad indirect synergies with their connected indicators.

4.3.2. Priority 2: Ramsar Sites' area

Similar situations can be applied to m-12 (Ramsar Sites' Area) (purple circle), 9-3 (Logistics Performance Index) (blue circle), and 11-1 (Urban Population Living in the Slums) (yellow circle). Although they are relatively located at the periphery of global sustainability clusters, their high betweenness centrality values indicate their influential roles in acting as 'bridge' indicators. For example, the mangrove metric: Ramsar sites' total area has the highest betweenness centrality value as 183.7, synergizing with 15 indicators whose betweenness centrality values are also high. Policy prioritizing expanding Ramsar sites to have more marine ecosystems protected by the global conservation alliance can improve other 'bridge' indicators' performance with a broad influence on sustainability, including enhancing marine protected areas' management capacity, reducing poverty, maintaining mangrove extent, etc. In one way, these wetland areas in Indonesia, protected by the Ramsar Convention, played an essential role in safeguarding biodiversity and providing valuable ecosystem services. Meanwhile, their total area can serve as a critical indicator in monitoring the formidable challenges in preservation due to the intricate interplay of natural factors, such as climate change and environmental degradation, and anthropogenic influences, such as urbanization and resource extraction from poverty.

4.3.3. Priority 3: Logistics Performance Index (LPI)

Similarly, 9-3 (Logistics Performance Index (LPI): Quality of trade and transport-related infrastructure) also has a high betweenness centrality value of 167.3 with low performance in Indonesia and is synergized with other poorly performed indicators, including m-14 (Night-time Lights Growth), m-6 (Varieties of Democracy (VDEM)), and m-9 (Economic Complexity Index (ECI). The LPI measures a country's logistics efficiency and performance, including customs procedures, infrastructure quality, and international shipments. It reflects economic vitality in the society and has a strong synergetic interplay with indicators of democracy, economic complexity, and the growth of night-time lights, which are also relevant to mangrove conservation efficiency and serve as mangrove deforestation drivers to augment a nation's logistics capabilities and facilitate trade and economic growth.

A well-functioning democracy may lead to more effective enforcement of laws related to mangrove protection, and citizen participation and transparency allow citizens to voice concerns for sustainable practices in mangrove preservation. Moreover, transparent governance with institutional effectiveness is characterized by greater accountability, reduced corruption, and improved regulatory frameworks, which create an environment conducive to efficient logistics operations with smoother trade flows and logistical processes, streamlined customs procedures, and reliable infrastructure investments. In addition, economic complexity, referring to a more diversified economy that can produce diverse and intricate products, indicates less dependency on specific resources such as mangrove forests for financial gains and may lead to a greater emphasis on sustainable resource management. Meanwhile, a complex economy is built upon a network of interconnected industries and specialization, which fosters the development of more sophisticated supply chains and manufacturing processes. These advancements improved logistics practices, including efficient transportation networks, streamlined customs procedures, and increased capability to handle complex trade transactions. Lastly, the growth of night-time lights often indicates urbanization and economic development. Rapid urbanization can pressure coastal ecosystems, including mangrove forests, due to infrastructure development and land reclamation.

In contrast, a well-managed urbanization process can bring the coexistence of mangrove conservation with planning and zoning regulations to prevent encroachments and urban expansion. At the same time, urbanization expansion indicates the evolvement of logistics infrastructure and capabilities, that infrastructure investment in transportation, ports, and distribution networks are driven by the need to support economic growth, and in return, leads to improved logistics efficiency and performance. These indicators are synergized with each other, and any improvement can help augment the enhancements of others. Policy prioritized on these indicators can help improve mangrove conservation success in mangrove extent gain and overall sustainability performance.

4.3.4. Priority 4: urban population living in the slums

Noticeably, 11-1 (Urban Population Living in the Slums) performed well compared to other 'bridge' indicators discussed above and compared to its synergized indicators in the yellow circle. Since this 'bridge' indicator performed better, we anticipate future improvements in its connected indicators including m-6 (Varieties of Democracy (VDEM)), m-8 (BDH2020), m-9 (Economic Complexity Index (ECI)), and m-11 (Indigenous Land Tenure), as well as a potential improvement of its nearby indicators, especially those with poor performance, such as 11-2 (New HIV Infections) and 2–3 (Prevalence of Wasting in Children under five years of age). Improvements to eradicate poverty in city slums and reduce inequality can generate synergies with enhancements in various aspects, such as improving the diversity of economic products with a more diversified economy, better-functioning democracy governance for natural resources management, better-performed institutions to reduce biodiversity loss, and more indigenous land tenures. Moreover, it can generate indirect enhancements such as health care, democracy conditions, children's education, etc. Policy priorities on the urban population in the slums can bring about improvements to a broad range of aspects for mangrove conservation and overall sustainability, and policies to ensure the indicator's performance can monitor the advances of its related indicators, leading to a more sustainable future in Indonesia.

5. Conclusions

Our study adopts an integrated network modeling approach to discuss the complementarities between sustainable development and mangrove governance. We construct global 'Mangrove-SDG spaces' by harnessing the framework of 17 SDGs, 95 indicators, and 21 mangrove metrics spanning 109 countries. Leveraging network science methodologies, we identify core-peripheral relationships, community compositions, and network structures within these spaces, offering insights into their complementarities across goal and indicator levels. Furthermore, we examine the robustness of the space by comparing it to correlation coefficient networks built on historical data and evaluating their matrix norms. Mangrove-SDG spaces exhibit stability, which indicates their relative resilience to data variations stemming from diverse data sources, quantities, and qualities encountered during data collection, preparation, and analysis phases.

This adaptability and stability to evolving real-world environmental complexities is paramount, underlining the significance of informed and effective decision-making processes. For example, unveiling complementarities between sustainable development and mangrove governance from 'Mangrove-space spaces' prioritize policies to focus on 'bridge' factors that facilitate the optimal performance with the most achievements from the systematic perspective. Moreover, the stable structure empowers long-term policy planning for sustainability efforts, offering tools to systematically monitor, evaluate, and analyze the performance of policy outcomes with lagged feedback.

Considering these advantages, we offer valuable insights into country-level strategies and pathways to promote sustainable development and mangrove conservation, using Indonesia as an illustrative example. The nuanced structure and complementarities embedded within Mangrove-SDG spaces empower countries to craft context-specific strategies rooted in benchmarking their sustainability performance. For Indonesia, this entails a strategic shift from the sole expansion of mangrove extent to a concentrated emphasis on four pivotal areas: adept nitrogen management, bolstering Ramsar site efficiency, optimizing logistical performance, and addressing urban population dynamics.

However, as a noteworthy limitation of the method, it does not offer specific policy actions to improve the performance of these prioritized indicators, and policymakers still need their expertise to devise practical strategies to implement the policy recommendations. Future studies can provide more discussions on the potential feasibility and challenges of implementing these 'bridge' indicators in specific country settings and explore their policy pathways through comparative studies between countries, considering political, economic, and social factors (e.g., governance structure, financial conditions, culture settings, etc.) for practical policy implementation.

6. Data and code availability

Data from 17 SDGs and the scores of 95 indicators across 177 countries were sourced from the SDG Dashboard (Sachs et al., 2022) (https://dashboards.sdgindex.org/downloads) within the Sustainable Development Report 2022. This extensive database spans 2000 to 2021 for 177 countries and has been meticulously normalized, encompassing a scale of 0–100. Here, a score of 0 denotes the lowest performance, while a perfect score of 100 signifies an apex of sustainability achieved by 2030.

The architecture of the goal-level mangrove SDG space was meticulously devised utilizing SDG data from 2016, the year with the most recent mangrove metrics data. Concurrently, the most recent data on mangrove loss was gleaned from two distinct sources. The first originates from the Global Mangrove Watch 1996–2016 dataset, curated by the UNEP World Conservation Monitoring Centre (WCMC) (http://data.unep-wcmc.org/datasets/45) for 2016 (Bunting et al., 2022). However, it's noteworthy that this source may err on the side of overestimation in certain regions. The second source, known as Goldenberg's estimate, calculated mangrove forest loss in 71 mangrove-holding countries during three periods, and we used the most recent period from 2011 to 2016 (Goldberg et al., 2022). This dataset (https://daac-news.ornl.gov/global-mangrove-land-cover-change-loss-drivers) is somewhat conservative, revealing an underestimation of loss compared to the GMW dataset in specific areas (Goldberg et al., 2020). This reflects a more subdued estimation of mangrove loss. Country-specific data was acquired from the Global Administrative Areas Database (GADM) (https://gadm.org/data.html).

To unlock the panoramic insights of the mangrove landscape, encompassing drivers and hotspots of both loss and gain, a comprehensive assortment of metrics was culled from a plethora of sources, consolidated within the reference paper following link: https://www.nature.com/articles/s41467-022-33962-x#data-availability (Hagger et al., 2022; Howard et al., 2022). A deliberate curation selected 41 indicators deemed representative of the entire spectrum of mangrove SES-related metrics from 1996 to 2016 across 109 countries. This selection was meticulously divided, comprising 21 indicators for 1996–2007 and an additional 21 indicators for 2007–2016. Each of these metrics underwent rigorous normalization to fit the 0–100 range, with a score of 0 earmarking the nadir of performance and a perfect score of 100, symbolizing a pinnacle of sustainability aspired for by 2030. The supplementary table has meticulously elucidated this normalization process's nuances and intricacies, including sign changes for four indicators to fit into the criteria that 100 means better sustainability achievement by 2030, and 19 indicators used 5th and 95th bounds as their maximum and minimum because of the existence of extreme values. In response to the dual timeframes of mangrove metrics, the SDG goal and indicator data were strategically anchored within the average years of 2001 and 2011, representing the average years of 1996–2007 and 2007–2016 of mangrove metrics data, respectively. This research is hosted on the GitHub repository, accessible at lwt852/mangrove SDG space (github.com), where the comprehensive research code is made available.

Supporting information

The supporting information provides supplemental data supporting the main text.

CRediT authorship contribution statement

Mimi Gong: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Noah Teller:** Writing – review & editing, Methodology. **Elizabeth J. Golebie:** Writing – review & editing. **Miriam Aczel:** Writing – review & editing, Conceptualization. **Zhimeng Jiang:** Conceptualization. **Joris Van Zeghbroeck:** Writing – review & editing. **Jianguo Liu:** Writing – review & editing, Conceptualization.

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

This research is hosted on the GitHub repository, accessible at lwt852/mangrove SDG space (github.com), where the comprehensive research code and data is made available.

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Appendix A. Supplementary data

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