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Harmonizing ecosystem services assessments with sustainable development goals: a case study of the Batticaloa Lagoon Watershed, Sri Lanka

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Abstract

By providing continuous and reliable ecosystem services, ecosystems help attain sustainable development goals (SDGs). Trade-offs between environmental conservation and socioeconomic development limit SDG success. Ecosystem services (ES) methods can help solve these problems and accomplish the SDGs. There is a gap in analyzing SDG progress regarding ESs. To fill this gap, we examined the spatial-temporal changes in ecosystem service values (ESV) and SDG scores in the Batticaloa Lagoon Watershed (BLW) over the past 40 years. The study found that the Western region's ecosystem service values and ES-SDG Index scores were higher than those of the Eastern regions. The drop in total ESV from 917.41 million US dollars per hectare in 1979 to 731.37 million in 2000 is noteworthy. By 2021, food production, erosion management, and water regulation helped it recuperate to 818.62 million US dollars per hectare. Nine environmental services were devalued between 1979 and 2000 due to agriculture, forest, and wetland losses. In contrast, between 2000 and 2021, wooded land, water bodies, and wetlands increased the value of nine ESs. The entire Batticaloa Lagoon ecosystem's ES-SDG Index score dropped from 32.1 in 1979 to 21.0 in 2000, then recovered to 24.3 by 2021. Based on worldwide regional data, food and water provisioning, climate regulation, nutrient cycling, habitat and biodiversity, and cultural services have primarily affected the ES-SDG Index score. The SDGs assessment emphasizes the importance of prioritizing SDG6, SDG11, and SDG12 to promote interrelated SDGs in the Batticaloa Lagoon watershed and the world. This prioritization aims to help stakeholders understand the region's progress toward global SDGs.

Keywords Ecosystems, Watershed, Lagoon, Water, SDGs, Land use

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Introduction

Ecosystem services (ESs) play a fundamental role in promoting human well-being and sustainable development (Costanza et al. 2016). The interplay between ESs, human well-being, and sustainable development has emerged as a central concern in sustainability science (Fu 2020). In 2015, the United Nations unveiled a collection of 17 SDGs with 169 associated targets, spanning sustainability's economic, social, and environmental aspects. Numerous countries have significantly promoted these SDGs, especially concerning socioeconomic development. Nevertheless, these achievements have often been accompanied by the unsustainable utilization of the natural environment. Approximately 60% of ESs have undergone degradation (IPBES Secretariat 2019). The decline in biodiversity and the fragmentation of ecosystems threaten the achievement of around 80% of the targets set by the SDGs (UNEP 2021).

Although intensive exploitation of ecosystems can lead to significant economic gains, it remains difficult to completely offset the losses incurred due to the degradation of the natural environment (Wood et al. 2018; Yin et al. 2021). The journey towards achieving SDGs often faces challenges arising from the need to balance protecting the environment with promotinguman well-being, resulting in trade-offs, as Yang et al. (2020) discussed. Numerous research endeavors have evaluated the effectiveness of SDGs by using a combination of environmental and socioeconomic indicators, as demonstrated in studies by (Huan et al. 2021). However, integrating ES indicators into these SDG assessments has been relatively limited, as highlighted by(Cochran et al. 2020; Pires et al. 2021). Approaches rooted in ESs, incorporating strategies related to ecological restoration, environmental service, and land and water management, offer valuable prospects for cultivating synergies and pathways to realize the SDGs. This is highlighted in the works of (Johnson et al. 2019; Keesstra et al. 2018; Liu et al. 2022; Yang et al. 2020). Numerous studies have explored the connections between ESs and SDGs using a range of methodologies, including expert surveys, network analysis, Delphi processes, and bibliometric network analysis. These studies, conducted by researchers such as Anderson et al. (2019), Hawken et al. (2021), Wood et al. (2018), have shed light on the intricate relationships between ESs and SDGs. Specific ESs, such as water provision, food provision, carbon storage, flood management, and habitat and biodiversity, have been identified as pivotal services that make significant contributions to multiple SDGs, particularly SDG6, SDG13, SDG14, and SDG15, as highlighted in research by (Wood et al. 2018; Yang et al. 2020). It is important to note that various ESs can contribute to different SDGs to varying degrees, and, in some cases, a single ES can focus positive effects on multiple SDGs, as evidenced in studies by Johnson et al. 2019; Yin et al. 2021. Although the interconnections between ESs and SDGs are strong, only a limited number of studies have examined the progress of SDGs through ES-SDG relationships. Therefore, integrating ESs into SDG evaluations becomes imperative for identifying pivotal ESs and SDGs crucial for informed decision-making. In the Eastern Sri Lankan region of Batticaloa Lagoon watershed (BLW), substantial socioeconomic advancement has been accompanied by environmental challenges (Partheepan et al. 2023). Efforts for eco-environmental protection have been underway since 2010, yet no previous investigations have measured ESs and SDG Index scores within the BLW. Nonetheless, the influence of alterations in ES values on SDG accomplishment within the BLW remains obscure and necessitates analysis.

As a result, this research examines the changing patterns of 11 ESs and their Value within the Batticaloa Lagoon Watershed (BLW) from 1979 to 2021. These 11 ESs were selected based on their relevance to the BLW's ecological and socioeconomic context and their capacity to directly link to twelve SDG targets (Wood et al. 2018; Yang et al. 2020). The BLW faces critical issues such as wetland degradation, urban encroachment, and overfishing, directly impacting ES. These critical ESs and SDGs were pinpointed to support informed land-use planning and sustainable development in the BLW region and other areas(Adikaram et al. 2017b; Hu et al. 2022). The selected 11 ES address these challenges. The ultimate goal is to provide valuable insights to inform and improve land-use management practices and foster sustainable development within the BLW.

Materials and methods

Study area

The Batticaloa Lagoon Watershed (BLW) in Sri Lanka's Eastern Province encompasses Batticaloa and Ampara Districts at coordinates 7°34' N and 81°41' E. This region includes Batticaloa Lagoon and 246 surrounding Grama Niladhari divisions, housing approximately 215,000 people, constituting about one-third of the Batticaloa district's total population. Grama Niladhari divisions are administrative units crucial to the watershed. Covering 85 square kilometers, the watershed, including land and the lagoon, is pivotal both ecologically and socio-economically. The Batticaloa Lagoon Watershed's ecological and socioeconomic importance emanates from the Batticaloa Lagoon and its surroundings, with the largest lagoon in Sri Lanka spanning 280 square kilometers, with its depth varying, transitioning from freshwater to saltwater dominance. The surrounding areas feature diverse ecosystems like salt marshes, mangroves, grass beds, and canals, contributing to the lagoon's status as a vital marine nursery for the western Bay of Bengal. This rich biodiversity supports ESs such as fisheries, agriculture, water supply, and tourism. Distinct land use patterns characterize the eastern and western sides of the lagoon, with the former being densely populated and the latter predominantly used for agriculture. Industrial, urban, and agricultural catchments indicate potential anthropogenic influences, particularly when combined with seasonal marine fluxes. Historical political instability impeded development until 2009, but neighboring regions experienced accelerated development post that period. Given the ecological significance and the livelihood dependence on this watershed, sustainable management practices are imperative. Responsible fishing practices should be implemented, including fishing quotas and by-catch-minimizing gear. Agricultural practices must avoid harmful chemicals and promote sustainable land management. The unique blend of marine and freshwater environments in the Batticaloa Lagoon and its reliance on aquaculture underscores the need for conservation efforts.

However, the watershed faces environmental challenges such as pollution, overfishing, and habitat degradation. Pollution from domestic, industrial, and agricultural sources has led to eutrophication and deteriorating water quality. Overfishing and destructive practices contribute to declining fish populations, while invasive plant species encroach upon wetland habitats. The lagoon exhibits a distinct transition from freshwater dominance in the southern zones to saltwater dominance in the northern zones, as reported by (Adikaram et al. 2017a). The surrounding areas of the lagoon are characterized by a diverse ecosystem, including salt marshes, mangroves, grass beds, and canals, as described by (Kularatne 2014).

The Batticaloa Lagoon Watershed (BLW) was selected for this study due to its dual role as a globally representative coastal system and a unique socio-ecological hotspot, offering critical insights into both universal and context-specific interactions between ecosystem services (ES) and Sustainable Development Goals (SDGs). Globally, the BLW mirrors challenges faced by regions such as the Beijing-Tianjin-Hebei area, where wetland degradation and urban expansion disrupt ES linked to clean water (SDG6) and terrestrial biodiversity (SDG15) (Zhang et al. 2019), and the Mekong Delta, where agricultural intensification (SDG2) clashes with biodiversity conservation (SDG15) under rapid land-use changes (Wood et al. 2018). Similarly, akin to the Jingjinji Urban Agglomeration, BLW's reliance on fisheries and agriculture highlights the interdependence between ES provision (e.g., water regulation) and socioeconomic goals like poverty alleviation (SDG1) and food security (SDG2) (Zhou et al. 2018), reflecting global patterns where coastal small-scale fisheries and agroecosystems remain vital yet vulnerable to ES declines (IPBES Secretariat 2019). Furthermore, forest-to-cropland conversions in BLW echo trends in the Yangtze River Economic Belt, where such shifts impair climate regulation (SDG13) and habitat preservation (SDG15) (Chen et al. 2022), and parallel the Amazonian frontiers, where competing demands for urbanization (SDG11) and agricultural productivity (SDG2) exacerbate land-use conflicts (Hu et al. 2022).

However, the BLW also possesses distinct characteristics that enrich its relevance. Post-conflict recovery dynamics following Sri Lanka's 2009 stabilization have accelerated development pressures, offering rare insights into balancing growth with ecological restoration, a challenge less pronounced in politically stable regions. The lagoon's saline-freshwater transitions also create a unique salinity gradient, influencing ES provision (e.g., water regulation) in ways that differ from homogeneous systems like monsoonal deltas. Localized conservation efforts, such as mangrove reforestation in the Vavunatheevu region, further distinguish the BLW, providing actionable lessons on nature-based solutions that complement global frameworks like the Ramsar Convention.

Methodologically, the study bridges global applicability and local specificity. The hybrid approach ensures scalability by applying standardized ES valuation coefficients (Xie et al. 2017) while adjusting for contextual factors like mangrove productivity. This balance enables replication in diverse coastal systems from the Niger Delta to the Sundarbans, where standardized methods require adaptation to local ecological and socioeconomic conditions. By addressing universal challenges such as urbanization and wetland loss through a localized lens, the BLW serves as a microcosm for understanding ES-SDG linkages in resource-dependent regions.

Ultimately, the Batticaloa Lagoon Watershed is ecologically significant and has a lifeline for local communities. Urgent conservation measures are needed to address pollution, overfishing, and habitat degradation, ensuring sustainable use for future generations. While its socio-political history and ecological nuances set it apart, the BLW's alignment with global coastal challenges underscores the broader relevance of its findings. The adaptable methodological framework provides a template for integrating ES into SDG assessments, making this study a vital reference for policymakers and researchers navigating the intersection of ecology and sustainable development worldwide.

Quantifying ecosystem service values (ESV)

Several studies have concentrated on assessing Ecosystem Service Values (ESV), as evident in research by(Costanza et al. 1997; de Groot et al. 2012; Gashaw et al. 2018; Honey-Rosés et al. 2014; Hu et al. 2008; Kindu et al. 2016; Li et al. 2010; Pilogallo et al. 2024; Scorza et al. 2020; Shao et al. 2020).The economic value for the standard equivalent factor used in ESV calculations is established at 1/7th of the market value of the national average food crop output per unit area, as explained in the study by Hu et al. (2021).Hu et al. 2021) also derived the 1/7th factor through empirical analysis of agricultural economies, where the net profit margin of food crop production (after accounting for labor, seeds, fertilizers, irrigation, and transportation costs) typically represents ~ 14.3% (≈ 1/7) of the gross market value. This aligns with global agricultural economics studies that report net profits averaging 10–20% of gross revenue in smallholder farming systems. By using net profit rather than gross value, the method avoids overestimating ESV while ensuring valuations reflect the real economic contributions of ecosystems to food security (SDG2). The 1/7th factor is especially relevant for the BLW because of its agrarian socioeconomic structure. This study chose this factor to ensure consistency with global ecosystem services (ES) valuation frameworks, which standardize ecosystem service value (ESV) calculations using equivalent coefficients scaled to agricultural productivity (Costanza et al. 1997; Xie et al. 2017).

This economic value is computed based on cropping area, yield, cost of production, and price data from the year 2021, and the equation for its calculation is as follows:

$$VC_0 = \frac{1}{7}\sum\nolimits_{i=1}^{n} \frac{p_i q_i}{m} (n = 1,\ 2,\ 3)$$

Where VC_0 represents the economic valuation of the standard equivalent factor for Ecosystem Services Value (ESV) per unit area, n signifies distinct crops such as paddy, ground nut, and maize, p_i denotes the yield of individual crops, q_i stands for the price of specific crops, and m represents the cumulative area under all crops. The computation yielded a VC_0 value of 2,406.5 USD for the BLW. The calculation of individual Ecosystem Services and the overall Ecosystem Services Valuation (ESV) was performed using the given equation and then represented visually using ArcGIS 10.9 software.

$$AESV_f = \frac{\sum (A_k \times VC_0 \times EC_{fk})}{S}$$

$$AESV = \sum\nolimits_{f=1}^{n} AESV_f \ (n = 1, 2, ..., 11)$$

Where $AESV_f$ represents the value associated with Ecosystem Service type "f," and AESV signifies the total Ecosystem Services Value (ESV) per unit area. Ak signifies the region corresponding to land-use type "k," The equivalent coefficient (EC_{fk})quantifies the relative contribution of a specific land-use type (k) to a particular ecosystem service (f) per unit area, scaled against a standardized economic value (VC_0). These coefficients, derived from Xie et al. (2017), are unitless multipliers that reflect the capacity of a land-use class to deliver an ecosystem service compared to a baseline (e.g., cropland's contribution to food production vs. water bodies' contribution to water regulation). For example, in Table 1, Cropland has an EC_{fk} of 1.36 for Food production, meaning cropland contributes 1.36 times the standard value (VC_0) to this service.

Derivation of Coefficients EC_{fk} are pre-established through meta-analyses of global ecosystem service valuations, reflecting empirical relationships between land-use types and service provision (Xie et al. 2017). Normalization results are spatially explicit, and mapped via ArcGIS, showing how land-use changes translate to shifts in ESV. This method links land-use structure to ecosystem service values, enabling spatial-temporal analysis of SDG progress in the BLW. Table 1 as outlined in the work by (Xie et al. 2017).

ES-SDG Index score

The Ecosystem Services Values (ESV) were normalized on a scale of 0 to 100 using min-max normalization

$$AESV_f' = \frac{AESV_f - min\,(AESV_f)}{max\,(AESV_f) - \min\,(AESV_f\,)} \times 100$$

Table 1 The equivalent coefficients for the value of ESs per unit area in the Batticaloa lagoon watershed

Ecosystem classification	Cropland	Bare land	Dense Vegetation	Settlement	Waterbody	Wetland
Food production	1.36	0	0.29	0	0.8	0.51
Raw material	0.09	0	0.66	0	0.23	0.5
Water supply	2.63	0	0.34	0	8.29	2.59
Air Quality regulation	1.11	0.02	2.17	0	0.77	1.9
Climate regulation	0.57	0	6.5	0	2.29	3.6
Waste treatment	0.17	0.1	1.93	0	5.55	3.6
Water regulation	2.72	0.03	4.74	0	102.24	24.23
Erosion control	0.01	0.02	2.65	0	0.93	2.31
Nutrient cycling	0.19	0	0.2	0	0.07	0.18
Biodiversity	0.21	0.02	2.41	0	2.55	7.87
Cultural service	0.09	0.01	1.06	0	1.89	4.73

In a research endeavor by Wood et al. (2018), an expert survey was conducted to investigate the contributions of 16 ESs toward 44 targets encompassing 12 distinct SDGs. In this subsequent analysis, the research focused on assessing the impact of 11 ESs on a specific set of 12 SDGs. These 12 SDGs were identified as follows: SDG1 (No Poverty), SDG2 (Zero Hunger), SDG3 (Good Health and Well-Being), SDG6 (Clean Water and Sanitation), SDG7 (Affordable and Clean Energy), SDG8 (Decent Work and Economic Growth), SDG9 (Industry, Innovation, and Infrastructure), SDG11 (Sustainable Cities and Communities), SDG12 (Responsible Production and Consumption), SDG13 (Climate Action), SDG14 (Life Below Water), and SDG15 (Life on Land). This framework, illustrated in Fig. 1, allowed us to focus our analysis on the specific interplay between these ESs and the identified SDGs (Hu et al. 2022).

On the flip side, it's important to note that SDG4 (Quality Education), SDG5 (Gender Equality), SDG10 (Reduced Inequalities), SDG16 (Peace, Justice, and Strong Institutions), SDG17 (Partnerships for the Goals), along with the remaining 125 targets, were excluded from our analysis. This decision was made due to the absence of apparent environmental correlations in these particular SDGs and targets. Our focus was primarily on those aspects of the SDGs and targets that had a more direct and measurable impact on the environment, reflecting the specific scope of our examination. Employing the "ES-SDG linkages" framework, we then computed the SDG score following the methodology outlined by (Chen et al. 2022; Hu et al. 2022).

The equivalent coefficients in Table 1 originate from Xie et al. (2017), who established a global framework for valuing ecosystem services (ES) using standardized coefficients derived from meta-analyses of more than 1,000 studies. These coefficients reflect empirical averages of ES provision per land-use type (e.g., wetlands for water regulation). For the BLW, the study retained Xie et al. 2017's core structure to ensure comparability with global studies (e.g., Yangtze River Basin) but adjusted coefficients to local conditions using BLW-specific data (e.g., mangrove productivity, saline transitions). This hybrid approach balances methodological rigour with contextual relevance, ensuring coefficients align with the BLW's ecological dynamics (e.g., cultural services tied to ecotourism) while maintaining transparency and scalability for SDG-focused policy applications.

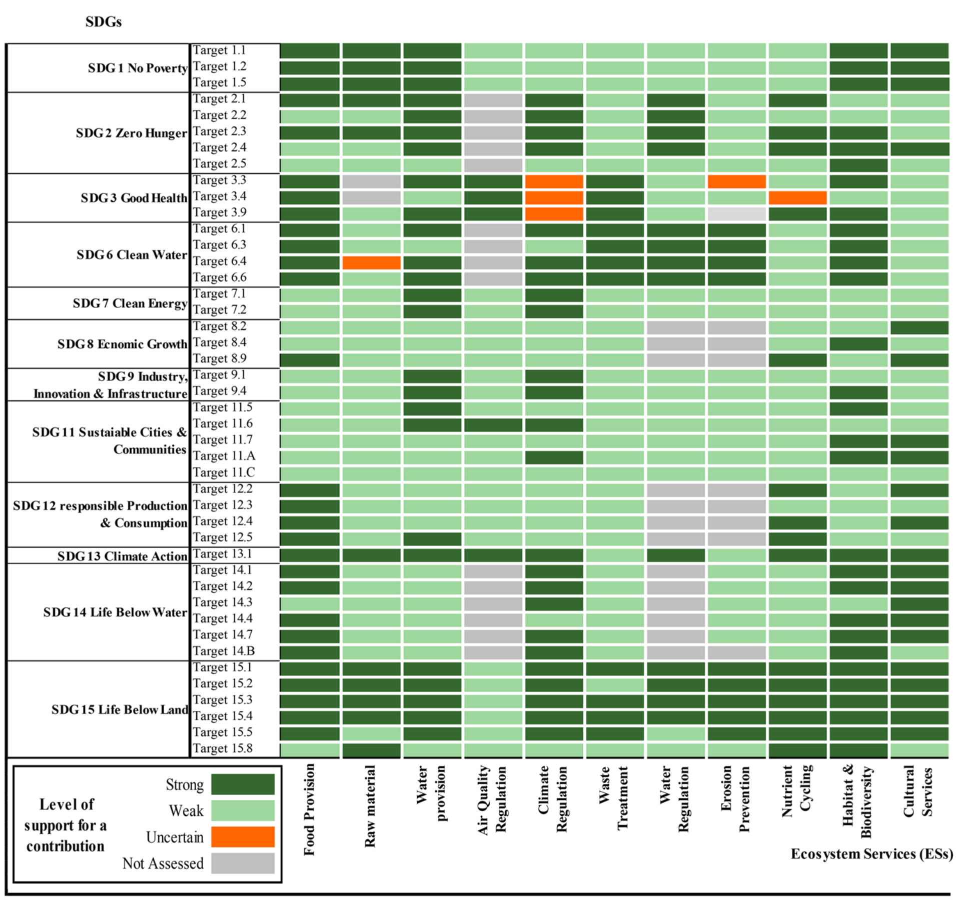

Fig. 1 Linkages between ES and SDG (adapted and modified source: Wood et al. 2018)

$$SDG_j = \frac{\sum_{f=1}^{n} \left(AESV_f' \times x_f \times T_{f,j} \times y_j\right)}{\sum_{f=1}^{n} \left(T_{f,j}\right)}$$

In this context, the calculated score for SDG_j (e.g., SDG6, SDG11), where $T_{f,j}$ signifies the number of associations between Ecosystem Service f (e.g., Water Regulation, Food Provision) and the targets under SDG_j. The terms x_f and y_j represent the weights assigned to Ecosystem Service f and the targets within SDG_j, respectively. For simplicity, we assume equal priority for all ESs and targets within each SDG, thereby setting both x and y to 1. This equal weighting ensures that no single ES or target disproportionately influences the SDG score calculation. To illustrate, for instance, SDG1 comprised three targets (1.1, 1.2, and 1.5), each robustly supported by four ESs (food provision, raw materials, water provision, and cultural services) (as shown in Fig. 1) (Hu et al. 2022).

The research integrates the ES-SDG linkage framework from Chen et al. 2022; Hu et al. 2022a to quantify how ecosystem services (ES) drive SDG progress. Chen et al. established a matrix linking ES to SDG targets (e.g., Water Regulation ➔ SDG6.4), while S. Hu et al. introduced spatial-temporal scoring using normalized ES values. The BLW study adopts this formula, where $T_{f,j}$ (ES-SDG target linkages) is derived from (Chen et al. 2022)'s matrix, and $AESV_f'$ (normalized ES values) follows S. Hu et al.'s approach. This enables tracking SDG progress in the BLW (1979–2021) by aligning ES dynamics (e.g., wetland restoration) with SDG outcomes (e.g., SDG15 recovery), ensuring methodological consistency with global frameworks while addressing local ecological priorities.

Components of the Formula:

$AESV_f'$: The normalized value of Ecosystem Service *f* (e.g., Water Regulation, Food Production), scaled to 0–100 using min-max normalization (Sect. 3). This ensures comparability across diverse ESs (e.g., a value of 80 for Water Regulation indicates strong performance relative to other services).

$T_{f,j}$: The number of linkages between Ecosystem Service *f* and the *targets* under SDG_j. These linkages are identified through expert surveys (Wood et al. 2018); Fig. 1). For example, if Food Production (*f*) supports 3 targets under SDG2 (Zero Hunger), $T_{f,j}$=3.

x_f and y_j: Weights assigned to Ecosystem Service *f* and SDG_j's targets. In this study, we assume *equal priority* for all ESs and targets, setting x_f =1 and y_j =1. This simplification avoids bias toward specific services or goals.

Denominator ($\sum T_{f,j}$): The total number of ES-SDG linkages for SDG $_j$. This normalizes the score, ensuring SDGs with more targets (e.g., SDG_1 has 3 targets linked to ESs) are not disproportionately weighted.

Consequently, the SDG1 score could be expressed as

$$\left[(ES_{\text{foodprovision}} \times 3) + (ES_{\text{rawmaterials}} \times 3) + (ES_{\text{waterprovision}} \times 3) + (ES_{\text{culturalservices}} \times 3)\right] / (3 + 3 + 3 + 3)$$

The combined ES-SDG Index score was computed as follows:

$$ES - SDGIndex = \frac{\sum_{j=1}^{m} SDG_j}{m}$$

Results

An overview of the LULCC changes

The land use dynamics within the Batticaloa Lagoon Watershed (BLW) underwent substantial changes, particularly concerning cropland, bare land, and urban areas, as depicted in Fig. 2. Notably, there was an initial increase of approximately 2,290.26 km² in cropland area from 1979 to 2000. However, between 2000 and 2021, a significant decrease of roughly 1,970.49 km² occurred, resulting in a net increase of 319.77 km² in cropland between 1979 and 2021.

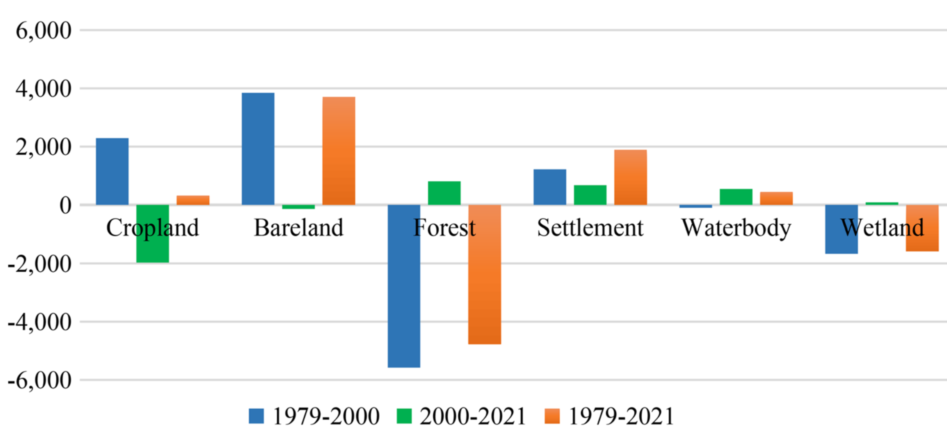

Fig. 2 Overview of land cover changes between 1979 and 2021 in the Batticaloa Lagoon Watershed

This shift in Cropland may be attributed to various factors such as urbanization, land degradation, or evolving economic conditions. These changes underscore the dynamic nature of land use patterns and the complex interplay of factors shaping them within the BLW region over the years. The notable increase in the Settlement area during both periods indicates urbanization and population growth in the Batticaloa Lagoon watershed. The substantial growth suggests increasing infrastructure development and residential expansion. This urbanization could be attributed to factors like economic opportunities, improved connectivity, and services. It's crucial to consider the potential environmental impacts of this growth on the watershed's ecological balance. The Forest area witnessed a remarkable decrease of around 5,581.34 km^2 between 1979 and 2000. However, between 2000 and 2021, there was a noteworthy increase of approximately 808.31 km^2. Despite this increase, the net change from 1979 to 2021 still shows a significant decline of 4,773.03 km^2 (Fig. 3).

Spatial and temporal variations in individual ecosystem service values (ESV)

The spatial distribution of 11 ESs within the Batticaloa Lagoon Watershed (BLW) reveals distinct patterns, as depicted in Fig. 4. Among these ESs, Water Regulation (WR) exhibited the highest Ecological Service Value (ESV) in the BLW, closely followed by Climate Regulation (CR) and Erosion Prevention (EP). In contrast, Water Provision (WP) and Nutrient Cycling (NC) displayed relatively lower ESV. Areas with substantial ESV for Food Provision (FP) were concentrated in the southeastern BLW and the northwest near the lagoon, where croplands were abundant. High-value regions for Water Provision (WP) and Water Regulation (WR) were observed in the western and southern parts of the BLW, characterized by the presence of large bodies of water and wetlands. Conversely, the high-value areas for other ESs like Climate Regulation (CR), Erosion Prevention (EP), and Habitat and Biodiversity (HB) were found in the north and western parts of the BLW, distinguished by extensive forestlands. These spatial variations underscore the diverse distribution and significance of different ESs in the BLW region. From 2000 to 2021, the ESV of four ESs increased, as shown in Fig. 4. Water Provision (WP), Water Regulation (WR), Waste Treatment (WT), and Climate Regulation (CR) all witnessed an increase in value. Conversely, Food Provision (FP), Raw Material (RM), Air Quality Regulation (AQR), and Nutrient Cycling (NC) consistently decreased during the same period (Hu et al. 2022).

Notably, during the 2000–2021 timeframe, regions along the southwestern BLW, particularly Vavunatheevu and Vellavely, experienced significant improvements in the value of Waste Treatment (WT) and Water Regulation (WR). However, the eastern BLW reported substantial decreases in the value of Food Provision (FP), Raw Material (RM), and Nutrient Cycling (NC). Moreover, areas around Pulliyantheevu and the suburbs of Batticaloa town reported a decrease in Air Quality Regulation (AQR) value, as indicated in Fig. 4. These changes underscore the dynamic nature of ESs in response to evolving

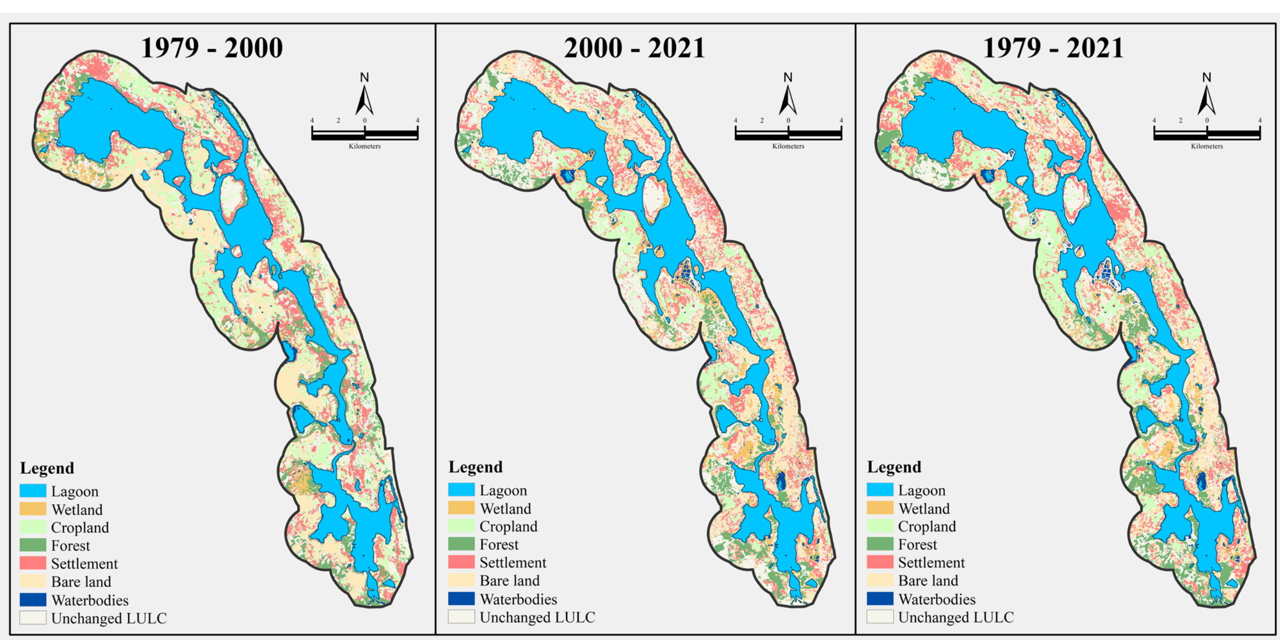

Fig. 3 Land use and land cover change in the Batticaloa Lagoon Watershed in the periods (left panel) 1979–2000, (center panel) 2000–2021, and (right panel) 1979–2021

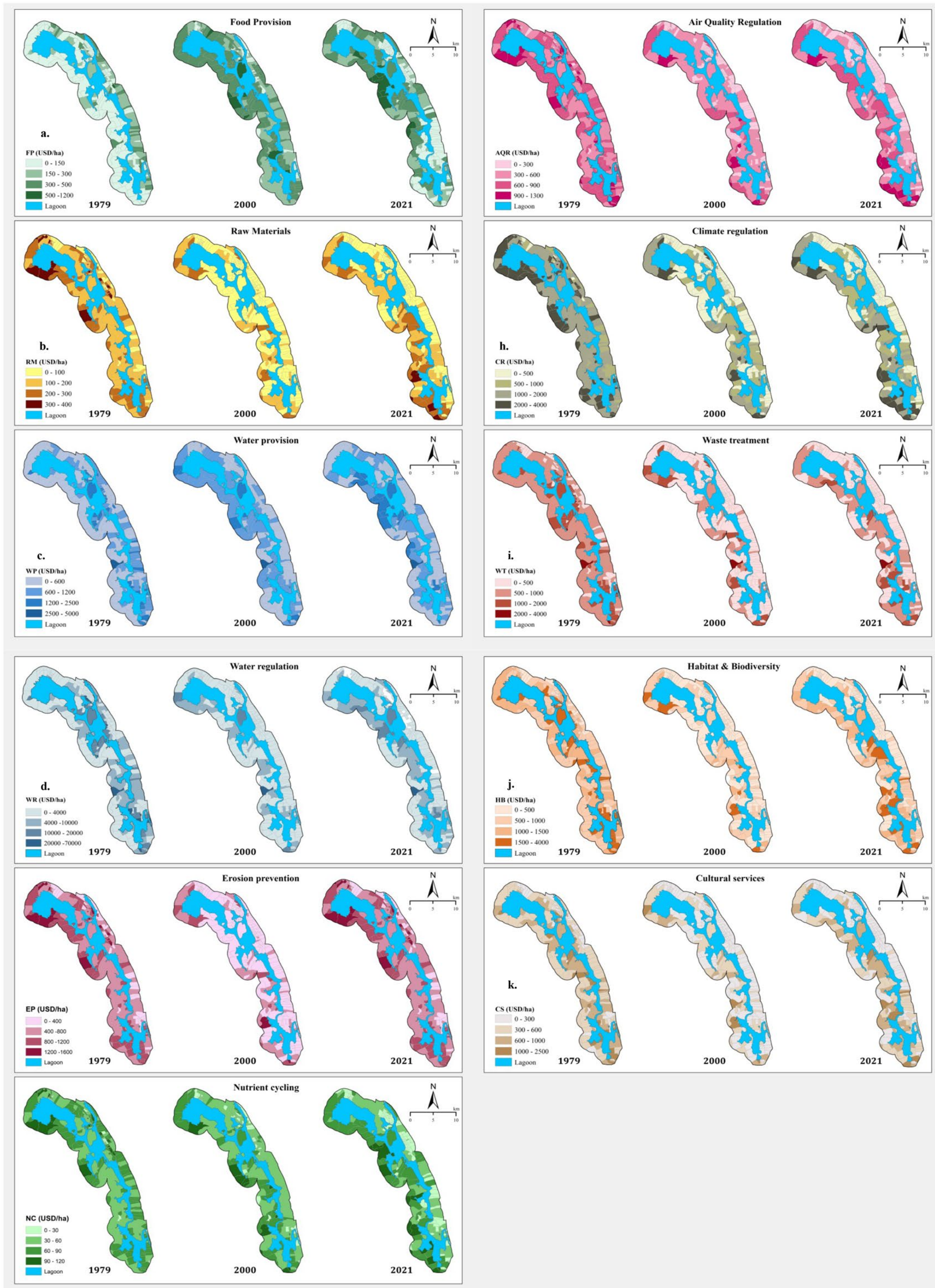

Fig. 4 Spatial views of the individual ecosystem service values of GNDs in the Batticaloa Lagoon watershed (BLW) **a**: Food Provision, **b**: raw materials **c**: Water Provision, **d**: Water regulation, **e**: Erosion Prevention, **f**: Nutrient Cycling, **g**: Air Quality regulation, **h**: Climate Regulation, **i**: Waste treatment, **j**: Habitat and biodiversity, **k**: Cultural Services

land use and environmental factors within the BLW region.

Spatial and temporal changes of the total ESV

The analysis of spatial-temporal changes in the overall Ecosystem Service Values (ESV) within the BLW region has unveiled clear patterns, as depicted in Fig. 4. Regions with high total ESV were primarily clustered in areas endowed with abundant forests or wetlands, including Vavunatheevu, Paddipalai, Vellavely, and the border areas adjacent to Ampara and Batticaloa. In contrast, regions with lower total ESV were identified in the eastern part of the Batticaloa district, predominantly characterized by urban land coverage.

These transformations have brought about a noticeable reduction in the natural habitat within the Batticaloa Lagoon area, resulting in a substantial 9.93% decrease in the total ecosystem service value (ESV) from 1979 to 2021. The primary reasons behind this decline are the remarkable 84.64% decrease in wetland coverage and a significant 52.53% decrease in forest coverage.

In 1979, wetlands and forests held the highest ESV values, representing the crucial contributions of these ecosystems to the region. However, by 2021, a shift had occurred, with cropland and waterbodies surpassing them in ESV values. Specifically, Cropland recorded an ESV value of 9.28 million US dollars, while waterbodies reached an ESV value of 23.98 million US dollars during the study period.

These shifts in ESV values underscore the profound impact of human-modified land uses on the ESs of the Batticaloa Lagoon.

They highlight the pressing need for thoughtful and sustainable land management practices and robust conservation efforts to safeguard these vital ecological contributions. The trends observed in ESV values emphasize the importance of balance and responsible stewardship of the environment as we navigate the evolving landscape of the Batticaloa Lagoon area.

Temporal changes in individual ecosystem service values (ESV) within the Batticaloa Lagoon Watershed (BLW) from 1979 to 2021was illustrated in Fig. 5. The study highlights that approximately 53% of Grama Niladhari divisions (GNDs) in the western BLW experienced ESV increases, driven by gains in water regulation, climate regulation, and waste treatment. Conversely, northwestern GNDs (e.g., Vavunatheevu) declined due to reduced food provision and nutrient cycling. Despite localized improvements, most areas exhibited an overall ESV decrease, attributed to cropland and wetland losses. These trends underscore the spatial heterogeneity and dynamic impacts of land-use changes on ESVs, emphasizing the need for targeted conservation strategies. However, some GNDs located in the northwestern areas, specifically in Vavunatheevu and Paddiapali Divisional Secretariats, experienced a decline in their ESV during the same period. These changes in ESV exhibited significant variation across different areas throughout the two decades. Overall, most areas within the BLW experienced a decrease in their ESV from 2000 to 202.

When examining the performance of SDGs within the Batticaloa Lagoon Watershed (BLW), it becomes evident that specific spatial patterns are consistently observed. Specifically, 11 SDGs (excluding SDG12) exhibited a recurring pattern, with higher scores prevalent in the western region of the lagoon and lower scores in the narrow eastern strip (as illustrated in Fig. 6). Among these SDGs, SDG1, SDG3, SDG11, SDG12, and SDG15 demonstrated the most commendable performance within the BLW. Conversely, SDG7 and SDG8 exhibited subpar performance levels.

Also, Fig. 6 presents the spatial and temporal changes in the ES-SDG Index scores across Grama Niladhari divisions (GNDs) in the Batticaloa Lagoon Watershed

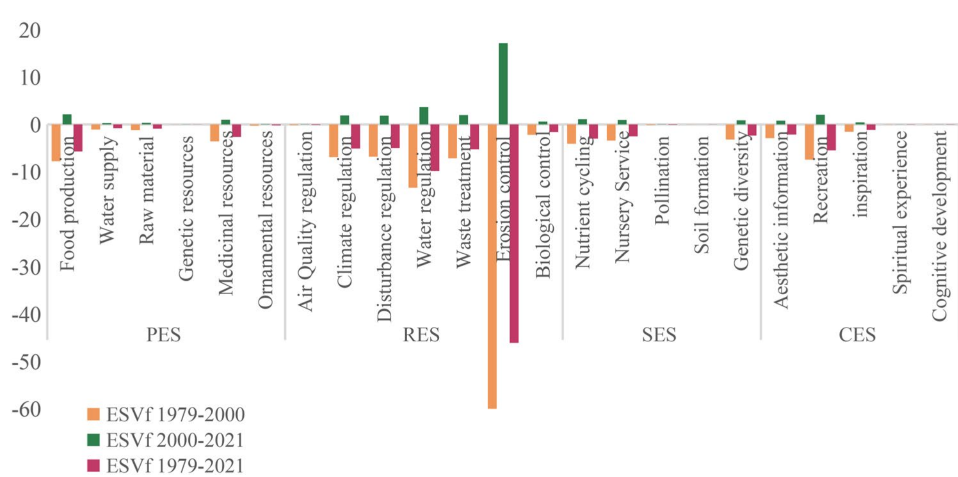

Fig. 5 Temporal changes of individual ecosystem service values in the Batticaloa Lagoon watershed (BLW)

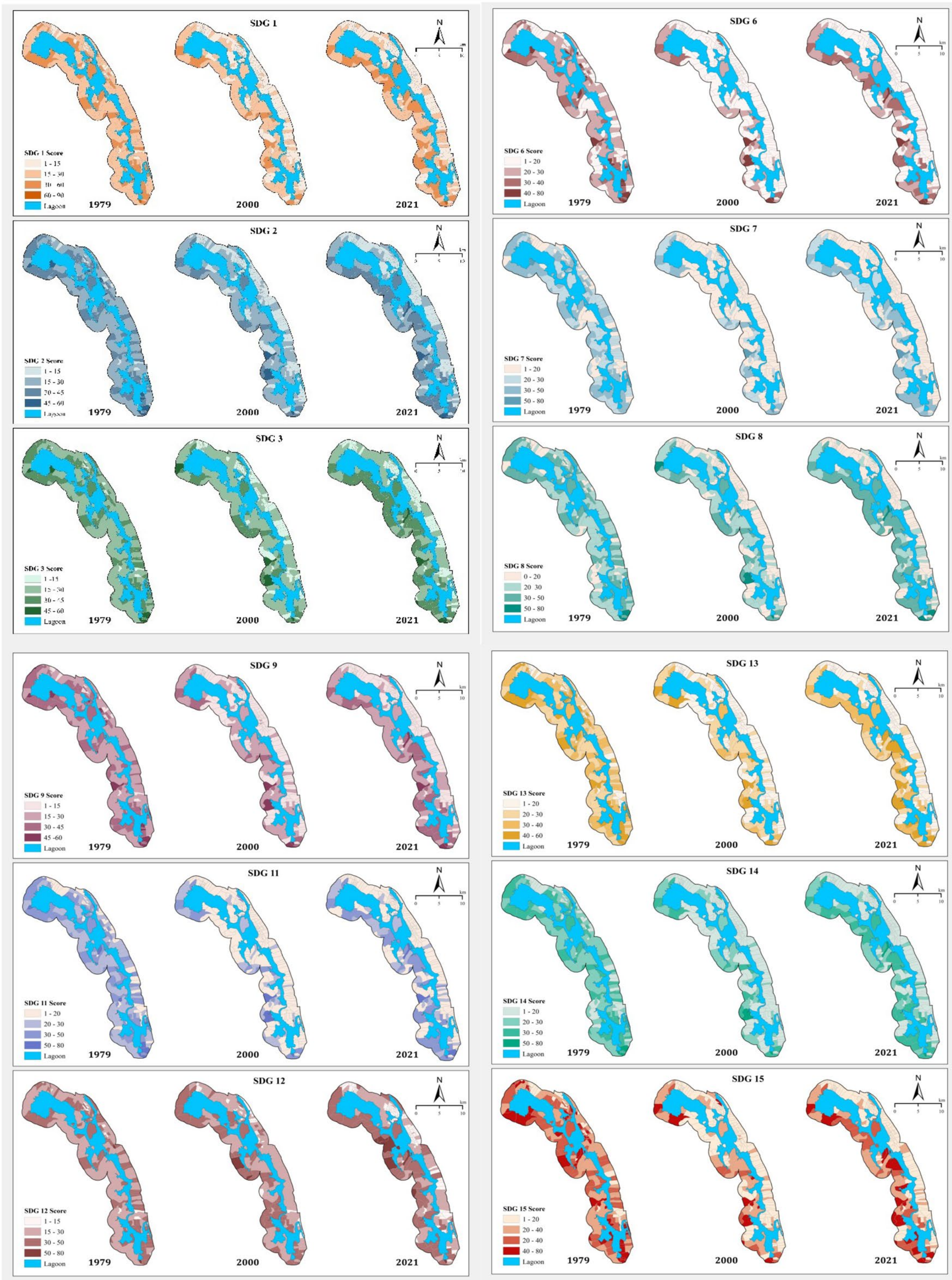

Fig. 6 Spatial and temporal changes in ES-SDG Index scores of GNDs in the Batticaloa Lagoon Watershed

(BLW). The results reveal a clear regional divide, with higher scores consistently observed in the western BLW, where forest and wetland restoration efforts (e.g., Vavunatheevu and Vellaveli) enhanced ecosystem services like water regulation and climate mitigation. In contrast, eastern GNDs, dominated by urban expansion, showed lower scores due to food provision and nutrient cycling declines. The overall ES-SDG Index dropped sharply

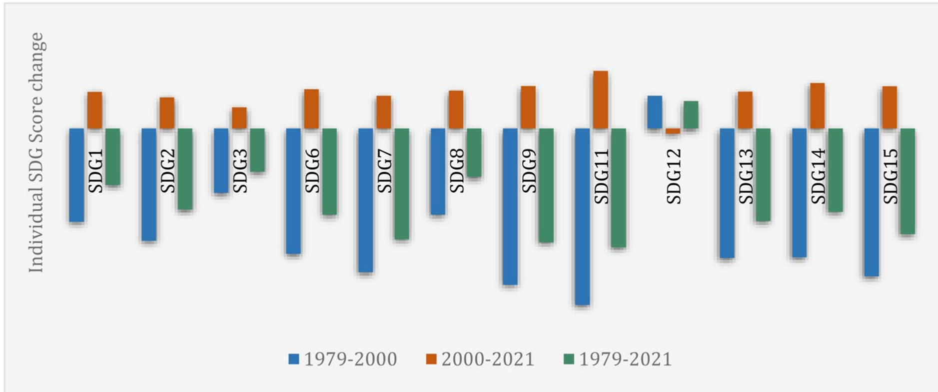

Fig. 7 Temporal changes in individual SDG scores in the Batticaloa Lagoon Watershed

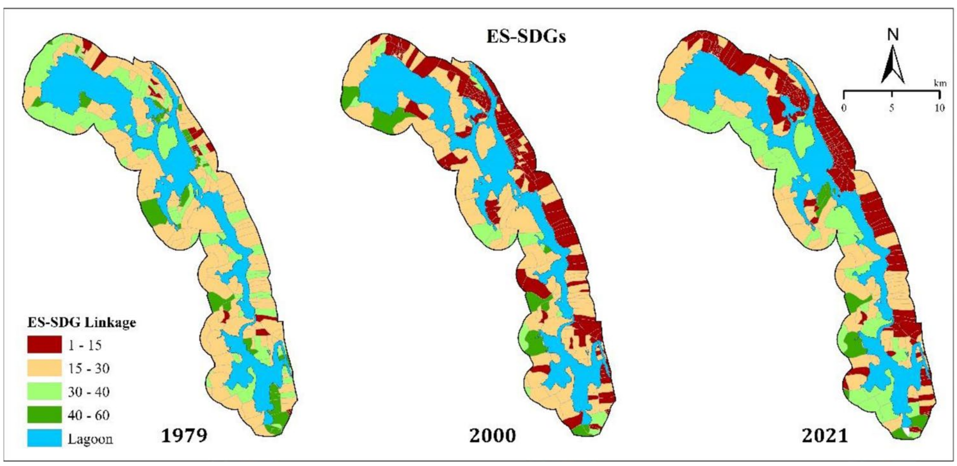

Fig. 8 Spatial view of individual SDG scores of GNDs in the Batticaloa Lagoon Watershed

from 1979 to 2000 but partially recovered by 2021, reflecting the dual pressures of land-use change and conservation policies. This spatial disparity underscores the need for balanced development strategies that integrate ecological restoration with urban planning.

The temporal trends in individual SDG scores in the BLW. Between 2000 and 2021, all SDG scores showed upward trajectories, with SDG12 (Responsible Consumption) improving continuously. SDG1 (No Poverty), SDG3 (Health), SDG11 (Sustainable Cities), and SDG15 (Life on Land) performed well, linked to enhanced water provision and biodiversity. However, SDG7 (Clean Energy) and SDG8 (Economic Growth) underperformed, reflecting insufficient energy access and economic inclusivity progress. The recovery post-2000 aligns with reforestation and wetland restoration initiatives, highlighting how ecosystem-driven interventions can synergize SDG progress despite persistent socioeconomic challenges. Notably, SDG12 scores exhibited continuous improvement throughout the entire period, and all SDG scores displayed an upward trajectory between 2000 and 2021 (as depicted in Fig. 7).

Spatial and temporal changes of ES-SDG Index scores

In the ES-SDG Index Scores, a clear spatial divide is noticeable. GNDs in the eastern region of the lagoon consistently maintained high scores. In contrast, those in the east part consistently scored low (as shown in Fig. 8). The overall ES-SDG Index score for the entire Batticaloa Lagoon ecosystem followed a distinct trajectory. It significantly declined, plummeting from 32.1 in 1979 to 21.0 in 2000. However, there was a modest recovery, with the score reaching 24.3 by 2021. Notably, the most substantial declines were observed in the suburbs of eastern coastal GNDs surrounding the lagoon, with the Batticaloa district lagoon experiencing the most pronounced decline, amounting to 64.82.

In contrast, GNDs near Vellaveli and Vavnuatheevu made substantial gains in their ES-SDG Index scores. Interestingly, the individual SDG scores in most of the Grama Niladhari divisions (GNDs) in the eastern part of the BLW showed a decline from 1979 to 2000. However, a contrasting trend emerged in GNDs primarily located in Vavunatheevu, Paddipalai, and Vellavelly, where all individual SDG scores increased from 2000 to 2021.

Discussion

Effects of land use on changes in ecosystem services value (ESV) and ES-SDG Index scores

Land use changes in the BLW region significantly affect Ecosystem Service Values (ESV) and ES-SDG Index scores. Between 2000 and 2021, the decline in cropland, grassland, and wetland areas had adverse consequences, resulting in a decrease in the value of eleven ESs. This decline affects crucial services such as food provision, air quality regulation, and nutrient cycling. Conversely, the expansion of forestland, waterbodies, and wetlands in the same period has positively contributed to the improvement of seven ESs. This includes enhancements in water provision, water regulation, waste treatment, and climate regulation. These shifts underscore the profound influence land use decisions can exert on delivering vital ESs.

Despite the decline in the value of all eleven ESs over four decades, the overall Ecological Service Value (ESV) of the BLW witnessed an increase of 10.2%. This increase can primarily be attributed to the expansion of waterbodies and forestland, which possess high equivalent coefficients and thus contribute significantly to the ESV. These findings underscore the importance of thoughtful land use planning and conservation efforts in maintaining and enhancing ESs in the BLW region.

The ES-SDG Index score of the BLW demonstrated a declining trend from 1979 to 2000, succeeded by an upward trajectory from 2000 to 2021. These fluctuations can be ascribed to the dynamic interplay between urbanization trends and eco-environmental protection policies in the region. During the rapid urbanization, the conversion of cropland into bare land led to a consistent decrease in the value of food provision, as highlighted by (Partheepan et al. 2023). Conversely, expanding forests, mangroves, and waterbodies, driven by initiatives like the "Community Forest" and "Aquaculture Project," significantly bolstered climate regulation, waste treatment, and erosion prevention. Furthermore, mangrove/wetland conservation efforts and the conversion of paddy fields into bare land have made significant contributions to the augmentation of water provision, improved waste treatment, and enhanced water regulation of the coastal belt (Zhang et al. 2019).

Additionally, restoring forests, mangroves, and waterbodies in rural areas substantially enhanced the Ecological Service Value (ESV), effectively counterbalancing the decline attributed to urban land expansion. The BLW's recovery of ESV (2000–2021) aligns with Zhou et al. 2018 findings, as reforestation and mangrove conservation (e.g., Vavunatheevu area) offset losses from urbanization. This validates the global relevance of rural-urban ecological balancing. In the context of SDG scores, there was a general trend of improvement across all SDGs except for SDG 12 from 2000 to 2021. Among these, SDG 9, SDG 11, and SDG 14 exhibited the most significant increases. Notably, SDGs 9 and 11 enhanced greatly due to water provision and climate regulation improvements. In contrast, SDG 8, SDG 12, and SDG 14 saw notable progress primarily driven by advancements in food provision, nutrient cycling, habitat and biodiversity preservation, and cultural services.

The fluctuations observed in individual SDG scores and the ES-SDG Index scores of the Batticaloa Lagoon were predominantly shaped by the ESs as mentioned above. This pattern resonates with findings from a parallel study conducted in the Beijing-Tianjin-Hebei Region, China, and the Yangtze River Economic Belt. In that study, the crucial role of enhancements in food and water provision was underscored as a driving force behind the escalation of SDG Index scores, as reported by (Chen et al. 2022; Hu et al. 2022).

Considerations for the management of sustainable development and ESs

ESs directly impact the advancement of SDGs in the BLW region. Attaining a harmonious equilibrium between provisioning and regulating services and concurrently promoting synergies among regulating services and supporting services is crucial for effective land-use management. This approach aims to enhance the interplay of multiple ESs (Shen et al. 2020).

Despite an overall increase in the total Ecological Service Value (ESV) observed from 2000 to 2021 in the BLW, it's noteworthy that all eleven ESs experienced an increase during this period. Approximately 20–25% of the area witnessed a rise in their ESV. A matter of considerable concern arises from the escalating importance of providing food and cycling nutrients, particularly in the western sections of the lagoon. While contributing to socioeconomic development, urbanization poses challenges to achieving SDGs by encroaching on vital cropland and disrupting ecological zones. Regulating the unplanned expansion of construction land becomes crucial, and land consolidation emerges as a pivotal strategy to release cropland for large-scale farming. It enhances food production in the western BLW region.

The western regions of the lagoon serve as crucial ecological barriers within the BLW, boasting high SDG scores. In contrast, the eastern areas of the lagoon witnessed a decline in their Ecological Service Values (ESV) from 2000 to 2021. Valuable insights can be gleaned from the effective mangrove reforestation and land cultivation initiatives undertaken in the western portion of the lagoon Watershed in Batticaloa, as documented Partheepan et al. (2023). These efforts have proven successful in safeguarding both the quantity and quality of water resources within the BLW. To accelerate progress in meeting SDG6, (Wang et al. 2024) recommend the implementation of advanced technologies and the adoption of cleaner production facilities. This strategy aims to improve water and nutrient use efficiency. In alignment with SDG11, (Cumming et al. 2017) advocate for investments in ecological infrastructure, emphasizing initiatives like the rehabilitation of wetlands. Such measures can enhance resilience against natural disasters and contribute to the reduction of pollution. Also, The BLW's wetland loss (-84.64%) and its impact on SDG6/SDG15 align with Cumming's warnings. Conversely, post-2000 mangrove restoration (e.g., Vellaveli area) supports their argument for nature-based solutions.

Notably, SDG7 has displayed a consistent and positive trajectory, while SDG12 has experienced a continuous decline over the past two decades. These trends align with similar findings at the provincial level in China, as reported by (Zhang et al. 2022). While the BLW lacks cryosphere dynamics, Zhang's focus on "priority SDGs" (e.g., SDG6, SDG15) resonates with the manuscript's emphasis on targeting water regulation and biodiversity to maximize SDG synergies. Consequently, prioritizing efforts towards SDG6, SDG11, SDG12, and SDG15 becomes imperative to foster the harmonious growth of SDGs within the BLW region.

Limitations

This research attempts to integrate ESs into the SDGs assessment, but the equivalent factor method used to quantify ESs based on land-use structure has certain limitations. The study adopted the equivalent factor method for quantifying ecosystem services through ES values despite its standardized framework for land-use structure analysis, which affects the interpretation of results. The study fails to account for localized ecological processes in the BLW because it depends on global coefficients disregarding regional differences. The BLW features saline-freshwater borders and invasive Avicennia marina encroachment, which generates varied ES delivery across wetlands and mangroves that standard coefficients cannot detect (Schröter et al. 2014). The method underrepresented the water regulation abilities of saline-tolerant wetlands relative to worldwide freshwater standards because of its rigid methodology. The technique uses static land-use-ES relationships to model the relationships between land use and ecosystem services. However, the BLW's dynamic changes, including its 84.64% wetland loss from 1979 to 2000 and partial restoration beginning in 2000, create a problem. The analysis by Lautenbach et al. (2019) shows that static frameworks cannot correctly track the time needed for ES recovery in similar coastal systems. The framework fails to capture cultural ES values, including artisanal fisheries and lagoon-based rituals, due to its limited focus on biophysical metrics, causing poor performance in SDG1 and SDG11, according to Pascual et al. (2017). The land-use proxy model fails to account for governance and community-led initiatives because it did not include the Vavunatheevu region's mangrove initiatives, thus missing essential data for participatory conservation research (Bennett et al. 2015). The economic valuation methods used in this study converted cultural services and habitat connectivity into monetary values that obscured their essential ecological and social value, according to (Kallis et al. 2013). The method produces inconsistencies that appear as the discrepancy between substantial waterbody ESV increases and delayed SDG6 indicators along with the combination of cropland growth (319.77 km^2 net gain) and declining food provision ESV values that demonstrate poor relationships between land-use area and ES output. The method provides a measurable framework. However, the BLW demonstrates that dynamic coefficients, participatory socio-cultural assessments, and spatially detailed models should be integrated to achieve better ES-SDG alignment with real-world complexities.

Conclusions

The BLW region's progress in achieving the SDGs was assessed by examining the linkages between ESs and SDGs from 2000 to 2021. The study observed a pattern in both the Ecosystem Service Value (ESV) and ES SDG Index scores, with higher values found in the western areas and lower values in the southwest region. Over the years, the ES-SDG Index score for the entire Batticaloa Lagoon ecosystem exhibited noteworthy fluctuations. It initially experienced a substantial decline, plummeting from 32.1 in 1979 to 21.0 in 2000, followed by a gradual but modest recovery to 24.3 by 2021. When considering the individual Grama Niladhari divisions within the region, an overwhelming majority, approximately 86%, witnessed a decrease in their ES-SDG Index scores from 1979 to 2021. When considering SDGs, SDG1 (No Poverty), SDG12 (Responsible Production and Consumption), and SDG15 (Life on Land) displayed performance, while SDG6 (Clean Water and Sanitation) and SDG11 (Sustainable Cities and Communities) performed less satisfactorily. Between 1979 and 2000, the BLW region experienced a decline in ten SDG scores over two decades. However, there was a rise in these scores between 2000 and 2021.

Conversely, SDG7 (Affordable and Clean Energy) scores demonstrated a consistent upward trend, primarily driven by improved climate regulation services and water provision. In contrast, the score for SDG12 exhibited a continuous decline, mainly attributable to the diminishing of nutrient cycling services and food provision.

When used for wider implementation, the BLW methodological framework demonstrates distinct pros and cons when considered for broader application. A primary pro is its scalability: The framework demonstrates scalability because its standardized ES coefficients allow researchers to compare regions while working in data-deficient coastal areas that experience rapid land-use transitions (Schröter et al. 2014). Another advantage lies in its policy relevance, because it connects ES metrics directly to SDG targets, enabling policymakers to select sustainability interventions that suit specific contexts. The framework demonstrates flexibility through its ability to modify coefficients for mangrove productivity, making it suitable for various systems, including semi-arid watersheds and tropical estuaries (Barbier et al. 2011; López-Hoffman et al. 2010). Additionally, its capacity to integrate multidisciplinary data (ecological and socioeconomic) provides a comprehensive approach for SDG monitoring according to transdisciplinary research on human-natural system interactions (Dawson et al. 2021). However, key cons include reliance on static coefficients, which do not capture the complexity of ecological changes such as saltwater-freshwater shifts (Costanza 2020) and because it fails to recognize indigenous knowledge systems that play a vital role in achieving SDG success in Pacific Island regions (López De La Lama et al., 2021). Finally, its data-intensive requirements limit applicability in regions its use in areas without detailed information and thus needs additional participatory methods to achieve equitable outcomes (Chaigneau et al. 2022). The methodology establishes a structured, flexible framework enabling global sustainability advancement through replicable design.

The research findings underscore the crucial importance of regulating services within the ESs framework for the BLW region. Alterations in SDGs and the ES-SDG Index scores are predominantly influenced by factors related to food and water provision, climate regulation, nutrient cycling, habitat and biodiversity preservation, and cultural services. To foster the harmonious advancement of SDGs in the BLW region, the evaluation of SDG targets highlights the need for focused efforts on SDG6, SDG11, and SDG12.

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Data availability
Data will be made available on request.

Declarations

Competing interests
On behalf of other authors, I declare that there is no competing interests in this paper financially, material, or any other third party interests.

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