frontiers in Environmental Science

TYPE Original Research
PUBLISHED 10 September 2026
DOI 10.3389/fenvs.2026.1843967

OPEN ACCESS

EDITED BY
Paul Leonard,
Consultant, London, Jersey

REVIEWED BY
Arantza Murillas Maza,
AZTI - Sustainable Fisheries Management, Spain
Ana Matias,
CIMA - Center for Marine and Environmental Research - University of Algarve, Portugal
Elena Kostopoulou,
National and Kapodistrian University of Athens, Greece

*CORRESPONDENCE
Maurizio Pinna,
maurizio.pinna@unisalento.it
Francesco Zangaro,
francesco.zangaro@unisalento.it

RECEIVED 31 March 2026
REVISED 20 August 2026
ACCEPTED 24 August 2026
PUBLISHED 10 September 2026

CITATION
Zangaro F, Marcucci F, Specchia V, Ayoub S, Bastid P, Bužan E, Duniš L, Ewald J, Filipović A, Georgiou P, Kenward R, Kounnamas C, Nienaber A-M, Schwalbe E, Vayanou P, Velkavrh Ž and Pinna M (2026) First application of the conservation and human use index (CHUI) for the evaluation of coastal social-ecological conditions across ten european case studies.
Front. Environ. Sci. 14:1843967.
doi: 10.3389/fenvs.2026.1843967

First application of the conservation and human use index (CHUI) for the evaluation of coastal social-ecological conditions across ten european case studies

Francesco Zangaro[1,2]*, Francesca Marcucci[1,2], Valeria Specchia[1,2], Sara Ayoub[3], Perline Bastid[4], Elena Bužan[5,6], Luka Duniš[5], Julie Ewald[4,7], Ana Filipović[8], Panagiotis Georgiou[9], Robert Kenward[4,10], Constantinos Kounnamas[9], Ann-Marie Nienaber[11], Emily Schwalbe[3], Phoebe Vayanou[9], Žiga Velkavrh[5] and Maurizio Pinna[1,2,12]*

[1]Department of Biological and Environmental Sciences and Technologies (DiSTeBA), University of Salento, Lecce, Italy, [2]Research Centre for Fisheries and Aquaculture of Aquatina di Frigole, DiSTeBA, University of Salento, Lecce, Italy, [3]Department of Environmental Studies ATU Sligo, Sligo, Ireland, [4]European Sustainable Use Group, Brussels, Belgium, [5]Department of Mathematics, Faculty of Mathematics, Natural Sciences and Information Technologies (FAMNIT), University of Primorska, Koper, Slovenia, [6]Faculty of Environmental Protection, Velenje, Slovenia, [7]Game and Wildlife Conservation Trust, Fordingbridge, United Kingdom, [8]Project Management Department, Chamber of Economy of Montenegro, Podgorica, Montenegro, [9]Nature Conservation Unit, Frederick University, Nicosia, Cyprus, [10]UK Centre for Ecology & Hydrology, Maclean Building, Benson Lane, Crowmarsh Gifford, Wallingford, Oxfordshire, United Kingdom, [11]Department of Business Ethics, Sustainability, and Societal Change, Technical University Braunschweig, Braunschweig, Germany, [12]National Biodiversity Future Center (NBFC), Palermo, Italy

Social-Ecological Systems (SESs) are shaped by complex interactions between natural processes, governance structures, environmental pressures, and human perceptions. To evaluate these multidimensional dynamics in diverse transboundary coastal areas, this study presents the first application of the Conservation and Human Use Index (CHUI) across ten case studies representing contrasting ecological, institutional, and socio-cultural contexts. The CHUI, grounded in the Social-Ecological Systems Framework (SESF), operationalises system performance through 134 standardised indicators spanning four equally weighted dimensions: Resource System, Environment, Governance, and Actors. Indicators were identified by scientific literature, management documents, and cross-stakeholder consultations, enabling qualitative insights to be translated into semi-quantitative metrics through a harmonised scoring protocol. Results reveal marked variation among the identified case studies, reflecting distinct combinations of ecological conditions, exposure to anthropogenic and climatic pressures, governance effectiveness, and the quality of human-nature relations. Overall, the first CHUI assessment results demonstrate the tool's effectiveness as both a diagnostic framework and a comparative platform for identifying leverage points, guiding adaptive governance, and supporting integrated coastal management. It highlights the importance of balancing ecological protection, institutional strength, and socially legitimate processes to enhance the assessment of baseline conditions and system vulnerabilities across coastal SESs.

KEYWORDS

citizen science, coastal management, comparative assessment, ecosystem services, participatory science, social perceptions, social-ecological systems, stakeholder engagement

1 Introduction

Understanding how ecosystems generate value for society and how this value is threatened under accelerating environmental change is critical for a wide range of stakeholders, including policymakers, resource managers, local communities, and economic decision-makers. In the context of climate change, biodiversity loss, and increasing pressure on natural resources, decisions regarding land use, conservation, and development must balance ecological integrity with socio-economic needs (Costanza et al., 1997; Hou et al., 2014; Schneider et al., 2020).

Ecosystem Services refer to the multitude of benefits that human societies derive, directly or indirectly, from natural ecosystems. Early ecological economists and systems ecologists had already emphasised the functional dependence of societies on nature decades earlier (Costanza et al., 1997; Daily, 2017), while similar notions can be traced back even further to classical natural history and land-use theory (Scholes, 2016). Ecosystem functioning and biodiversity are fundamental components of natural systems, underpinning their stability, resilience, and capacity to sustain life. These ecological properties also generate benefits that are directly or indirectly relevant to human wellbeing (Daily et al., 2000; Carpenter et al., 2006). By framing ecosystems as providers of essential services, the concept sought to bridge ecological science and socio-economic systems, highlighting the often-overlooked contributions of natural capital to human prosperity (Costanza et al., 2014). At present, the most widely adopted and influential classification of ecosystem services is that proposed by the Millennium Ecosystem Assessment, organising ecosystem services into four broad categories, namely, provisioning services, cultural services, regulating services, and supporting services (Millennium Ecosystem Assessment and World Resources Institute, 2005; Boyd and Banzhaf, 2007; Wallace, 2007; Carpenter et al., 2009; De Groot et al., 2010; Gómez-Baggethun et al., 2010; Norgaard, 2010; Díaz et al., 2015).

In recent decades, the capacity of ecosystems to sustain service provision has been increasingly compromised by a combination of global and local threats. Climate change, land-use alteration, biological invasions by non-indigenous species (NIS), pollution, overexploitation of resources, and habitat fragmentation and degradation are among the most significant pressures affecting biodiversity and ecosystem functioning worldwide (Vitousek et al., 1997; Sala et al., 2000; IPBES, 2019). These drivers often act synergistically, amplifying their impacts on ecosystems and reducing their resilience to disturbances (Brook et al., 2008; Steffen et al., 2015). Recent studies highlight how climate change alters temperature regimes, precipitation patterns, and extreme events, with cascading effects on ecosystem structure, species interactions, and ecosystem services (Scholes, 2016). At the same time, non-indigenous species can profoundly disrupt native communities, modify trophic networks, and impair key ecosystem functions, ultimately leading to the degradation of ecosystem services (Pinna et al., 2024; Zangaro et al., 2024; Shauer et al., 2025; Shauer et al., 2026). Human-mediated pressures, including coastal development, urbanisation, agricultural intensification, and resource extraction, further increase these impacts, particularly in ecologically sensitive systems such as wetlands, coastal lagoons, and coastal and marine ecosystems (Specchia et al., 2023; Pinna et al., 2024; Zangaro et al., 2025). A global synthesis conducted within the Millennium Ecosystem Assessment revealed that more than 60% of ecosystem services worldwide have been degraded or used unsustainably due to human activities, with the most pronounced losses occurring over the last half-century (Millennium Ecosystem Assessment and World Resources Institute, 2005). This period coincides with unprecedented rates of population growth, economic expansion, and technological development (Steffen et al., 2015). The scale and intensity of human influence on ecosystems have become so pervasive that traditional distinctions between natural and human-dominated ecosystems are increasingly blurred. As a result, some hypotheses assume that the planet has entered a new phase, called Anthropocene, characterised by the dominance of human-modified ecosystems (Alessa and Chapin, 2008; Ellis and Ramankutty, 2008; Mooney et al., 2009).

Understanding the dynamics of ecosystem services under such conditions, therefore, requires analytical frameworks capable of explicitly accounting for the interactions between ecological processes and human systems. The growing recognition of ecosystems as deeply intertwined with social, economic, and institutional dimensions has encouraged a shift toward more integrative approaches that move beyond purely biophysical assessments. Ecosystems and human societies are deeply intertwined, co-evolving across spatial and temporal scales through reciprocal feedback (Folke et al., 2005; Carpenter et al., 2009). This realisation has prompted a shift toward more integrative conceptual models capable of explicitly capturing the dynamic, nonlinear, and multilevel nature of human-environment interactions. Within this context, the Social-Ecological Systems (SES) framework emerged as a foundational analytical approach for understanding sustainability, resource governance, and ecosystem service dynamics under conditions of pervasive human influence (Ostrom, 2009). The intellectual roots of the SES framework can be traced to critiques of reductionist resource management paradigms, especially those derived from Hardin's "tragedy of the commons" (Hardin, 1968). For decades, dominant theory predicted that common-pool resources would inevitably be overexploited unless controlled through centralised regulation or privatisation. This perspective strongly influenced environmental policy, often resulting in uniform, top-down management solutions that overlooked local ecological variability and social institutions (Ostrom et al., 1999; Dietz et al., 2003). In this context, the work of Elinor Ostrom fundamentally reshaped the understanding of human-environment interactions. Based on extensive comparative research across fisheries, forests, irrigation systems, and grazing lands, Ostrom showed that resource users are not inevitably trapped in overexploitation cycles. Instead, under certain conditions, communities can self-organise by establishing rules, norms, and institutions that promote sustainable resource use over long periods (Ostrom et al., 1999; Ostrom, 2005). Building on this empirical foundation, Ostrom developed a general SES framework specifically designed to analyse sustainability outcomes in complex human-environment systems (Ostrom, 2007; 2009).

At the highest level of organisation, the SES framework distinguishes four core subsystems: resource systems (e.g., forests, lagoons, fisheries), resource units (e.g., trees, fish, water volumes), users (e.g., fishers, farmers, local communities), and governance systems (e.g., legal regulations, customary rules, enforcement mechanisms). These subsystems interact within broader social, economic, and political settings and are embedded in related ecosystems, generating outcomes that feed back to influence system dynamics over time (Ostrom, 2009). Crucially, each core subsystem is further decomposed into multiple second- and lower-level variables, including resource productivity, predictability of system dynamics, user group size, leadership, social capital, system knowledge, and institutional flexibility. Empirical studies have shown that sustainability outcomes depend not on any single variable, but on the specific configuration and interaction of these variables within a given SES (Agrawal, 2001; Janssen et al., 2007; Cox et al., 2010). This emphasis on contextual dependency represents a decisive departure from one-size-fits-all management approaches. The SES framework also explicitly incorporates feedback between social and ecological processes, recognising that human actions alter ecosystem structure and function, which in turn reshape the incentives, constraints, and decision-making contexts faced by users and institutions (Levin et al., 2013; Folke et al., 2016). In this sense, SESs are inherently adaptive systems, characterised by nonlinearity, thresholds, and emergent properties that cannot be understood through linear cause-and-effect reasoning alone (Levin, 1998; Norberg and Cumming, 2008).

By framing ecosystems and societies as co-evolving components of a single system, the SES approach provides a powerful conceptual foundation for analysing how ecosystem services are produced, degraded, or sustained under changing environmental and socio-economic conditions. Importantly, it allows ecosystem services to be interpreted not merely as outputs of ecological processes, but as emergent properties of interactions among ecological dynamics, human behaviour, and governance arrangements (Bennett et al., 2015; Díaz et al., 2015). Over the past two decades, the SES framework has been widely applied and refined across disciplines, including ecology, economics, political science, and sustainability science. It has proven particularly valuable for comparative analyses of resource systems, enabling systematic investigation of why similar ecosystems may exhibit divergent trajectories of degradation or resilience under comparable external pressures (Schlüter et al., 2012; Partelow, 2018). As such, the SES framework now represents a central analytical lens for addressing contemporary sustainability challenges in an era of rapid environmental change.

While the Social-Ecological Systems (SES) framework provides a robust conceptual structure for analysing coupled human-environment dynamics, its practical application to climate change assessment requires explicit operational tools capable of translating system complexity into measurable and comparable indicators. Climate change impacts are inherently multi-dimensional, affecting not only ecological processes but also social organisation and the ability of human societies to anticipate and cope with environmental variability. Consequently, addressing climate-related challenges demands indices that explicitly integrate ecological sensitivity, social vulnerability, and institutional capacity within a unified analytical framework. Despite SESF representing a highly valuable diagnostic tool for understanding natural resource management, its operationalisation in the literature remains predominantly context related. Existing research has traditionally focused on SESF in isolated case-study areas, specific resource management scenarios, or single subsystems within the broader framework (Gain et al., 2019; Kenward et al., 2011; Leslie et al., 2015; Thiel et al., 2015; Basurto et al., 2013; Schlüter et al., 2014; Vogt et al., 2015; Palomo and Hernández-Flores, 2019). Notable examples of this targeted application include indicator-based quantitative assessments of small-scale fisheries in Mexico (Leslie et al., 2015), localised conservation policies for multiple resources in the Mexican coastal community of Punta Allen (Palomo and Hernández-Flores, 2019), and evaluations of spatio-temporal variations in coastal floodplain management within the Ganges-Brahmaputra delta (Gain et al., 2019). Even when studies attempt to apply the SESF across diverse area-based conservation contexts, they tend to overemphasise specific dimensions like governance, which ultimately restricts broader cross-site comparability (Kenward et al., 2011; Palomo and Hernández-Flores, 2019; Mahajan et al., 2023; Colding and Barthel, 2019). Furthermore, recent critiques emphasise that many SES applications still rely on relatively static assessments. These approaches often struggle to adequately capture longitudinal trajectories, systemic shocks, and multi-scalar dynamics, highlighting a critical need for structured, repeatable diagnostic tools capable of supporting adaptive management and long-term analysis. Concurrently, emerging empirical research is increasingly integrating ecological processes, governance frameworks, and stakeholder perceptions into composite models. This shift reinforces the necessity of holistic, multidimensional approaches to SES analysis. Ultimately, while the SESF excels at dissecting complex social-ecological interactions, effectively operationalising it across multiple resource units or diverse geographical case studies remains a persistent methodological challenge (Ezzine-de-Blas et al., 2024; Charieg et al., 2025; Solís-Mendoza et al., 2025).

In response to this need, the Conservation and Human Use Index (CHUI; Vayanou et al., 2026) was developed as an integrative metric explicitly grounded in the SES framework, with the aim of capturing the degree to which social-ecological systems are exposed, sensitive, and responsive to human-mediated stressors acting on ecosystems. The primary objective of the CHUI is to provide a standardised diagnostic tool to identify points of conflict and

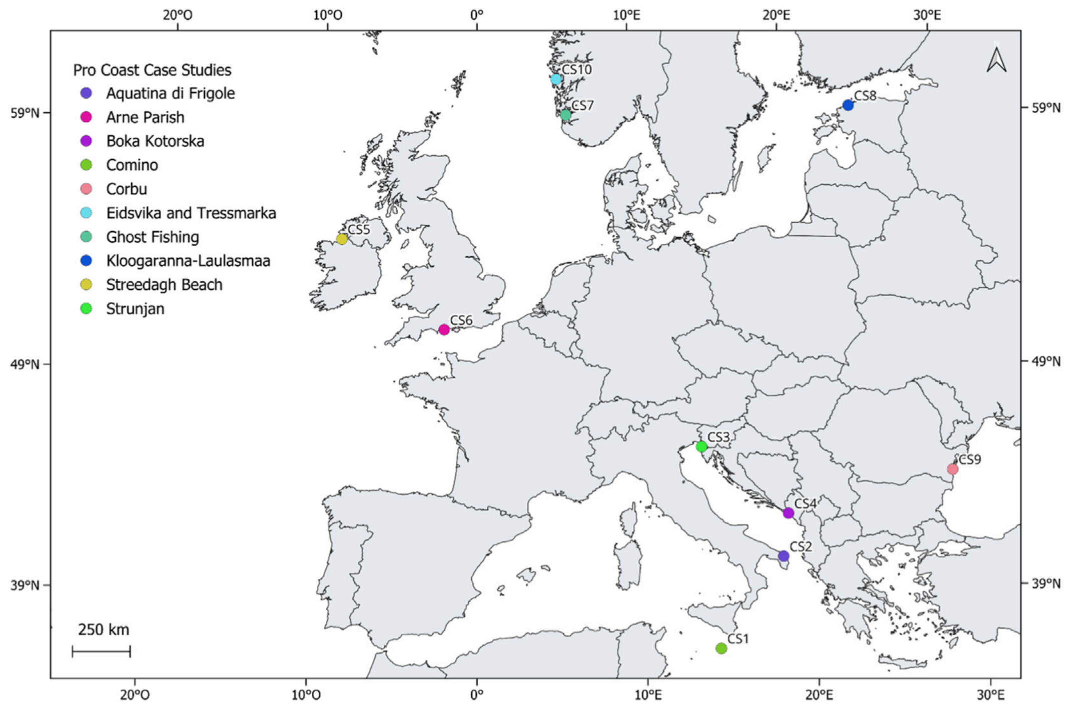

FIGURE 1
Location of the 10 Case Studies involved in the first application of the Conservation and Human Use Index (CHUI).

synergy between biodiversity conservation and human activities within coastal regions. Although traditional ecological assessments do not directly exclude the socio-economic component from ecological quality evaluation, the CHUI is explicitly rooted in Elinor Ostrom's Social-Ecological Systems Framework (SESF). This approach acknowledges that coastal areas are not solely ecological entities but complex systems in which "Resource Systems" (nature) and "Actors" (people) are inextricably linked through "Governance Systems" (Ostrom, 2009; Vayanou et al., 2026).

By explicitly applying SESF principles, translated and operationalised across resource systems, governance systems, and actors, the CHUI is capable of unveiling the sustainability, baseline conditions and system vulnerabilities of the entire social-ecological interface (Vayanou et al., 2026). The Index serves two primary functions: baseline characterisation, establishing a qualitative and semi-quantitative snapshot of a Case Study (CS) area's current ecological health and management efficiency; and decision support, providing ecosystem managers and local stakeholders with evidence-based insights to prioritise data-driven interventions in governance, threat mitigation, or ecosystem service restoration (Vayanou et al., 2026).

To evaluate the index performance and the quality of information it delivers to decision-makers, the CHUI was applied, for the first time, in ten Case Studies across Europe from Malta, Montenegro, Italy, Romania, Slovenia, England, Ireland, Estonia, and Norway (PRO-COAST, 2023). Each case study is characterised by distinct and contrasting human-mediated pressures. This latitudinal and social-ecological diversity allowed for a robust assessment of the Index's capacity to generate actionable, context-sensitive information across a wide range of governance contexts and coastal management challenges (PRO-COAST, 2023).

2 Materials and methods

2.1 Case studies

Following the methodology described in Vayanou et al., 2026, the CHUI was applied for the first time in ten Case Studies (CS) distributed across the European coastline, including Mediterranean, Atlantic, Baltic, and Black Sea environments (Figure 1).

Each CS was selected based on four criteria: (i) the biodiversity of the area and the pressures threatening it; (ii) the resident community and its cultural context; (iii) the prevailing economic drivers and primary production activities; and (iv) existing governance arrangements. Together, these sites encompass a wide spectrum of coastal ecosystems, from island and coastal lagoon ecosystems to estuaries, fjords, and open sandy beaches. All CSs are subjected to diverse and contrasting human-mediated pressures, thus providing a robust and representative framework for evaluating the capacity of CHUI to generate actionable information for managers and decision-makers (PRO-COAST, 2023). The ten European case studies were purposively selected as demonstrator sites to evaluate the CHUI index across a diverse gradient of institutional, ecological, and socio-economic conditions. Rather than representing homogeneous systems, this set spans a wide spectrum of cultural heritage profiles, varying from highly institutionalised, state-supported sites to community-led, fragmented management structures (Table 1).

TABLE 1 Comparative matrix of the ten European case studies.

Case study	SES profile and ecological typology	Key anthropogenic and environmental pressures	Governance structure
CS1: Comino Island, Malta	Small biological reserve (2.75 km^2). SAC/SPA protected habitats	Mass seasonal tourism, soil trampling, non-indigenous species (NIS), overgrazing, and pig farm pollution	Structurally limited, only two permanent residents, absence of sustainable management frameworks
CS2: Aquatina di Frigole, Italy	NATURA 2000 site; coastal lagoon; sandy beaches, dunes, and *Posidonia oceanica* meadows	Limited hydraulic connectivity, marine and lagoon plastic and microplastic litter, NIS, and intense summer tourism	Shared multi-level governance
CS3: Strunjan, Slovenia	High-value adriatic landscape park; diverse coastal and marine habitats	Coastal tourism, soil erosion, wildlife disturbance, littering, and zoonotic disease risks	Multi-level governance and management structure
CS4: Boka Kotorska bay, Montenegro	Deep adriatic bay; high marine biodiversity; strong cultural/religious heritage	Cruise tourism, coastal construction, anchor damage to seagrass, uncontrolled fishing	Shared local municipalities and national bodies, the public enterprise for coastal zone management
CS5: Streedagh beach, Sligo, Ireland	Dynamic atlantic coastal system; dunes, sandy shores, and mesic grasslands	Sea-level rise, extreme storm events, coastal erosion, tourism pressures	Embedded in the sligo living lab; joint management by ATU sligo and sligo county council
CS6: Arne Parish, Dorset, England	River estuary and rural coastal mosaic (grasslands, heathlands, wetlands)	Intensive agricultural grazing, nutrient run-off, NIS, mineral extraction impacts	60% of land holds environmental protection status, but local community conservation engagement is low
CS7: Bergen ghost fishing, Norway	Fjord ecosystem; rocky shores, shallow bays, and islands	Ghost fishing; heavy aquaculture/maritime industry presence	Co-managed under traditional public right-to-roam/fish laws
CS8: Kloogaranna-Laulasmaa, Estonia	Baltic sea coast with high urban proximity; sandy beaches and coastal dunes	Intense seasonal visitor pressure, rapid urban encroachment, second-home/real estate expansion	Regulated via municipal planning tools integrating green infrastructure and coastal protection laws
CS9: Corbu beach, Romania	Pristine black sea beach inside the danube delta biosphere reserve; riparian forests and lakes	Overtourism, severely under-resourced/absent supervisory body, low local environmental awareness	Legally protected under a biosphere reserve but lacks a localised supervisory body with coastal expertise
CS10: Eidsvika, Norway	Pristine wilderness island area; red-listed bird habitats; coastal bog carbon sink	Encroachment threat from a proposed 1.2 km cruise ship quay and electric boat transport hub	Municipal/regional developmental planning facing intense local conservation pushback

2.1.1 CS1 - Comino Island, Malta

Comino (2.75 km^2) is Malta's largest biological reserve, designated as both a Special Area of Conservation (SAC) and a Special Protection Area (SPA) under the EU Habitats and Birds Directives. Despite its protected status, the island suffers from severe human-mediated pressures driven by mass seasonal tourism, soil trampling and littering, vehicle use, invasive alien species (IAS), overgrazing by feral rabbits and rodents, and pollution from a pig farm. With only two permanent residents, governance capacity is structurally limited, and sustainable management frameworks are largely absent.

2.1.2 CS2 - Aquatina di Frigole, Italy

The NATURA 2000 Site "Aquatina di Frigole" (IT9150003), situated along the southern Adriatic Apulian coast, encompasses several protected habitats, including a coastal lagoon, sandy beaches, coastal dunes, *Posidonia oceanica* meadows, and Mediterranean maquis (Fanini et al., 2021). The site hosts emblematic protected species, including *Pinna nobilis* (Marrocco et al., 2018; 2019) and *Caretta caretta*, occasionally hosts *Monachus monachus* specimens (Zangaro et al., 2020) and has a high biodiversity (Caroppo et al., 2023; Specchia et al., 2022; Orfanidis et al., 2007). Key pressures acting on the area include limitations in hydraulic connectivity between the lagoon and the sea (Margiotta et al., 2021), decomposition, accumulation of plastic and microplastics marine and lagoon litter (Bozzeda et al., 2021), non-indigenous species (NIS), and intense summer tourism (Menéndez et al., 2003). Governance is shared between the University of Salento, the Puglia Region, and the Municipality of Lecce.

2.1.3 CS3 - Strunjan, Slovenia

The Landscape Park Strunjan and its surrounding areas, located on the Slovenian Adriatic coast, comprise diverse coastal habitats supporting protected species such as *Cladocora caespitosa*, *P. nobilis*, *Ruppia cirrhosa*, *Zostera marina*, as well as various birds, mammals, and reptile species. Despite its high ecological value, the area faces human-mediated pressures from coastal tourism, including soil erosion, wildlife disturbance, and littering that attracts large seagull populations and raises zoonotic disease risks. Governance involves a multi-actor structure including the Landscape Park Strunjan, the Municipality of Piran and Izola, and the University of Primorska.

2.1.4 CS4 - Boka Kotorska bay, Montenegro

Boka Kotorska Bay is the largest bay in the Adriatic and hosts exceptional marine biodiversity, including benthic habitat types, coralligenous aggregations, and extensive seagrass meadows. The ecosystem is threatened by human-mediated pressures such as coastal construction, cruise tourism (causing hydrocarbon pollution, noise, and waste), uncontrolled fishing, coral harvesting, and anchor damage to seagrass. The bay also carries a strong cultural and religious heritage, and its economy is largely tourism- and nautical-based. Governance is shared between local municipalities and national bodies, with the Public Enterprise for Coastal Zone Management overseeing the maritime domain.

2.1.5 CS5 - Streedagh Beach, Sligo, Ireland

Streedagh Beach, located on Ireland's north-west Atlantic coast, is a dynamic system of coastal dunes, sandy shores, and mesic grasslands. The site is under increasing pressure from sea-level rise, extreme storm events, and coastal erosion. Tourism is a key economic driver, alongside cultural and archaeological heritage. Governance is embedded within the Sligo Living Lab framework, testing vegetated buffer zones as hybrid nature-based solutions under the joint management of ATU Sligo and Sligo County Council.

2.1.6 CS6 - Arne Parish, Dorset, England

The Arne Parish case study encompasses a river estuary and rural coastal mosaic of grasslands, heathlands, woodlands, and wetlands in southern England. Key pressures acting on this area include intensive agricultural grazing, hedge cutting, nutrient run-off, NIS, and the impacts of mineral extraction. Approximately 60% of the land holds some environmental protection status, yet community engagement in conservation remains low. The local economy is driven by agriculture, mineral extraction, and tourism.

2.1.7 CS7 - Bergen ghost fishing, Norway

This case study contains rocky shores, shallow bays, fjords, and island archipelagos of Norway's west coast in the wider Bergen region. The central environmental challenge is ghost fishing, representing the continued trapping of marine organisms by lost or abandoned fishing gear like fishing nets and crab and lobster pots. In Norway, the sea and fjords are central to the cultural concept of *allemannsretten*, which grants public access for recreational activities such as fishing, reinforcing the deep connection between Norwegians and the environment. Fish production and aquaculture are economically dominant, alongside a range of maritime industries.

2.1.8 CS8 - Kloogaranna-Laulasmaa, Estonia

Located along the Baltic Sea coast west of Tallinn, this case study features sandy beaches, coastal dunes, and high urban proximity. The area experiences intense seasonal visitor pressure and urban development encroachment driven by second-home development and real estate expansion. Social tensions arise between resident communities concerned about environmental degradation and economic interests pushing for further development. Governance involves planning tools incorporating green infrastructure and coastal zone protection legislation.

2.1.9 CS9 - Corbu beach, Romania

Corbu is a largely pristine sandy beach on the Black Sea coast, embedded within the Danube Delta Biosphere Reserve and surrounded by riparian forests, dystrophic lakes, and sandbanks. The site faces the dual challenge of an absent or under-resourced supervisory body with coastal expertise and growing overtourism pressure. Limited environmental awareness among the local community, combined with inadequate sustainable tourism infrastructure, risks undermining the ecological integrity of the area. Tourism is the primary economic driver.

2.1.10 CS10 - Eidsvika, Norway

Eidsvika is one of the few remaining wilderness areas on the island of Askøy, near Bergen, providing coastal access and habitat for several red-listed bird species, as well as a coastal bog functioning as a carbon sink. The site is under direct development threat from a proposed 1.2 km cruise ship quay and electric boat transport hub. The case uniquely highlights the tension between biodiversity conservation, ecosystem service provision, and green transition infrastructure.

2.2 Data collection and participatory approach

Rather than developing an *ad hoc* set of indicators for the selected case studies, this study strictly applied the standardised diagnostic matrix of the CHUI framework (Vayanou et al., 2026). In each case study, data collection was overseen by an identified "Case Study Leader" (PRO-COAST, 2023). For each CS leader, the first step in data collection was a desk-based review of local scientific literature and governance plans used to draft preliminary scores based solely on the available documentation about the case study area. In particular, scientific literature, NATURA 2000 Standard Data Forms, management plans, governance documentation, and any other relevant information from scientific or grey literature were systematically consulted to inform the baseline case study scores. Next, each CS leader was responsible for identifying expert stakeholders in their CS area including, where possible, representatives from higher education and research institutions, local managers, governance actors, and local residents, in order to train them on the CHUI and organise at least one bilateral meeting aimed at comparing, adjusting, and finalising the baseline scores.

To minimise individual bias, scoring was performed collectively using a consensus-based approach (Vayanou et al., 2026). Such an approach foresees that whenever disagreements arise regarding specific indicator scores, participants are required to justify their positions based on documented evidence or grounded operational experiences (Vayanou et al., 2026). If a strict consensus could not be reached, the local case study leaders resolved the disagreement by selecting the median score of the stakeholder inputs (Vayanou et al., 2026). The same protocol for assigning scores or designating indicators as 'Not Applicable' (N/A) was applied uniformly across all ten European sites to guarantee cross-case comparability. Specifically, when a question does not logically pertain to a specific CS (e.g., when a particular pressure or ecosystem service is absent or ecologically irrelevant), the N/A option removes that indicator from the total number of indicators used to define the scoring denominator (Vayanou et al., 2026). The application of this participatory choice is particularly relevant within the CHUI framework application, as it acknowledges that ecological conditions and management effectiveness cannot be fully understood without incorporating the perceptions, lived experiences, and grounded knowledge of those directly interacting with the area.

Specifically, the inclusion of stakeholder consultations ensured that the "Social Perceptions" and "Governance" dimensions reflected the real perceptions by the case studies' end users, as well as the real gaps and strengths in the case studies' governance and management actions. This is crucial because social dynamics, such as reliance on authorities, perceived fairness of rules, community engagement in decision-making, and experiences related to access, justice, or conflict, are deeply shaped by the daily interactions between people, institutions, and ecosystems. Such elements often leave limited traces in written reports but strongly influence the sustainability of management actions (Reed, 2008; Bennett, 2016; Rice et al., 2025). Furthermore, the combined desk-based approach facilitated the integration of cross-stakeholder viewpoints, enabling triangulation between official management perspectives, scientific evidence, citizen science, and community-level insights.

For each case study, the output values derived from the baseline data compilation and the subsequent stakeholder consultation process were systematically recorded and annotated within the Excel spreadsheet designated for the calculation of the CHUI, as provided by Vayanou et al. (2026). This procedure ensured that all quantitative and qualitative inputs obtained during the two phases were consistently integrated into a standardised computational framework, thereby facilitating a coherent and reproducible determination of the CHUI across the different case studies under investigation.

2.3 Index calculation and aggregation

The CHUI evaluates a total of 136 indicators, although of the 27 questions under Governance Systems (GS), 2 (Management mechanism overview) are not included in the final scoring calculation. So, the total number of scored questions across all four SESF variables is 134, each of which is scored using a standardised four-point semi-quantitative ordinal scale: 0 (Absent/Highly Degraded), 1 (Low), 2 (Moderate), and 3 (High/Good Status). This uniform scoring system enables the conversion of qualitative assessments, based on scientific evidence or stakeholder perspectives, into semi-quantitative values that can be compared across indicators, attributes, and case studies. The structured scale ensures consistency across users, reduces subjective variability, and supports transparent aggregation (Vayanou et al., 2026; Table 2).

For each SESF dimension, a percentage score was obtained by dividing the sum of the scores assigned to its constituent questions (0–3 scale) by the maximum possible score for that dimension, excluding any questions marked as "Not Applicable" from both the sum of scores and the maximum possible score. Since each of the four dimensions contributes equally to the overall assessment, this percentage was weighted at 25% of the total CHUI score (Table 3).

The Final CHUI Score was calculated as the arithmetic mean of the four dimension percentages, giving each dimension equal weight in the final evaluation. This equal weighting reflects the index's theoretical foundation in the SES Framework, where ecological, institutional, environmental, and social components are considered intrinsically interdependent and equally essential to system sustainability (Vayanou et al., 2026):

$$CHUI = \frac{R\% + E\% + G\% + A\%}{4}$$

where R%, E%, G%, A% represent the percentage score (0%–100%) obtained independently within each of the four SESF dimensions.

The resulting final score (0%–100%) was subsequently used to assign the Case Study to one of four management tiers, which guide practitioners in identifying appropriate management responses and strategic priorities: Plan [0%, 25%], Build (25%, 50%], Strengthen (50%, 75%], and Maintain (75%, 100%] (Vayanou et al., 2026; Table 4). This four-point ordinal scale is intrinsic to the CHUI as originally developed and was applied here without modification. While coarser categorical scales can concentrate responses in central categories and reduce discriminatory power, the scale was retained unchanged.

The free, open-access, web-based platform for automatic CHUI calculation is also available at https://chui.pro-coast.eu/.

2.4 Index visualisation and formal analysis

The four CHUI dimension scores and the composite CHUI score calculated for the ten case studies (CS) were spatially mapped in QGIS v4.0.0 (Dawson et al., 2026) to illustrate geographic patterns and spatial heterogeneity across Europe.

To examine how SES dimensions co-vary across case studies and to evaluate the structural validity of the composite CHUI index, a multivariate analysis was performed on the four standardised SES indicators characterising the ten CS. All variables were mean-centred, and unit-variance scaled before analysis to ensure comparability across dimensions.

Principal Component Analysis (PCA) was applied to identify the primary axes of variation structuring differences among CS. By projecting the four-dimensional indicator space onto a reduced set of orthogonal components, PCA summarises the main gradients of SES configuration while preserving the maximum proportion of total variance (Jolliffe, 1986). PCA allows for evaluating whether the composite index retains the distinct multivariate identity of each social-ecological system, thereby ensuring that unique local trade-offs are not shaded by the aggregation process. Case studies were represented in the two-dimensional PCA biplot to enable visual comparison of their SES profiles. The composite CHUI score, computed as the arithmetic mean of the four standardised indicator scores, was excluded from the PCA to avoid circularity,

TABLE 2 Indicators used in the Conservation and Human Use Index (CHUI) for each of the four key SESF variables (adapted from Vayanou et al., 2026).

SESF variable	Indicator	Examples
Resource System (R)	Key natural values of the case study area	Does the area include important natural landscapes?
	Status of natural values in the case study area	What is the overall status of habitats in the area?
	Ecosystem services values	Is the area important for climate change mitigation?
Environment (E)	Primary threats/pressures impacting the overall conservation status of the case study area	Climate change
	Primary challenges or impacts affecting the overall conservation status of the case study area	Biodiversity loss
	Degree to which ecosystem services are affected by pressures and threats in the case study area	Climate regulation
Governance System (G)	Management mechanism overview	Is there any authority responsible for the biodiversity management and conservation of the CS area?
	Existence of management Plan(s) and implementation procedure for the case study area	Existence of (a) management Plan(s) and its implementation procedure for the CS area
	Existence of monitoring programmes or initiatives in the case study area	Are the results of monitoring, research and evaluation routinely incorporated into decisions and/or policies related to CS area management?
	Operational capacity-allocation of resources	Are there enough people employed or engaged to manage the CS area?
	Regulations and enforcement	Are there any regulations in force in the CS area?
	Diversity of expertise	Are there established processes to ensure the integration of different knowledge types (scientific, experiential, local, and traditional) into decision-making?
	Coordination and collaboration	Do different levels of management (i.e., local, regional, national or different authorities for different spatial scales) exist within the CS area that function as a coordinated unit?
	Transparency and accountability	Do local stakeholders/actors receive information from CS area authorities in a timely manner?
	Perceived environmental outcomes	To what extent do you feel the ecological outcomes are being achieved?
	Perceived social outcomes	To what extent do you feel the social outcomes are being achieved?
Actors (A)	Wellbeing and health	How has the CS area affected the quality of life of local communities?
	Human rights and access to resources	Do local communities have legal access to land and resources within the CS area?
	Knowledge and education	How accessible are environmental education programs for local communities?
	Livelihoods and economic impacts	Has the CS area improved or worsened job availability for local communities?
	Local culture and values	Have local cultural or sacred sites been preserved within the CS area?
	Social relations	How cooperative are local communities in working together on management efforts in the CS area?
	Social equity (inclusion and empowerment)	How well are local voices represented in decision-making?
	Diversity	How are individuals with disabilities involved and accommodated in the management of the CS area?

but was superimposed as a supplementary variable using a continuous colour gradient. This allowed to assess whether the composite index meaningfully discriminates among CS along the principal SES gradients, providing an empirical check on its internal coherence.

Partial Least Squares (PLS) regression (Wold et al., 2001) was subsequently employed to quantify the directional relationships between the four SES dimensions and the composite CHUI score. Given the sample size ($n = 10$), model stability was evaluated through leave-one-out cross-validation (LOOCV), and interpretation was restricted to the first latent component to minimise the risk of overfitting. This analysis provided the exploratory assessment of CHUI internal consistency, sensitivity to individual SES dimensions, and robustness to variation in case study composition.

TABLE 3 Four-level grading of Individual Variables according to performance (adapted from Vayanou et al., 2026).

Score range	Performance level
0.00%–6.25%	Minimal
6.26%–12.50%	Low
12.51%–18.75%	Moderate
18.76%–25.00%	High

TABLE 4 Compositional CHUI score management tiers (adapted from Vayanou et al., 2026).

Final score (0–100)	Interpretation
0%–25%	Plan
26%–50%	Build
51%–75%	Strengthen
76%–100%	Maintain

Collectively, these analytical steps were designed to evaluate CHUI as a comparative SES assessment tool, characterising dominant structural gradients, inter-dimensional trade-offs, and the discriminant capacity of the composite index across contrasting system configurations.

3 Results

The first application of the Conservation and Human Use Index (CHUI) across the ten Case Study (CS) areas produced a detailed picture of the ecological, environmental, governance, and social conditions characterising coastal Social-Ecological Systems (SESs). The spatialisation of results was rendered through associated maps, enabling a fine-scale visual comparison of performance across the four CHUI dimensions, as well as for the composite CHUI score. These associated maps reveal clear geographical patterns and meaningful variation in the relative strengths and weaknesses of each CS area, illustrating the multi-dimensional nature of coastal sustainability and the value of a diagnostic index approach (Figure 2; Table 5).

3.1 Resource System (R): natural values and ecosystem services

Scores for the Resource System (R) dimension ranged from 11% to 22% (out of a total possible 25%), reflecting moderate variation in the ecological significance and ecosystem service provision across the CS (Figure 2; Table 5). The highest values were observed in Arne Parish (22.0%), Aquatina di Frigole (19.9%), and Boka Kotorska (19.4%), indicating areas where landscapes, habitats, protected species, and ecosystem service functions are comparatively well preserved or particularly valuable. These sites likely benefit from a combination of ecological integrity, long-standing conservation initiatives, and environmental characteristics conducive to biodiversity maintenance.

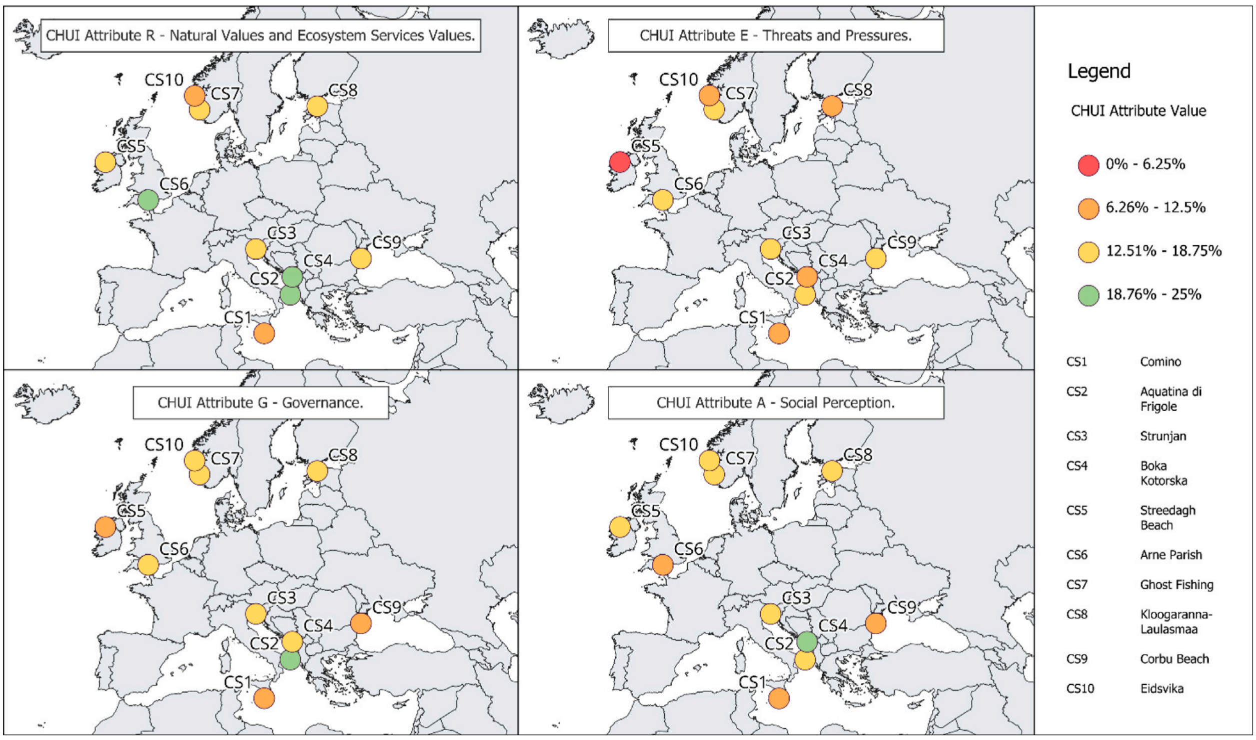

FIGURE 2
Spatial distribution of the CHUI attribute scores across the ten Case Study areas.

TABLE 5 CHUI attribute scores across the ten Case Study areas.

Case study	R - natural values and ESS	E – threats and pressures	G - governance	A- social perception
CS1 - Comino	12.30	9.90	9.00	8.60
CS2 - Aquatina di Frigole	19.90	13.30	18.90	14.40
CS3 - Strunjan	14.50	16.20	18.70	13.20
CS4 - Boka Kotorska	19.40	6.60	16.30	19.60
CS5 - Streedagh beach	17.00	5.20	11.00	15.70
CS6 - Arne Parish	22.00	13.60	14.30	9.80
CS7 - Ghost fishing	13.30	13.90	13.60	13.30
CS8 - Kloogaranna-Laulasmaa	17.40	11.00	15.70	15.10
CS9 - Corbu beach	14.00	14.00	11.70	9.50
CS10 - Eidsvika	11.00	8.00	17.90	12.60

Conversely, lower R-scores were recorded in Comino (12.3%) and Eidsvika (11.0%), suggesting more pronounced degradation of the natural assets. The spatial distribution of R-scores highlights a gradient in ecological conditions, with some systems maintaining robust levels of habitat quality and ecosystem service production, while others display early signs of stress or long-term ecological decline. This dimension, therefore, captures the heterogeneity of ecological baselines that the CHUI is designed to quantify.

3.2 Environment (E): threats and pressures

The Environment dimension exhibited the broadest range of scores, spanning from 5.2% to 16.2%, and visibly clustered CS areas into high-pressure versus moderate-pressure categories (Figure 2; Table 5). Strunjan (16.2%), Ghost Fishing (13.9%), Aquatina di Frigole (13.3%), and Arne Parish (13.6%) displayed the highest E-scores, indicating comparatively lower levels of human-mediated disturbance or more effective mitigation of environmental impacts. These values likely reflect conditions where major pressures, such as over-exploitation, pollution, NIS, and climate-related impacts are present but either managed or not yet severe.

On the opposite side, Streedagh Beach (5.2%), Boka Kotorska (6.6%), and Eidsvika (8.0%) scored the lowest E-scores. These low scores suggest high exposure to environmental pressures and limited buffering capacity against climatic, hydrological, or human-mediated stressors. For instance, coastal erosion, habitat fragmentation, and tourist pressure are common drivers in such settings. The corresponding map visualises clear geographical contrasts, as some CS areas experience diffuse, multi-faceted pressures, while others bear the influence of highly concentrated, site-specific disruptions. This result supports the CHUI's ability to unveil where environmental pressures might undermine ecosystem resilience.

3.3 Governance (G): institutional capacity and management effectiveness

Governance scores ranged from 9.0% to 18.9%, reflecting substantial variation in institutional performance, management structures, and policy implementation across sites (Figure 2; Table 5). Aquatina di Frigole (18.9%), Strunjan (18.7%), and Boka Kotorska (16.3%) emerged as the strongest G-performers. These results highlight areas where management plans exist and are at least partially implemented, monitoring programmes are in place, and authorities hold recognised mandates, collectively enhancing institutional capacity.

Lower governance scores, observed in Comino (9.0%), Corbu (11.7%), and Streedagh Beach (11.0%), may indicate gaps in management frameworks, insufficient enforcement capacity, or fragmented coordination across institutional levels. These weaknesses are consistent with known limitations in multi-level coastal governance, especially in contexts where responsibilities are shared among competing authorities or rely heavily on volunteer-driven management models (Shipman and Stojanovic, 2007; Fleischman et al., 2014; Koontz and Thomas, 2006). The spatial governance map underscores these contrasts and demonstrates how institutional conditions are as geographically variable as ecological ones.

3.4 Social perceptions (A): engagement, reliance, equity, and human-nature relationships

The Social Perception dimension ranged from 8.6% to 19.6%, revealing marked divergence in how local communities and stakeholder groups perceive management effectiveness, social justice, and benefits derived from the Case Study areas (Figure 2; Table 5). Boka Kotorska (19.6%), Aquatina di Frigole (14.4%), and Kloogaranna-Laulasmaa (15.1%) scored the highest A-scores, suggesting relatively high levels of reliance in management institutions, opportunities for stakeholder engagement, and perceived benefits linked to the CS area.

In contrast, Comino (8.6%), Corbu (9.5%), and Arne Parish (9.8%) scored lowest. These values may reflect limited stakeholder participation, concerns over transparency or fairness, or weaker connections between local livelihoods and conservation outcomes. Because social indicators rely heavily on local experience and perception, they are particularly sensitive to governance quality

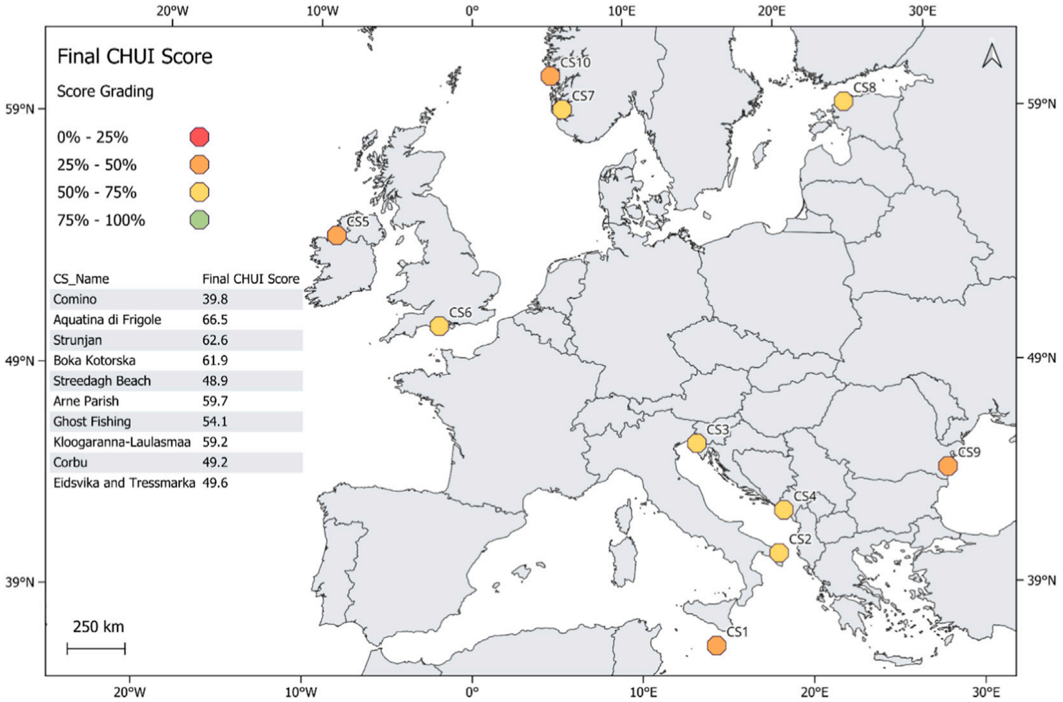

FIGURE 3
Composite map showing the overall sustainability performance of each Case Study area, derived from the average of the four CHUI dimensions. Higher values reflect more balanced SES configurations, where ecological, institutional, environmental, and social components reinforce one another. Lower values indicate systems where multiple stressors or cross-subsystem mismatches constrain resilience capacity.

and local socio-economic dynamics. These findings reinforce the importance of integrating lived experience into SES-based assessments, ensuring that management approaches account for both ecological and social realities.

3.5 Composite CHUI score: integrated SES performance

The Final CHUI Score, representing the average performance across all four dimensions, ranged from 39.8% to 66.5%, showing that no Case Study fell within the lowest "Plan" category, but several remained in the transition between "Build" and "Strengthen" (Figure 3).

The highest-scoring CS area was Aquatina di Frigole (66.5%), followed by Strunjan (62.6%) and Boka Kotorska (61.9%), all of which displayed balanced strengths across ecological, governance, and social dimensions. These areas are characterised by intact ecological systems, moderate to strong governance capacity, and engaged local communities.

At the lower end, Comino (39.8%), Streedagh Beach (48.9%), and Corbu (49.2%) showed weaker composite performance, driven by combinations of environmental pressures, governance gaps, or limited stakeholder reliance. The spatial visualisation (Figure 3) of the overall CHUI score across CS areas highlights these disparities, illustrating how system-level sustainability is the product of interacting ecological, environmental, institutional, and social components.

Taken together, the results reveal a diverse landscape of coastal SES conditions. Some systems exhibit strong ecological baselines but face governance or social challenges, while others show robust governance but remain environmentally vulnerable. This multidimensional diagnostic perspective demonstrates the value of the CHUI as a tool for identifying system-specific leverage points and informing targeted management interventions.

3.6 Multivariate structure of the CHUI

PCA revealed a coherent multivariate structure among case studies, with the first two principal components jointly accounting for 76.1% of total inertia (PC1: 42.0%; PC2: 34.1%). This level of explained variance indicates that the four SES dimensions are not orthogonally independent but share underlying structural gradients, and that the primary axes of differentiation among CS are adequately captured in a two-dimensional ordination space. The PCA biplot (Figure 4) illustrates the distribution of case studies along these gradients and the relative contributions of individual SES indicators to each component.

The loading vectors represent the four SES dimensions and indicate both their direction and relative contribution to the ordination axes. Notably, case studies with comparable composite CHUI scores do not systematically cluster in PCA space, demonstrating that the index is sensitive to differences in the internal configuration of SES dimensions; that is, similar aggregate performance can arise from structurally distinct SES profiles. Conversely, when the composite score is projected as a supplementary colour gradient onto the biplot, higher-scoring systems tend to align along a common multivariate gradient,

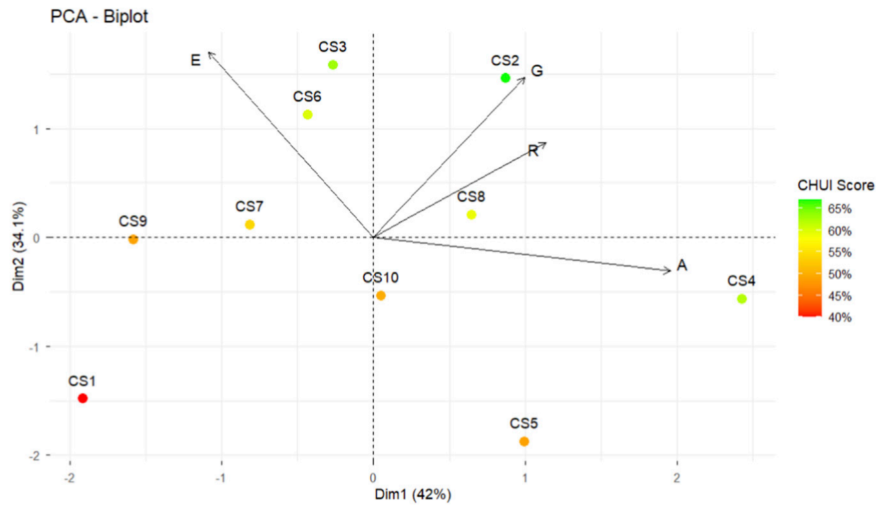

FIGURE 4
Principal Component Analysis (PCA) biplot of the ten case studies based on the four standardised SES indicators of the CHUI (R, E, G, A). Arrows represent variable loadings on the first two principal components, reflecting the direction and relative magnitude of each indicator's contribution to the ordination space. Points correspond to individual case studies and are coloured along a continuous gradient according to their composite CHUI score.

TABLE 6 Partial least squares (PLS) regression analysis for CHUI score predictors.

Parameter/Predictor variable	Component 1	Component 2
Cumulative variance explained (R^2)	37.83%	75.54%
Root mean squared error (RMSEP)	0.0169	0.0123
R (resilience/Resource)	0.574	−0.0079
E (ecological/Economic)	0.1974	0.7933
G (governance)	0.6732	0.0338
A (awareness/Attachment)	0.4363	−0.6514
VIP: R	1.0775	-
VIP: E	0.9686	-
VIP: G	1.0557	-
VIP: A	0.8867	-
Std beta (β): R	0.4576	-
Std beta (β): E	0.4114	-
Std beta (β): G	0.4484	-
Std beta (β): A	0.3766	-

suggesting that the CHUI captures coherent and consistent structural characteristics rather than arbitrary score combinations. Taken together, these patterns support both the discriminant capacity and the interpretability of the CHUI across contrasting SES configurations.

PLS regression (Table 6) strengthened these findings. The first latent component accounted for 37.83% of the variance in the composite CHUI score and was predominantly structured by the governance (G) and resource (R) dimensions, which both exhibited VIP scores exceeding the 1.0 significance threshold. The second latent component brought the cumulative variance explained to 75.54% and revealed a strong directional trade-off between the ecological (E) and actor-related (A) dimensions (loadings of 0.7933 and −0.6514, respectively). This indicates that comparable aggregate performance can be achieved through structurally compensatory configurations, a pattern highly consistent with the multivariate heterogeneity observed in the PCA.

Collectively, these analyses support that the CHUI is internally consistent, sensitive to variation in underlying SES dimensions, and structurally interpretable across diverse European contexts. This first application across ten European case studies provides preliminary empirical support for its validity as a comparative tool for structured SES assessment. Taken together, these multivariate results directly address the study's aim of evaluating CHUI performance, showing that the composite score is neither redundant with any single SES dimension nor an artefact of aggregation, but reflects a structurally coherent signal that decision-makers can interpret with confidence.

4 Discussion

The application of the Conservation and Human Use Index (CHUI) across the ten European coastal Social-Ecological Systems (SESs) provides a first, comprehensive understanding of the multi-layered interactions shaping ecosystem conditions. Grounded in the SES Framework, the CHUI conceptualises sustainability as an emergent property arising from the interplay of ecological, institutional, environmental, and social components (Ostrom, 2005; 2009; Carpenter et al., 2009). By structuring the Index around these four core dimensions, and operationalising them through 133 standardised indicators, the CHUI enables meaningful cross-case comparisons while preserving sensitivity to local context. This allows the tool to function simultaneously as a diagnostic instrument and as a comparative framework for analysing patterns across heterogeneous coastal environments.

The ten case studies assessed through the CHUI span the European coastline from the Mediterranean to the North Sea and the Norwegian fjords, representing a heterogeneous mosaic of coastal social-ecological systems. Despite their geographical diversity, they share a common ecological background, as most sites are formally designated under protection frames (e.g., NATURA 2000 Network), and all provide critical ecosystem services, including carbon sequestration, biodiversity support, water filtration, and cultural or recreational values (Table 1; Table 5; Figure 2; Figure 3). The Mediterranean sites (Comino Island in Malta, Aquatina di Frigole in Italy, Landscape Park Strunjan and its surrounding areas in Slovenia, and Boka Kotorska Bay in Montenegro) represent meaningful hotspots of priority habitats such as *Posidonia oceanica* meadows, coastal lagoons, salt pans, and coralligenous reefs, often hosting endemic or highly protected species. The other sites (Streedagh in Ireland, Arne Parish in the UK, Bergen and Eidsvika in Norway, Kloogaranna-Laulasmaa in Estonia, and Corbu in Romania) present a different ecological profile, mostly centred on coastal dunes, heathlands, kelp forests, bogs, and wetland systems (Table 1; Table 5; Figure 2; Figure 3). Two sites stand out in terms of formal protection, as Bergen is not a designated protected area *per se* but constitutes a nationally significant marine zone, while Eidsvika currently holds no formal protection status at all, making it unique and particularly vulnerable among the CS (PRO-COAST, 2023).

Threats and pressures are where the case studies display the strongest convergence. Unregulated or poorly managed tourism emerges as a shared pressure across all ten CS, manifesting as dune trampling, marine and lagoon litter, noise and light pollution, and infrastructural encroachment (Table 1; Table 5; Figure 2; Figure 3). The intensity appears highest at Comino Island, where up to 5000 daily summer visitors descend on an uninhabited island, and at Boka Kotorska Bay, where cruise ship traffic adds a structural dimension to the problem. Non-indigenous species (NIS) constitute a second cross-cutting threat, though their nature varies markedly from the blue crab (*Callinectes sapidus*) affecting the food web of the Aquatina di Frigole lagoon, to coypu (*Myocastor coypus*) undermining saline banks in Landscape Park Strunjan, to grey squirrels (*Sciurus carolinensis*) outcompeting native red squirrels (*Sciurus vulgaris*) in Arne Parish. Marine and lagoon litter and plastic pollution connect several sites across national boundaries, particularly the Adriatic Sea and the Black Sea CS, pointing to the macro-regional nature of this pressure. Bergen stands out for its focus on a more specific form of marine pollution, represented by ghost fishing gear, which is the primary ecological threat in the CS. Coastal erosion, amplified by climate change, is a shared challenge, especially in Streedagh, Kloogaranna-Laulasmaa, and Corbu, where sediment dynamics are further disrupted by human infrastructure. Agricultural runoff contributes to eutrophication in Landscape Park Strunjan and its surrounding areas, Streedagh, and Corbu. At Eidsvika-Kildn, the threat is more prospective than current, where a proposed cruise terminal has triggered meaningful conflict, making it the only case study where the primary pressure is a planned intervention rather than an ongoing one (PRO-COAST, 2023).

Governance structures and the actors involved in their management reveal perhaps the sharpest contrasts among the CS (Table 1; Table 5; Figure 2; Figure 3). A pattern shared by most is institutional fragmentation, described as the coexistence of multiple overlapping authorities (municipal, regional, national, and EU-level) that leads to coordination gaps and limits effective enforcement of existing regulations. This problem is particularly pronounced in Comino, where the absence of a Marine Protected Area (MPA) management plan leaves critical habitats unprotected despite their NATURA 2000 designation, and in Corbu, where weak enforcement of construction limits and pollution controls persists despite a robust national and EU regulatory framework. By contrast, Bergen benefits from comparatively stronger institutional capacity and a well-established relationship between fishing communities, NGOs such as the Green Warriors of Norway, and national fisheries authorities, though even here, ghost fishing reporting and policy incentives need strengthening. Eidsvika-Kildn presents a particularly contested governance landscape, where society is directly opposing a private developer in an active land-use planning process. Aquatina di Frigole offers a notable model in the opposite direction, as the site is directly managed by the University of Salento, providing a unique link between scientific monitoring and governance, although stakeholder coordination beyond academia still requires strengthening (PRO-COAST, 2023).

Across all sites, NGOs and the local community play a vital but often informal role, and citizen science is consistently identified as both an underutilised resource and a key opportunity (Table 1; Table 5; Figure 2; Figure 3). Social perceptions vary considerably, as in some CS (e.g., Arne Parish, Bergen, Eidsvika-Kildn), community engagement is relatively strong and informed, while in others (e.g., Boka Kotorska, Corbu), communities remain largely dependent on extractive or tourism-based economies and have limited formal involvement in conservation governance. A recurring tension throughout the ten CS is the conflict between short-term economic reliance on tourism, fishing, or development, and the long-term ecological and social resilience capacity of the coastal ecosystem (PRO-COAST, 2023).

Accordingly, PCA and PLS analyses (Figure 4; Table 6) revealed distinct configurations of SES dimensions that reflect the underlying ecological, governance, and social characteristics described for each CS. The first PCA axis and the primary PLS component, dominated by G and R contributions, highlight systems where strong institutional capacity and well-managed resource systems coincide with higher composite scores. Sites such as Bergen and Aquatina di Frigole, characterised by comparatively robust governance structures and active ecosystem management, occupy the positive end of this gradient, reflecting their favourable SES configurations. In contrast, sites like Comino, Corbu, and Eidsvika-Kildn, where institutional fragmentation, contested governance, or emerging pressures limit effective management, are positioned toward the opposite end, even when ecological conditions or community engagement partially compensate. The second PCA and PLS components reveal trade-offs between ecological conditions and actor engagement, capturing heterogeneity that cannot be expressed by the composite score alone. Mediterranean hotspots, such as Comino, Landscape Park Strunjan, and Boka Kotorska Bay, exemplify this pattern. While ecological value is high, governance and community coordination vary, producing distinct system configurations with similar overall scores. Similarly, northern and western sites (e.g., Streedagh, Arne Parish, Kloogaranna-Laulasmaa) differ in ecological composition and local actor involvement, illustrating that multiple pathways can lead to comparable performance levels. The multivariate analysis confirms that the CHUI index captures meaningful variation in SES structure across geographically and socially diverse coastal systems, while also providing a framework to interpret how governance, actors, ecological conditions, and resources interact to shape system performance.

One critical strength of the CHUI lies in its methodological design, which explicitly reflects the SES perspective that sustainability challenges cannot be assessed through ecological data alone. Instead, system behaviour must be understood holistically, recognising that ecological conditions, governance structures, environmental pressures, and human perceptions are deeply intertwined. The CHUI architecture, in which each dimension contributes equally to the final score, ensures that no single subsystem dominates the overall evaluation, thereby aligning with SESF principles of subsystem interdependence. For instance, if a coastal site scores in the 'Maintain' tier for the Resource System (R) but falls into the 'Plan' tier for Governance (G) and Actors (A), the index signals to decision-makers that the immediate priority should not be ecological restoration, but rather institutional capacity-building and conflict resolution. Conversely, a high Governance score paired with a low Environment (E) score directs funding specifically toward mitigating external pressures, such as pollution or NIS, instead of overhauling management structures. Moreover, because social perceptions (A) are inherently subjective, the CHUI addresses uncertainty through triangulation and consensus-building. When stakeholder perception scores strongly diverge from documented ecological data (R), this divergence is flagged for decision-makers as an operational reality, highlighting a communication gap or a lack of local trust that must be addressed before conservation policies can be successfully implemented.

However, the interpretability of results depends on methodological safeguards. The CHUI incorporates several features to ensure robustness and fairness across contexts. One central consideration is the potential subjectivity inherent in the Social Perception dimension, where scores reflect lived experiences, cultural norms, and personal interactions with management institutions. Because these perceptions cannot always be verified empirically, they introduce variability into the dataset. To address this, the CHUI requires training to improve objectivity and cross-stakeholder consensus during scoring, ensuring that social indicators capture an aggregated, negotiated perspective rather than the views of a single group. This participatory requirement strengthens the representativeness and legitimacy of social scores, improving their diagnostic value. In addition, the CHUI applies systematic triangulation across data sources, comparing stakeholder perceptions with evidence from scientific literature, policy documents, and management reports. This allows for the identification of convergence and divergence between perceived and documented conditions, thereby increasing the robustness of the assessment. Where discrepancies arise, these are explicitly documented and interpreted as analytically meaningful signals rather than treated as noise, as they may indicate governance gaps, communication failures, or mismatches between policy design and lived experience. Furthermore, the scoring process follows standardised guidelines and transparent documentation protocols, ensuring consistency across case studies and enabling traceability of how individual scores were derived. This includes the recording of justification narratives, stakeholder composition, and data sources used for each indicator. By combining participatory consensus-building with structured validation and transparent reporting, the CHUI minimises bias while preserving the context-sensitive insights that are essential for understanding social-ecological dynamics. A second methodological safeguard is the use of the "Not Applicable" (N/A) function, which allows indicators that are irrelevant to a Case Study to be excluded from scoring. Because coastal SESs differ widely in environmental features, governance structures, and social contexts, some indicators may not apply to certain sites. The CHUI prevents misinterpretation by avoiding penalisation for the absence of features that are ecologically or institutionally irrelevant. Instead, N/A indicators are removed from the denominator, improving fairness and maintaining cross-context comparability. This mechanism addresses a long-standing challenge in environmental indices by reducing structural bias while preserving diagnostic precision.

Despite these safeguards, some degree of interpretation remains unavoidable due to the mixed qualitative and semi-quantitative nature of CHUI. Ecological scores may depend on monitoring frequency and technology; governance assessments may rely on both documented procedures and perceived implementation; and social perceptions may be influenced by differing expectations and knowledge among local communities. These limitations are not flaws, but intrinsic characteristics of SES assessment, in which many dimensions critical to system functioning cannot be meaningfully quantified without incorporating human experience. Accordingly, the CHUI should be viewed not only as an evaluation tool but also as a platform for dialogue, reflexivity, adaptive learning, and temporal comparison, encouraging practitioners to interpret results contextually and supplement findings with additional datasets, where needed.

The CHUI results show pronounced but interpretable variation across the ten assessed coastal SESs, illustrating how subsystem interactions shape ecosystem performance. Systems such as Aquatina di Frigole, Landscape Park Strunjan and its surrounding areas, and Boka Kotorska scored highly across multiple dimensions, indicating cases where governance capacity, positive stakeholder relationships, moderate levels of environmental pressure, and relatively strong ecological conditions align. These systems reflect SESF predictions that positive feedback between governance, actors, ecological baseline conditions and system vulnerabilities, fosters higher system stability. Strong governance tends to enhance monitoring, enforcement, transparency, and participation, which in turn strengthens social reliance, improves compliance, and maintains or restores ecological conditions (Lockwood et al., 2010). In contrast, systems such as Comino, Streedagh Beach, and Corbu reflect more fragmented interactions, where weaknesses in one subsystem propagate through the SES. For example, limited governance capacity or low stakeholder reliance often coincides with higher exposure to environmental pressures and lower ecological performance. SES theory describes these situations as maladaptive feedback, where institutional gaps undermine both ecological baseline conditions and social legitimacy, producing lower overall sustainability scores

(Ostrom, 2005; 2007; 2009; 2015). Importantly, the environmental dimension revealed that systems like Streedagh Beach and Boka Kotorska face intense pressures regardless of governance or social conditions. This finding aligns with SESF concepts of external drivers, in which even well-structured SESs remain vulnerable when exposed to climate-related pressures, hydrological alteration, or intense human activity. The ability of CHUI to isolate environmental stressors as an independent subsystem underscores the value of assessing pressures separately from ecological outcomes (Ostrom, 2007; 2009). However, despite this first application establishing a cross-sectional baseline, the CHUI is designed to be applied longitudinally, repeated over time. True resilience dynamics will be captured by tracking how these baseline scores change over time, for example, in response to shocks or management interventions.

The operationalisation of coastal social-ecological systems relies on a robust baseline understanding of both ecological and environmental dimensions across variable spatio-temporal scales. In European coastal waters, ecological assessments have demonstrated substantial inter- and intra-habitat variability in fundamental processes, highlighting how underlying resource systems respond to environmental heterogeneity (Fonnesu et al., 2004; Sangiorgio et al., 2004). Furthermore, assessing the structural complexity and biodiversity patterns of these fragile ecosystems requires accurate diagnostic tools (Barbone et al., 2007; Basset et al., 2008). Recently, DNA-based applications have emerged as extremely innovative methodologies to describe biodiversity, particularly improving the scalability and resolution of ecological status assessments in coastal and marine ecosystems (Specchia et al., 2020; Pinna et al., 2021; Tzafesta et al., 2021; Tzafesta et al., 2022; Ismailaj et al., 2024). To systematically synthesise these multi-dimensional ecological data and integrate them with socio-economic layers, recent research increasingly deploys machine learning approaches and novel artificial intelligence tools to evaluate ocean productivity and build repeatable diagnostic structures (Cazzetta et al., 2026; Semeraro et al., 2026). Consequently, the development of composite frameworks that synthesise ecological baselines, environmental drivers, and management layers is vital for moving beyond the limitations of isolated case studies. Thus, the SES approach emphasises that improving system resilience baseline conditions and vulnerabilities requires targeted interventions that address subsystem interactions rather than focusing solely on one component (Ostrom, 2009).

The CHUI results highlight several leverage points. Areas with comparatively strong governance (e.g., already established protection), such as Aquatina di Frigole and Landscape Park Strunjan and its surrounding areas, tend to score higher across other dimensions. Transparent management, participatory processes, and clear institutional mandates produce stabilising feedback that supports both ecological and social outcomes. Negative stakeholder experiences and perceptions towards conservation actions or CS management can quickly undermine conservation efforts, even where ecological conditions remain strong. Because social perception responds rapidly to institutional performance, it should be monitored closely as an early warning indicator. High-pressure systems highlight the need for external interventions, including stricter regulation, habitat restoration, or climate adaptation strategies. Governance improvements alone cannot offset intense external stressors. Finally, cases such as Arne Parish show that robust ecological baselines do not ensure future sustainability if governance or social foundations are weak. SES resilience capacity requires the co-evolution of all four subsystems (Berkes and Folke, 2002; Carpenter et al., 2006; Ostrom, 2009; IPCC, 2023).

The integrated outcome of the CHUI suggests that policy approaches should be tailored to subsystem configurations rather than adopting uniform strategies across sites. Systems with strong governance but fragile ecosystems may require ecological restoration and pressure mitigation, while systems with strong ecology but weak social reliance may require investment in community engagement and equity-centred governance reforms. More broadly, the CHUI demonstrates that sustainable management in coastal SESs depends on balancing ecological protection, institutional effectiveness, and socially legitimate processes. The Index, therefore, serves not only as a measurement instrument but also as a strategic guide for identifying intervention points and fostering adaptive, evidence-based governance. While this initial application supports the internal coherence and structural validity of the CHUI framework across diverse contexts, full predictive validation will require longitudinal datasets to track how these baseline metrics respond to ecological shocks and management interventions over time.

In conclusion, the first CHUI assessment results provide a robust, SES-aligned diagnostic baseline across ten coastal case studies, highlighting system-specific leverage points and underscoring the necessity of integrative, adaptive, and socially grounded approaches to sustain the long-term resilience capacity of coastal Social-Ecological Systems.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

FZ: Conceptualization, Formal Analysis, Methodology, Writing – original draft, Writing – review and editing. FM: Formal Analysis, Investigation, Writing – original draft, Writing – review and editing. VS: Conceptualization, Writing – original draft, Writing – review and editing. SA: Writing – review and editing. PB: Writing – review and editing. EB: Writing – review and editing. LD: Writing – review and editing. JE: Writing – review and editing. AF: Writing – review and editing. PG: Writing – review and editing. RK: Writing – review and editing. CK: Writing – review and editing. A-MN: Writing – review and editing. ES: Writing – review and editing. PV: Writing – review and editing. ŽV: Writing – review and editing. MP: Conceptualization, Methodology, Writing – original draft, Writing – review and editing.

Funding

The author(s) declared that financial support was received for this work and/or its publication. This research was supported by the project titled "A PROactive approach for COmmunities to enAble Societal Transformation - PRO-COAST, code: 101082327, funded by EU HORIZON-CL6-2022-BIODIV-01.

Acknowledgments

We acknowledge all Pro-Coast Case Study members for their contribution. We acknowledge Tero for their contribution in developing the web-based platform for the Index, digitalising CHUI into a free, open-access, web-based platform available at: https://chui.pro-coast.eu/.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author EB declared that they were an editorial board member of Frontiers at the time of submission. This had no impact on the peer review process and the final decision.

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

References

Agrawal, A. (2001). Common property institutions and sustainable governance of resources. *World Dev.* 29, 1649–1672. doi: 10.1016/S0305-750X(01)00063-8

Alessa, L., and Chapin, F. (2008). Anthropogenic biomes: a key contribution to earth-system science. *Trends Ecol. Evol.* 23, 529–531. doi: 10.1016/j.tree.2008.07.002

Barbone, E., Rosati, I., Pinna, M., and Basset, A. (2007). Taxonomic and dimensional structure of benthic macroinvertebrate guilds in the Margherita di Savoia Salt Pans (Italy). *Trans. Waters Bull.* 1, 21–31. doi: 10.1285/i1825229Xv1n4p1

Basset, A., Pinna, M., Sabetta, L., Barbone, E., and Galuppo, N. (2008). Hierarchical scaling of biodiversity in lagoon ecosystems. *Trans. Waters Bull.* 2, 75–86. doi: 10.1285/i1825229Xv2n3p75

Basurto, X., Gelcich, S., and Ostrom, E. (2013). The social-ecological system framework as a knowledge classificatory system for benthic small-scale fisheries. *Glob. Environ. Change* 23 (6), 1366–1380. doi: 10.1016/j.gloenvcha.2013.08.001

Bennett, N. J. (2016). Using perceptions as evidence to improve conservation and environmental management. *Conserv. Biol.* 30, 582–592. doi: 10.1111/cobi.12681

Bennett, E. M., Cramer, W., Begossi, A., Cundill, G., Díaz, S., Egoh, B. N., et al. (2015). Linking biodiversity, ecosystem services, and human well-being: three challenges for designing research for sustainability. *Curr. Opin. Environ. Sustain.* 14, 76–85. doi: 10.1016/j.cosust.2015.03.007

Berkes, F., and Folke, C. (2002). "Linking social and ecological systems: management practices and social mechanisms for building resilience," *Transferred to Digital Printing* (Cambridge: Cambridge Univ. Press).

Boyd, J., and Banzhaf, S. (2007). What are ecosystem services? The need for standardized environmental accounting units. *Ecol. Econ.* 63, 616–626. doi: 10.1016/j.ecolecon.2007.01.002

Bozzeda, F., Zangaro, F., Colangelo, M. A., and Pinna, M. (2021). Relationships between size and abundance in beach plastics: a power-law approach. *Mar. Pollut. Bull.* 173, 113005. doi: 10.1016/j.marpolbul.2021.113005

Brook, B., Sodhi, N., and Bradshaw, C. (2008). Synergies among extinction drivers under global change. *Trends Ecol. Evol.* 23, 453–460. doi: 10.1016/j.tree.2008.03.011

Caroppo, C., Pinna, M., and Vadrucci, M. R. (2023). Phytoplankton size structure and diversity in the transitional system of the aquatina lagoon (southern adriatic sea, mediterranean). *Microorganisms* 11 (1277), 1–17. doi: 10.3390/microorganisms11051277

Carpenter, S. R., DeFries, R., Dietz, T., Mooney, H. A., Polasky, S., Reid, W. V., et al. (2006). Millennium ecosystem assessment: research needs. *Science* 314, 257–258. doi: 10.1126/science.1131946

Carpenter, S. R., Mooney, H. A., Agard, J., Capistrano, D., DeFries, R. S., Díaz, S., et al. (2009). Science for managing ecosystem services: beyond the millennium ecosystem assessment. *Proc. Natl. Acad. Sci.* 106, 1305–1312. doi: 10.1073/pnas.0808772106

Cazzetta, A., Zangaro, F., Marcucci, F., Julius, O. T., Rainò, M., Shauer, M., et al. (2026). Applying artificial intelligence (AI) innovative tools for ecological research and monitoring of transitional water ecosystems: a systematic review. *Environments* 13, 193. doi: 10.3390/environments13040193

Charieg, H., Dhraief, M. Z., Gharbi, I., and Ben Saad, A. (2025). Enhancing the resilience of vulnerable social-ecological systems: pathways toward sustainable oases in southeastern Tunisia. *Front. Sustain. Food Syst.* 9, 1623641. doi: 10.3389/fsufs.2025.1623641

Colding, J., and Barthel, S. (2019). Exploring the social-ecological systems discourse 20 years later. *Ecol. Soc.* 24, 2. doi: 10.5751/ES-10598-240102

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., et al. (1997). The value of the world's ecosystem services and natural capital. *Nature* 387, 253–260. doi: 10.1038/387253a0

Costanza, R., De Groot, R., Sutton, P., Van Der Ploeg, S., Anderson, S. J., Kubiszewski, I., et al. (2014). Changes in the global value of ecosystem services. *Glob. Environ. Change* 26, 152–158. doi: 10.1016/j.gloenvcha.2014.04.002

Cox, M., Arnold, G., and Tomás, S. V. (2010). A review of design principles for community-based natural resource management. *Ecol. Soc.* 15 (4). Available online at: https://www.jstor.org/stable/26268233 (Accessed March 21, 2026).

Daily, G. C. (2017). "Nature's services: societal dependence on natural ecosystems (1997)," in *The Future of Nature*. Editors L. Robin, S. Sörlin, and P. Warde (Yale University Press), 454–464. doi: 10.12987/9780300188479-039

Daily, G. C., Söderqvist, T., Aniyar, S., Arrow, K., Dasgupta, P., Ehrlich, P. R., et al. (2000). The value of nature and the nature of value. *Science* 289, 395–396. doi: 10.1126/science.289.5478.395

Dawson, N., Fischer, J., Kuhn, M., Pasotti, A., Rouzaud, D., mhugent., et al. (2026). *qgis/QGIS: 4.2.2 (Versions final-4_2_2) [Computer software]. Zenodo.* doi: 10.5281/ZENODO.6139224

De Groot, R. S., Alkemade, R., Braat, L., Hein, L., and Willemen, L. (2010). Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. *Ecol. Complex.* 7, 260–272. doi: 10.1016/j.ecocom.2009.10.006

Díaz, S., Demissew, S., Carabias, J., Joly, C., Lonsdale, M., Ash, N., et al. (2015). The IPBES conceptual framework — connecting nature and people. *Curr. Opin. Environ. Sustain.* 14, 1–16. doi: 10.1016/j.cosust.2014.11.002

Dietz, T., Ostrom, E., and Stern, P. C. (2003). The struggle to govern the commons. *Science* 302, 1907–1912. doi: 10.1126/science.1091015

Ellis, E. C., and Ramankutty, N. (2008). Putting people in the map: anthropogenic biomes of the world. *Front. Ecol. Environ.* 6, 439–447. doi: 10.1890/070062

Ezzine-de-Blas, D., Hayes, T., Corbera, E., and Avila-Foucat, V. S. (2024). Looking back to shape the future: Trajectories and resilience of social-ecological systems in the global south. *Ambio* 53 (12), 1715–1721. doi: 10.1007/s13280-024-02087-4

Fanini, L., Defeo, O., Elliott, M., Paragkamian, S., Pinna, M., and Salvo, V. S. (2021). Coupling beach ecology and macroplastics litter studies: current trends and the way ahead. *Mar. Pollut. Bull.* 173, 112951. doi: 10.1016/j.marpolbul.2021.112951

Fleischman, F. D., Ban, N. C., Evans, L. S., Epstein, G., Garcia-Lopez, G., and Villamayor-Tomas, S. (2014). Governing large-scale social-ecological systems: lessons from five cases. *Int. J. Commons* 8 (2), 428–456. doi: 10.18352/ijc.416

Folke, C., Hahn, T., Olsson, P., and Norberg, J. (2005). Adaptive governance of social-ecological systems. *Annu. Rev. Environ. Resour.* 30, 441–473. doi: 10.1146/annurev.energy.30.050504.144511

Folke, C., Biggs, R., Norström, A. V., Reyers, B., and Rockström, J. (2016). Social-ecological resilience and biosphere-based sustainability science. *Ecol. Soc.* 21, art41. doi: 10.5751/es-08748-210341

Fonnesu, A., Pinna, M., and Basset, A. (2004). Spatial and temporal variations of detritus breakdown rates in the river flumendosa basin (sardinia, Italy). *Int. Rev. Hydrobiol.* 89, 443–452. doi: 10.1002/iroh.200410740

Gain, A. K., Ashik-Ur-Rahman, M., and Vafeidis, A. (2019). Exploring human-nature interaction on the coastal floodplain in the ganges-brahmaputra Delta through the lens of Ostrom's social-ecological systems framework. *Environ. Res. Commun.* 1 (5), 051003. doi: 10.1088/2515-7620/ab2407

Gómez-Baggethun, E., De Groot, R., Lomas, P. L., and Montes, C. (2010). The history of ecosystem services in economic theory and practice: from early notions to markets and payment schemes. *Ecol. Econ.* 69, 1209–1218. doi: 10.1016/j.ecolecon.2009.11.007

Hardin, G. (1968). The tragedy of the commons: the population problem has no technical solution; it requires a fundamental extension in morality. *Science* 162, 1243–1248. doi: 10.1126/science.162.3859.1243

Hou, Y., Zhou, S., Burkhard, B., and Müller, F. (2014). Socioeconomic influences on biodiversity, ecosystem services and human well-being: a quantitative application of the DPSIR model in Jiangsu, China. *Sci. Total Environ.* 490, 1012–1028. doi: 10.1016/j.scitotenv.2014.05.071

Intergovernmental Panel On Climate Change (IPCC) (2023). *Climate Change 2022 - Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. 1st Edn. Cambridge University Press. doi: 10.1017/9781009325844

IPBES (2019). in *Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. Editors Brondizio, E., Diaz, S., Settele, J., and Ngo, H. T. (Zenodo). doi: 10.5281/ZENODO.6417333

Ismailaj, M., Zangaro, F., Specchia, V., Sangiorgio, F., Marcucci, F., Kiçaj, H., et al. (2024). Biodiversity patterns and DNA barcode gap analysis of COI in coastal Lagoons of Albania. *Biology* 13, 951. doi: 10.3390/biology13110951

Janssen, M. A., Anderies, J. M., and Ostrom, E. (2007). Robustness of social-ecological systems to spatial and temporal variability. *Soc. Nat. Resour.* 20, 307–322. doi: 10.1080/08941920601161320

Jolliffe, I. T. (1986). *Principal Component Analysis*. New York, NY: Springer New York. doi: 10.1007/978-1-4757-1904-8

Kenward, R. E., Whittingham, M. J., Arampatzis, S., Manos, B. D., Hahn, T., Terry, A., et al. (2011). Identifying governance strategies that effectively support ecosystem services, resource sustainability, and biodiversity. *PNAS* 108 (13), 5308–5312. doi: 10.1073/pnas.1007933108

Koontz, T. M., and Thomas, C. W. (2006). What do we know and need to know about the environmental outcomes of collaborative management? *Public Adm. Rev.* 66, 111–121. doi: 10.1111/j.1540-6210.2006.00671.x

Leslie, H. M., Basurto, X., Nenadovic, M., Sievanen, L., Cavanaugh, K. C., Cota-Nieto, J. J., et al. (2015). Operationalizing the social-ecological systems framework to assess sustainability. *PNAS* 112 (19), 5979–5984. doi: 10.1073/pnas.1414640112

Levin, S. A. (1998). Ecosystems and the biosphere as complex adaptive systems. *Ecosystems* 1, 431–436. doi: 10.1007/s100219900037

Levin, S., Xepapadeas, T., Crépin, A.-S., Norberg, J., De Zeeuw, A., Folke, C., et al. (2013). Social-ecological systems as complex adaptive systems: modeling and policy implications. *Environ. Dev. Econ.* 18, 111–132. doi: 10.1017/S1355770X12000460

Lockwood, M., Davidson, J., Curtis, A., Stratford, E., and Griffith, R. (2010). Governance principles for natural resource management. *Soc. Nat. Resour.* 23, 986–1001. doi: 10.1080/08941920802178214

Mahajan, S. L., Obiene, S., Ojwang, L., Olwero, N., Valdivia, A., Wosu, A., et al. (2023). Introducing elinor for monitoring the governance and management of area-based conservation. *Conserv. Biol.* 38, e14213. doi: 10.1111/cobi.14213

Margiotta, S., Marini, G., Fay, S., D'Onghia, F. M., Liso, I. S., Parise, M., et al. (2021). Hydro-stratigraphic conditions and human activity leading to development of a sinkhole cluster in a mediterranean water ecosystem. *Hydrology* 8, 111. doi: 10.3390/hydrology8030111

Marrocco, V., Sicuro, A., Zangaro, F., and Pinna, M. (2018). First record of the protected species *Pinna nobilis* (linnaeus, 1758) in the aquatina lagoon (NATURA 2000 site IT9150003, south-east Italian coastline). *Nat. Conserv.* 28, 51–59. doi: 10.3897/natureconservation.28.26112

Marrocco, V., Zangaro, F., Sicuro, A., and Pinna, M. (2019). A scaling Down mapping of *Pinna nobilis* (linnaeus, 1758) through the combination of scientific literature, NATURA 2000, grey literature and citizen science data. *Nat. Conserv.* 33, 21–31. doi: 10.3897/natureconservation.33.30397

Menéndez, M., Carlucci, D., Pinna, M., Comin, F. A., and Basset, A. (2003). Effect of nutrients on decomposition of *Ruppia cirrhosa* in a shallow coastal lagoon. *Hydrobiologia* 506-509, 729–735. doi: 10.1023/B:HYDR.0000008568.27981.3d

Millennium Ecosystem Assessment and World Resources Institute (2005). in *Ecosystems and Human well-being: Opportunities and Challenges for Business and Industry* (Washington, DC: World Resources Inst).

Mooney, H., Larigauderie, A., Cesario, M., Elmquist, T., Hoegh-Guldberg, O., Lavorel, S., et al. (2009). Biodiversity, climate change, and ecosystem services. *Curr. Opin. Environ. Sustain.* 1, 46–54. doi: 10.1016/j.cosust.2009.07.006

Norberg, J., and Cumming, G. S. (2008). *Complexity Theory for a Sustainable Future* (New York: Columbia University Press).

Norgaard, R. B. (2010). Ecosystem services: from eye-opening metaphor to complexity blinder. *Ecol. Econ.* 69, 1219–1227. doi: 10.1016/j.ecolecon.2009.11.009

Orfanidis, S., Papathanasiou, V., Sabetta, L., Pinna, M., Gigi, V., Gounaris, S., et al. (2007). Benthic macrophyte communities as bioindicators of transitional and coastal waters: relevant approaches and tools. *Trans. Waters Bull.* 1 (3), 45–49. doi: 10.1285/i1825229Xv1n3p45

Ostrom, E. (2005). *Understanding Institutional Diversity*. Princeton: Princeton University Press.

Ostrom, E. (2007). A diagnostic approach for going beyond panaceas. *Proc. Natl. Acad. Sci.* 104, 15181–15187. doi: 10.1073/pnas.0702288104

Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. *Science* 325, 419–422. doi: 10.1126/science.1172133

Ostrom, E. (2015). *Governing the Commons: The Evolution of Institutions for Collective Action*. Cambridge: Cambridge University Press.

Ostrom, E., Burger, J., Field, C. B., Norgaard, R. B., and Policansky, D. (1999). Revisiting the commons: local lessons, global challenges. *Science* 284, 278–282. doi: 10.1126/science.284.5412.278

Palomo, L. E., and Hernández-Flores, A. (2019). Application of the ostrom framework in the analysis of a social-ecological system with multiple resources in a marine protected area. *PeerJ* 7, e7374. doi: 10.7717/peerj.7374

Partelow, S. (2018). A review of the social-ecological systems framework: applications, methods, modifications, and challenges. *Ecol. Soc.* 23, art36. doi: 10.5751/es-10594-230436

Pinna, M., Saccomanno, B., Marini, G., Zangaro, F., Kabayeva, A., Khalaj, M., et al. (2021). Testing the influence of incomplete DNA barcode libraries on ecological status assessment of mediterranean transitional waters. *Biology* 10, 1092. doi: 10.3390/biology10111092

Pinna, M., Zangaro, F., and Specchia, V. (2024). Assessing benthic macroinvertebrate communities' spatial heterogeneity in mediterranean transitional waters through eDNA metabarcoding. *Sci. Rep.* 14, 17890. doi: 10.1038/s41598-024-69043-w

PRO-COAST (2023). A PROactive approach for COmmunities to enAble societal transformation. doi: 10.3030/101082327

Reed, M. S. (2008). Stakeholder participation for environmental management: a literature review. *Biol. Conserv.* 141, 2417–2431. doi: 10.1016/j.biocon.2008.07.014

Rice, C., Searle, R., and Nienaber, A.-M. (2025). "Trust and public sector work: how public service motivation helps explain multi-level trust relations," in *Handbook on Trust in Public Governance*, (Edward Elgar Publishing), 425–439. Available online at: https://www.elgaronline.com/edcollchap/book/9781802201406/chapter26.xml (Accessed March 28, 2026).

Sala, O. E., Stuart Chapin, F., Dirzo, R., Armesto, J. J., Berlow, E., Bloomfield, J., et al. (2000). Global biodiversity scenarios for the year 2100. *Science* 287, 1770–1774. doi: 10.1126/science.287.5459.1770

Sangiorgio, F., Pinna, M., and Basset, A. (2004). Inter-and intra-habitat variability of plant detritus decomposition in a transitional environment (lake alimini, adriatic sea). *Chem. Ecol.* 20, 353–366. doi: 10.1080/02757540310001638367

Schlüter, M., Mcallister, R. R. J., Arlinghaus, R., Bunnefeld, N., Eisenack, K., Hölker, F., et al. (2012). New Horizons for managing the environment: a review of coupled social-ecological systems modeling. *Nat. Resour. Model.* 25, 219–272. doi: 10.1111/j.1939-7445.2011.00108.x

Schlüter, M., Hinkel, J., Bots, P. W., and Arlinghaus, R. (2014). Application of the SES framework for model-based analysis of the dynamics of social-ecological systems. *Ecol. Soc.* 19 (1), art36. doi: 10.5751/ES-05782-190136

Schneider, F., Feurer, M., Lundsgaard-Hansen, L. M., Myint, W., Nuam, C. D., Nydegger, K., et al. (2020). Sustainable development under competing claims on land: three pathways between land-use changes, ecosystem services and human well-being. *Eur. J. Dev. Res.* 32 (2), 316–337. doi: 10.1057/s41287-020-00268-x

Scholes, R. J. (2016). Climate change and ecosystem services. *WIREs Clim. Change* 7, 537–550. doi: 10.1002/wcc.404

Semeraro, T., Titocci, J., Liberatore, L., Monti, F., Cazzetta, A., Pinna, M., et al. (2026). A machine learning framework for assessing the sensitivity of regional ocean productivity to climate change. *Environments* 13, 137. doi: 10.3390/environments13030137

Shauer, M., Zangaro, F., Specchia, V., and Pinna, M. (2025). Investigating invasion patterns of *Callinectes sapidus* and the relation with research effort and climate change in the Mediterranean Sea. *Sci. Rep.* 15, 34967. doi: 10.1038/s41598-025-18982-z

Shauer, M., Rainò, M., Antolini, P., Arnosti, P., Bergamin, S., Boban, J., et al. (2026). Heterogeneity of Atlantic blue crab (*Callinectes sapidus*) invasion stages and population structure in the adriatic sea. *Front. Mar. Sci.* 13, 1852490. doi: 10.3389/fmars.2026.1852490

Shipman, B., and Stojanovic, T. (2007). Facts, fictions, and failures of integrated coastal zone management in Europe. *Coast. Manag.* 35 (2-3), 375–398. doi: 10.1080/08920750601169659

Solís-Mendoza, L. E., Galicia, L., Ávila-Foucat, S. V., and Mwampamba, T. H. (2025). Conceptual model of social-ecological resilience in Mexican forests communities. *Front. For. Glob. Change* 8, 1490278. doi: 10.3389/ffgc.2025.1490278

Specchia, V., Tzafesta, E., Marini, G., Scarcella, S., D'Attis, S., and Pinna, M. (2020). Gap analysis for DNA barcode reference libraries for aquatic macroinvertebrate species in the apulia region (southeast of Italy). *J. Mar. Sci. Eng.* 8, 538. doi: 10.3390/jmse8070538

Specchia, V., Saccomanno, B., Zangaro, F., Tzafesta, E., and Pinna, M. (2022). Exploring the biodiversity of a european NATURA 2000 mediterranean lagoon through eDNA metabarcoding. *Diversity* 14 (911), 1–9. doi: 10.3390/d14110991

Specchia, V., Zangaro, F., Tzafesta, E., Saccomanno, B., Vadrucci, M. R., and Pinna, M. (2023). Environmental DNA detects biodiversity and ecological features of phytoplankton communities in mediterranean transitional waters. *Sci. Rep.* 13, 15192. doi: 10.1038/s41598-023-42389-3

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., et al. (2015). Planetary boundaries: guiding human development on a changing planet. *Science* 347, 1259855. doi: 10.1126/science.1259855

Thiel, A., Adamseged, M. E., and Baake, C. (2015). Evaluating an instrument for institutional crafting: how Ostrom's social-ecological systems framework is applied. *Environ. Sci. Policy* 53, 152–164. doi: 10.1016/j.envsci.2015.04.020

Tzafesta, E., Zangaro, F., Specchia, V., and Pinna, M. (2021). An overview of DNA-Based applications for the assessment of benthic macroinvertebrates biodiversity in mediterranean aquatic ecosystems. *Diversity* 13, 112. doi: 10.3390/d13030112

Tzafesta, E., Saccomanno, B., Zangaro, F., Vadrucci, M. R., Specchia, V., and Pinna, M. (2022). DNA barcode gap analysis for multiple marker genes for phytoplankton species biodiversity in mediterranean aquatic ecosystems. *Biology* 11, 1277. doi: 10.3390/biology11091277

Vayanou, P., Georgiou, P., and Kounnamas, C. (2026). Conservation and human use index: a practical, multi-parameter assessment tool to identify and track conflicts and synergies in conservation area management. *Sustainability* 18 (9), 4197. doi: 10.3390/su18094197

Vitousek, P. M., Mooney, H. A., Lubchenco, J., and Melillo, J. M. (1997). Human domination of earth's ecosystems. *Science* 277, 494–499. doi: 10.1126/science.277.5325.494

Vogt, J. M., Epstein, G. B., Mincey, S. K., Fischer, B. C., and McCord, P. (2015). Putting the "E" in SES: unpacking the ecology in the ostrom social-ecological system framework. *Ecol. Soc.* 20 (1), art55. doi: 10.5751/ES-07239-200155

Wallace, K. J. (2007). Classification of ecosystem services: problems and solutions. *Biol. Conserv.* 139, 235–246. doi: 10.1016/j.biocon.2007.07.015

Wold, S., Sjöström, M., and Eriksson, L. (2001). PLS-regression: a basic tool of chemometrics. *Chemom. Intell. Lab. Syst.* 58, 109–130. doi: 10.1016/S0169-7439(01)00155-1

Zangaro, F., Schifano, V., Specchia, V., Tzafesta, E., and Pinna, M. (2020). A new extralimital sighting of *Monachus monachus* (Hermann, 1779) in the Aquatina di Frigole NATURA 2000 site (IT9150003) beach (Salento peninsula, Apulia Region, Italy) after two decades: strategies for conservation are needed. *Biodivers. Data J.* 8, e53950. doi: 10.3897/BDJ.8.e53950

Zangaro, F., Pinna, M., and Specchia, V. (2024). Environmental DNA as early warning for alien species in mediterranean coastal Lagoons: implications for conservation and management. *Diversity* 16, 525. doi: 10.3390/d16090525

Zangaro, F., Vadrucci, M. R., Ismailaj, M., Specchia, V., and Pinna, M. (2025). eDNA metabarcoding for qualitative and semi-quantitative assessment of phytoplankton towards eco-sustainable mariculture in the Mediterranean Sea. *Front. Mar. Sci.* 12, 1688716. doi: 10.3389/fmars.2025.1688716