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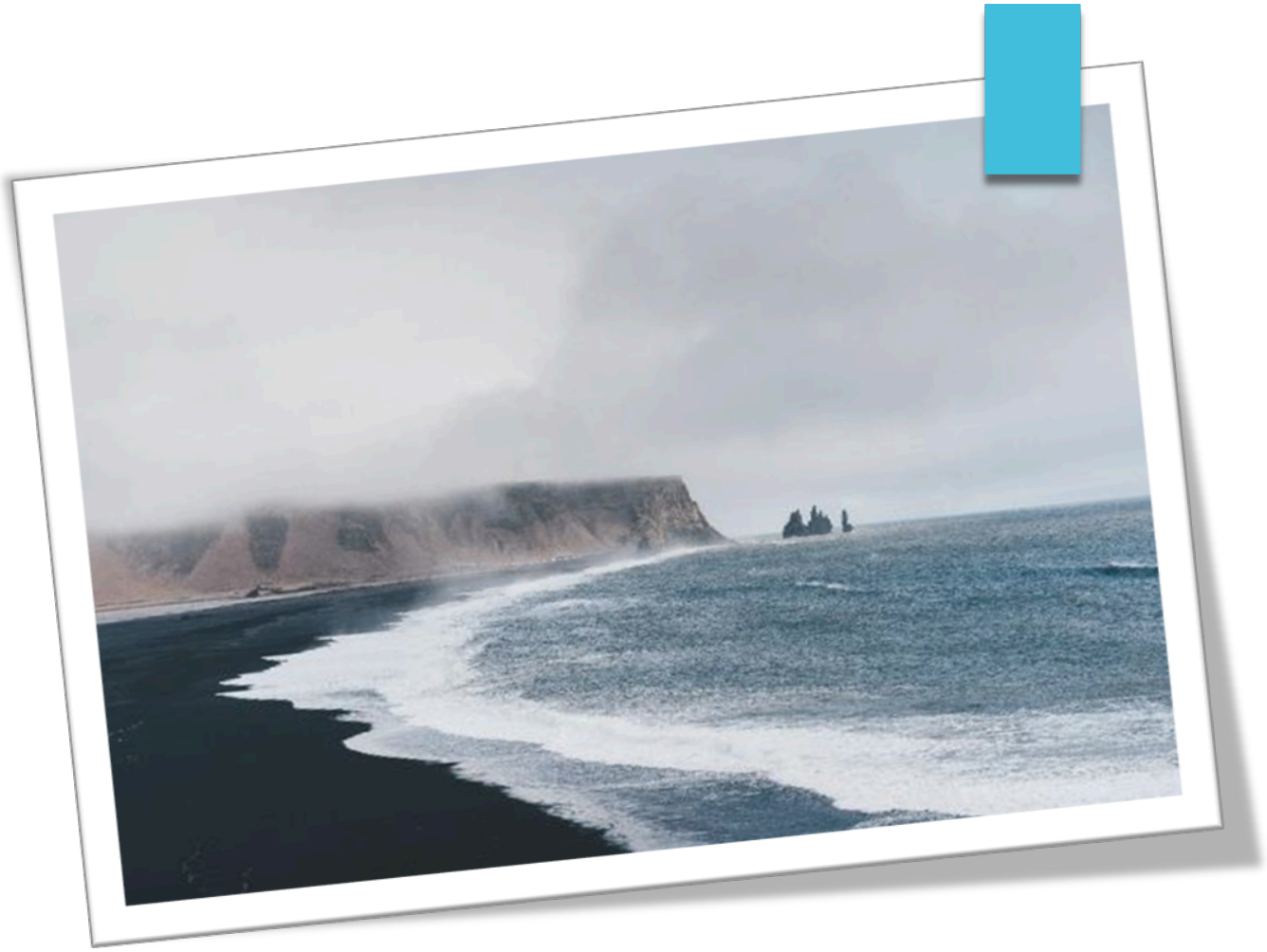
PROCoast

A PROactive approach for Communities
to enAble Societal Transformation

D3.4 - Coastal ecosystem management with the use of the Conservation and Human Use Index

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BACKGROUND: ABOUT PRO-COAST PROJECT

Europe's coastlines are among the most biologically rich and socially vital ecosystems on the planet, and they are under threat. Climate change, pollution, and the accelerating spread of non-indigenous species (NIS) are eroding the very foundations of coastal and marine biodiversity, putting at risk the ecosystem services that millions of people depend on for their livelihoods, culture, and wellbeing. The communities most exposed to this degradation are often the least equipped to respond to it.

PRO-COAST project was born from the conviction that lasting change requires more than the sole scientific expertise, but it requires the active participation of the people who know and live within these ecosystems. The project's mission is to empower local communities across Europe to become genuine agents of biodiversity restoration and preservation, bridging the gap between local knowledge, conservation science, and effective policymaking.

Currently in full implementation, **PRO-COAST** brings together 20 partners from 14 countries, coordinating efforts across 10 carefully selected Case Studies. Each study explores a distinct coastal ecosystem, testing a range of conservation methods, governance models, and social incentives designed to engage local stakeholders in adopting meaningful, practical actions for biodiversity protection. Together, these case studies form a living laboratory for evidence-based, community-led conservation.

What sets **PRO-COAST** apart is its holistic, interdisciplinary framework. The project treats social-ecological systems as fundamentally interconnected, recognising that environmental challenges cannot be meaningfully addressed in isolation from the social, economic, and political forces that shape them. By working across micro-, meso-, and macro-scales, the project identifies the precise leverage points where targeted interventions can catalyse transformative, systemic change.

At its core, **PRO-COAST** champions a bottom-up approach to decision-making. Through extensive citizen engagement, informed by the best of ecological and conservation science, the project builds community capacity, elevates local voices, and develops scalable solutions that genuinely balance conservation priorities with socio-economic realities. The ultimate ambition is to help shape adaptive, participatory governance frameworks that not only prevent further biodiversity loss, but secure sustainable, equitable access to coastal resources and marine ecosystem services for current and future generations alike.

EXECUTIVE SUMMARY

The manuscript presents a preliminary application of the Conservation and Human Use Index (CHUI) across the ten diverse transboundary coastal case studies of Pro-Coast, representing contrasting ecological, institutional, and socio-cultural contexts across Europe. The study demonstrates the effectiveness of the CHUI as both a diagnostic framework and a comparative platform for guiding adaptive governance and supporting integrated coastal management.

Key Sections:

1. Conceptual Foundation and Dimensions: The CHUI is grounded in the work of Elinor Ostrom and conceptualises sustainability outcomes as emergent properties of interactions among ecological systems, resource users, and governance arrangements. The index is organised into four functionally interconnected dimensions: “Resource System” (R) evaluates natural values and the condition of provisioning, regulating, cultural, and supporting ecosystem services; “Environment” (E) captures the magnitude of human-mediated and environmental pressures, such as pollution, over-exploitation, invasive species, and climate-related stressors; “Governance” (G) assesses the effectiveness of management structures, the implementation of monitoring programs, and the transparency of decision-making; and “Actors” (A) focuses on social perceptions, including stakeholder engagement, trust in authorities, and principles of social justice.

2. Methodology and Indicators: The index consists of 133 standardised indicators scored on a uniform four-point scale, enabling the translation of qualitative insights into semi-quantitative metrics. This structured approach reduces subjective variability and ensures consistent comparison across different case studies.

3. Participatory Data Collection: A combined desk-based approach was employed, integrating scientific literature and policy documents with primary insights from cross-stakeholder consultations. This ensures that dimensions like “Social Perceptions” and “Governance” reflect grounded realities, such as trust and perceived fairness, which are often absent from formal reports but critical for sustainable management.

4. Case Study Diversity: The CHUI was tested across ten European sites spanning Mediterranean, Atlantic, Baltic, and Black Sea environments. These include: Island and Lagoon Ecosystems, such as Comino Island (Malta) and Acquatina di Frigole (Italy), facing pressures from intense tourism and non-indigenous species; Estuaries and Fjords, including Arne Parish (England) and Bergen (Norway), where challenges range from agricultural runoff to “ghost fishing” from abandoned gear; Sandy Beaches and Wilderness, such as Corbu Beach (Romania) and Eidsvika (Norway), highlighting tensions between pristine biodiversity and infrastructure development or overtourism.

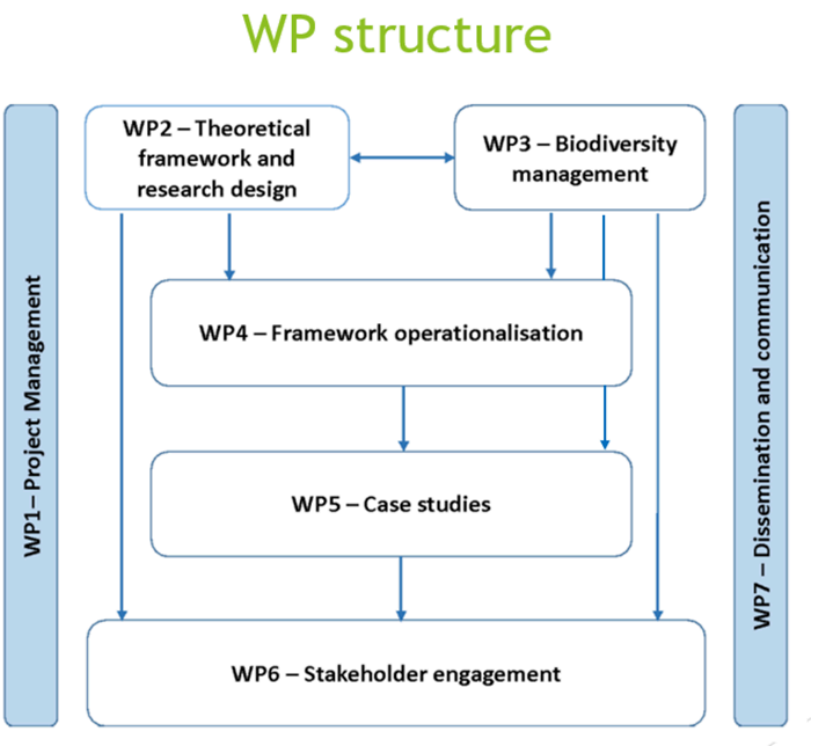
5. Results and Resilience: Preliminary results reveal marked variations among the case studies, reflecting distinct combinations of ecological conditions, governance effectiveness, and human-nature relations. The assessment highlights that resilience in coastal social-ecological systems depends on balancing ecological protection with institutional strength and socially legitimate processes.

6. Diagnostic Value for Management: The CHUI serves as a powerful diagnostic tool for identifying institutional blind spots and social tensions. By foregrounding local knowledge and lived experiences, the index functions not only as an evaluative metric but also as an instrument for dialogue and the co-production of shared management strategies.

LINKS WITH OTHER PROJECT ACTIVITIES

The first application of the CHUI is a central component of the **PRO-COAST** project’s efforts to operationalise theoretical frameworks. It directly supports Work Package 4 (Framework opera-

tionalisation) and Work Package 5 (Case studies) by providing a harmonised protocol for cross-site comparison. Furthermore, its emphasis on stakeholder engagement and social perceptions aligns with Work Package 6, ensuring that scientific assessments are integrated with local socio-economic priorities for transformative change.



PRO-COAST Work Package structure

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RUNNING TITLE

First Assessment of Coastal Social-Ecological Conditions Using the Conservation and Human Use Index (CHUI) Across Ten European Case Studies

ABSTRACT

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 & 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 resilience across coastal SESs.

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 policy-makers, 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 social-economic needs. However, these decisions are often made under conditions of uncertainty and fragmented knowledge, where the links between ecological processes, human well-being, and governance structures remain insufficiently understood or operationalised. Addressing this gap is essential not only for improving environmental management outcomes, but also for ensuring socially legitimate, economically viable, and institutionally robust pathways toward sustainability.

The concept of “ecosystem services” refers to the multitude of benefits that human societies derive, directly or indirectly, from natural ecosystems. Although the term itself gained widespread prominence only in the 1990s, particularly following the influential work of Daily (Daily, 2017), the underlying idea that human well-being is fundamentally dependent on ecological processes has much deeper intellectual roots. Early ecological economists and systems ecologists had already emphasised the functional dependence of societies on nature decades earlier (Costanza et al., 1997), 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 well-being. In this context, the rapid diffusion of the ecosystem services concept was largely driven by the need to make the value of ecosystems more explicit and communicable to decision-makers and the broader public, especially in an era of accelerating environmental degradation and biodiversity loss (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 (Millennium Ecosystem Assessment and World Resources Institute, 2005). This framework organises ecosystem services into four broad categories. Provisioning services include tangible goods such as food, freshwater, clean air, healthy soil, timber, fibre, and genetic resources, which directly support human survival and economic activities. Cultural services encompass non-material benefits derived from ecosystems, including recreational opportunities, aesthetic enjoyment, biophilia, spiritual enrichment, cultural identity, and educational values. Regulating services refer to the benefits derived from regulating ecosystem processes, such as climate mitigation, water purification, pollination, disease control, erosion prevention, and protection from extreme events such as floods and storms. Finally, supporting services represent the fundamental ecological processes that underpin all other services, including primary production, photosynthesis, nutrient cycling, soil formation, and habitat provision (Millennium Ecosystem Assessment and World Resources Institute, 2005; De Groot et al., 2010).

Despite its widespread adoption, the ecosystem services framework has also been the subject of conceptual refinement and debate. Some authors have questioned the separation between supporting and regulating services, arguing that supporting services may be better understood as ecological functions rather than services per se (Boyd and Banzhaf, 2007; Wallace, 2007). Others have emphasised the risk of oversimplifying or commodifying nature when ecosystem services are framed primarily in economic terms (Gómez-Baggethun et al., 2010; Norgaard, 2010). Nonetheless, the framework remains a central reference point in sustainability science, conservation biology, and environmental policy, precisely because of its capacity to link ecological integrity with human well-being in an integrative manner (Carpenter et al., 2009; 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). 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 Chapiniii, 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. The growing recognition that ecosystem services are generated, maintained, and transformed through complex interactions between ecological processes and human activities has highlighted important limitations in approaches that treat ecosystems and societies as analytically separable entities. Early ecosys-

tem services frameworks, while effective in communicating the value of nature, often implicitly assumed relatively stable ecological systems responding to external social drivers. However, 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.

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). Rather than providing a prescriptive model, the SES framework functions as a diagnostic and classificatory tool, enabling researchers to identify key variables, interactions, and feedback shaping system behaviour. Its main strength lies in its capacity to incorporate ecological, social, economic, and institutional dimensions within a unified analytical structure (Figure 1).

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 inher-

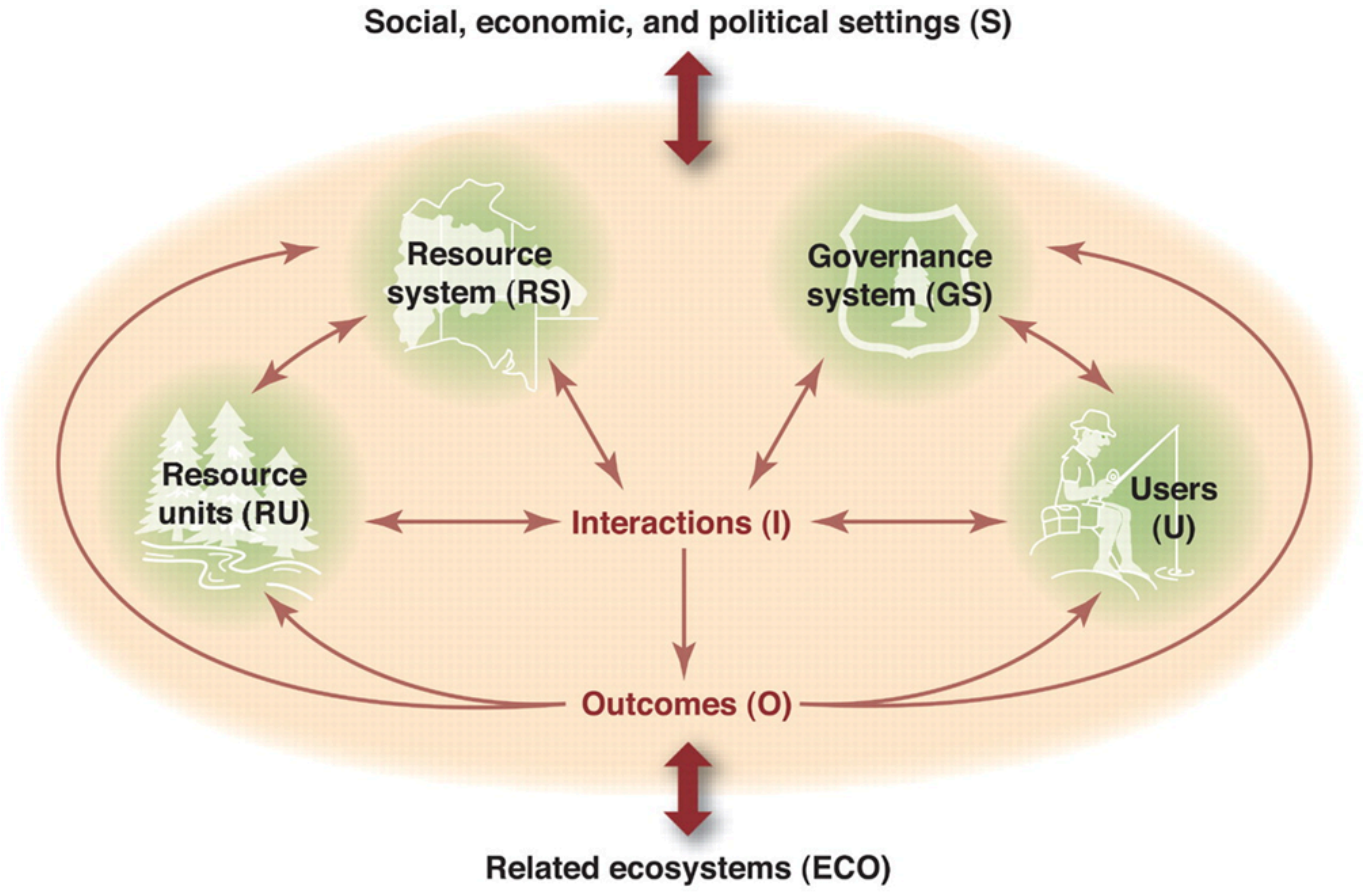


Figure 1. The four core subsystems in the Social-Ecological System Framework (Ostrom, 2009).

ently 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.

In response to this need, the Conservation & Human Use Index (CHUI) 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 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). By explicitly applying SESF principles, translated and operationalised across resource systems, governance systems, and actors, the CHUI is capable of unveiling the sustainability and resilience of the entire social-ecological interface. 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.

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. Conceptual Theorisation of the CHUI Index

Consistent with SES theory, The Conservation & Human Use Index (File S1; File S2) serves as a diagnostic tool to identify synergies and conflicts between biodiversity conservation and human activities. The Index is conceptualised around four analytically distinct, but functionally interconnected, dimensions derived from the first-tier variables of the Social-Ecological Systems Framework. These comprise: the Resource System (R), assessed through Natural and Ecosystem Service Values; the Environment (E), capturing threats and pressures; the Governance System (G); and the Actors (A), reflected through Social Perceptions.

2.2. Index Structure and Operationalisation

The CHUI consists of 134 standardised indicators, each scored using a uniform, four-point assessment scale that converts qualitative judgements into semi-quantitative values. This standardised scoring procedure enables consistent comparison across case study areas and ensures that non-applicable items are excluded from the calculation.

2.2.1. Natural Values & Ecosystem Services Values (R)

This dimension evaluates both the ecological significance and the overall condition of the resource system. It does so by examining how valuable the area is from a natural perspective, considering the importance of its landscapes, the presence of protected flora and fauna, and the role of critical habitats that sustain them, as well as assessing the state of the ecosystem services that these natural components provide. In this context, the evaluation considers the capacity of the system to deliver provisioning services such as food and water, as well as its ability to regulate ecological processes, including climate moderation and natural hazard mitigation. It also accounts for the cultural contributions it offers through recreation, heritage, and aesthetic appreciation, and for the supporting functions, such as nutrient cycling and nursery habitats, that underpin all other ecological processes.

2.2.2. Threats and Pressures (E)

This dimension examines the overall magnitude of pressures acting on the system by considering both human-mediated stressors and natural environmental factors. Within the CHUI, human-mediated pressures are not treated as a separate category but are instead embedded across the broader “Environment” dimension, where they are assessed alongside other ecological stress drivers. The indicators used in this dimension evaluate how intensely human activities like pollution, resource over-exploitation, or the introduction and spread of invasive species affect the ecological integrity of the area, while also accounting for environmental drivers including climate-

related impacts and hydrological alterations. Together, these elements provide an integrated understanding of how multiple pressures combine to influence ecosystem condition and resilience.

2.2.3. Governance (G)

This dimension represents the institutional components of the Social-Ecological System and evaluates how effectively the system is able to manage resources and respond to emerging pressures through both formal and informal mechanisms. It considers the extent to which management structures are in place and functioning, including the development and implementation of management plans, the presence and operationalisation of ecological and social monitoring programmes, the degree to which authorities responsible for the area are formally recognised, and the transparency and accountability of decision-making processes. Together, these elements provide insight into the governance capacity that underpins the sustainable management of the system.

2.2.4. Social Perception (A)

This dimension captures the human component of the Social-Ecological System, focusing on how the various “Actors” engage with, perceive, and influence the study area. It examines the quality of interactions between stakeholders and the system, considering how people participate in management processes, the degree of reliance they place in governing authorities, and the extent to which principles of social justice are reflected in access, rights, and decision-making. It also evaluates how local communities and other users perceive the benefits, opportunities, and challenges associated with the area, thereby providing insight into the social conditions that shape cooperation, conflict, and long-term support for conservation and sustainable use initiatives.

2.3. Case Studies

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 2). 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).

2.3.1. 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

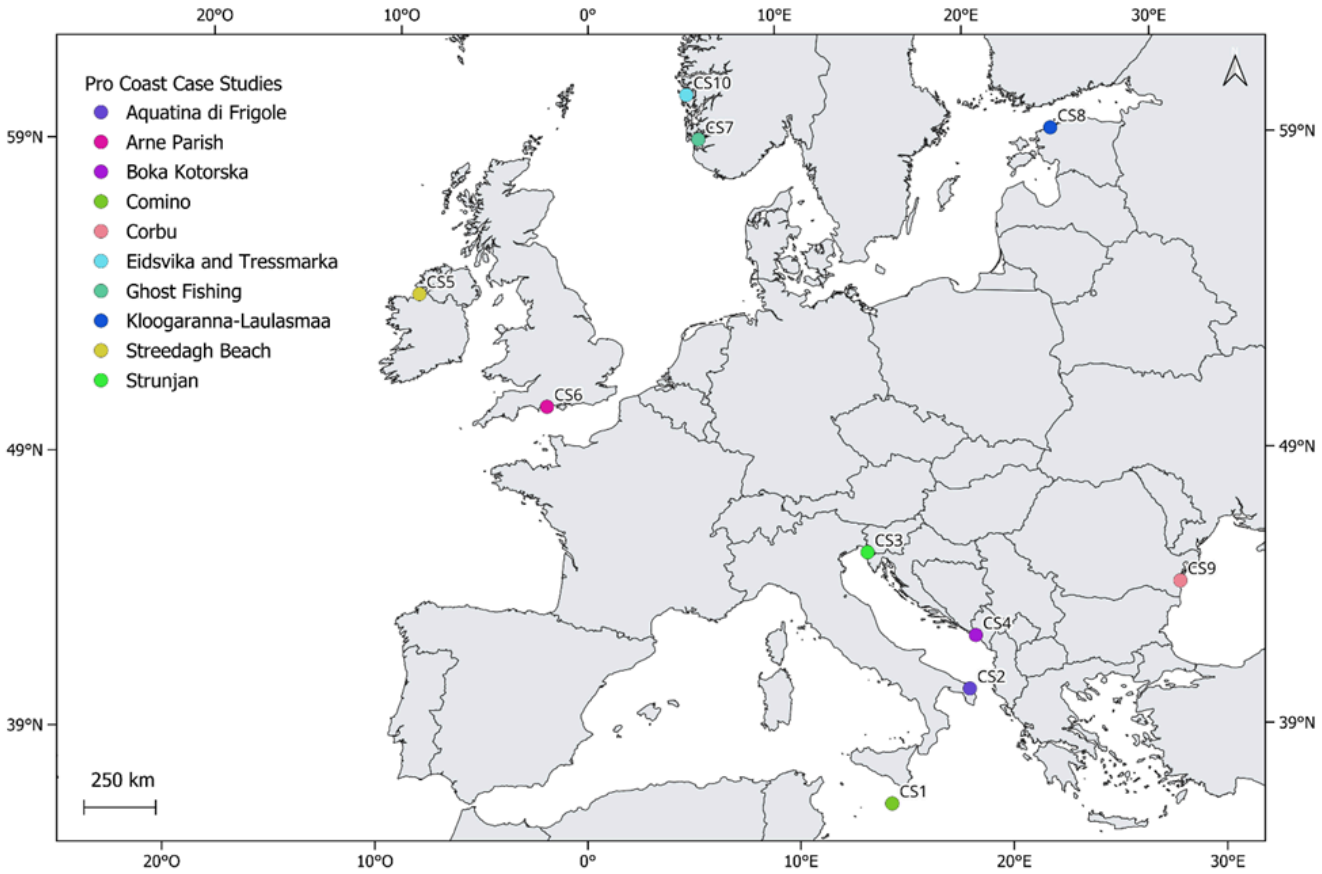


Figure 2. Location of the 10 Case Studies involved in the first application of the Conservation & Human Use Index (CHUI).

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.

2.3.2. CS2 - Acquatina di Frigole, Italy

The NATURA 2000 Site “Acquatina 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. The site hosts emblematic protected species, including *Pinna nobilis* and *Caretta caretta*, and occasionally hosts *Monachus monachus* specimens (Zangaro et al., 2020). Key pressures acting on the area include limitations in hydraulic connectivity between the lagoon and the sea, accumulation of plastic and microplastics marine and lagoon litter, non-indigenous species (NIS), and intense summer tourism. Governance is shared between the University of Salento, the Puglia Region, and the Municipality of Lecce.

2.3.3. 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*, *Pinna 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.

2.3.4. 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.

2.3.5. 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.

2.3.6. 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.

2.3.7. 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.

2.3.8. 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.

2.3.9. 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.

2.3.10. 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.

2.4. Data Collection and Participatory Approach

The CHUI assessment in each of the ten investigated case studies employed a combined desk-based approach, integrating multiple sources of evidence to ensure a comprehensive and context-sensitive understanding of each case study area. Data were assembled from scientific literature, management and policy documents, and consultations with relevant stakeholder groups, thereby combining both secondary information and primary, experience-based insights. This methodological 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.

The inclusion of stakeholder consultations ensures that the “Social Perceptions” and “Governance” dimensions reflect realities on the ground rather than relying solely on formal documentation or expert interpretation. This is crucial because social dynamics, such as reliance in

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 facilitates the integration of cross-stakeholder viewpoints, enabling triangulation between official management perspectives, scientific evidence, and community-level insights. This increases the reliability and robustness of the assessment and ensures that the evaluation does not privilege a single knowledge system. It also supports the CHUI diagnostic nature, which aims to capture governance strengths, social tensions, ecological conditions, and institutional blind spots transparently and inclusively.

In addition to the desk-based and consultation-based approach, targeted stakeholder workshops were conducted in Case Studies, providing a structured space for collective reflection and exchange among key actors. These workshops enabled the discussion and validation of preliminary CHUI findings, facilitated the identification of context-specific governance challenges, and allowed for the co-interpretation of ecological and social dynamics. By bringing together representatives from public authorities, local communities, and sectoral stakeholders, the workshops supported a deeper understanding of diverging perspectives, conflict lines, and opportunities for collaborative management.

Complementing these workshops, additional qualitative insights were gathered through bilateral meetings, allowing for more in-depth, context-sensitive discussions with individual stakeholders who may not have been able to participate in larger workshop settings or who preferred a more focused exchange. This approach ensured that diverse voices, including those less represented in formal participatory formats were incorporated into the assessment. Together, the combination of workshops and bilateral engagements strengthened the empirical basis of the CHUI application by enhancing stakeholder inclusivity, improving the contextual richness of the data, and supporting the validation of findings through iterative feedback loops. This multi-layered engagement approach further reinforces the CHUI's role as both an analytical and participatory tool, capable of capturing complex social-ecological interactions while fostering dialogue and shared understanding among stakeholders.

This participatory dimension aligns with the broader logic of the SESF, acknowledging that resource systems, governance structures, and actor interactions are inherently intertwined. By foregrounding the role of local knowledge and lived experience in shaping assessment outcomes, the CHUI strengthens its capacity to function not only as an evaluative tool but also as an instrument for dialogue, shared learning, and co-production of management strategies.

2.5. Index Calculation and Aggregation

The CHUI evaluates a total of 134 indicators, each of which is scored using a standardised four-point 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.

A key methodological element of the CHUI is the treatment of indicators deemed “Not Applicable” (N/A). 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 scoring denominator. In this way, the CHUI ensures that areas are not penalised for lacking features that are genuinely absent due to natural or contextual reasons rather than management failure or degradation. This adjustment maintains the comparability and fairness of results across ecologically diverse regions and reduces biases potentially emerging from a fixed-denominator index.

Following indicator-level scoring, the CHUI aggregates results through a hierarchical procedure. First, each of the four major dimensions (Resource System, Environment, Governance, and Actors) is scored separately. Within each dimension, the sum of all valid indicator scores is divided by the maximum possible score (after exclusion of N/A items), yielding a dimension-specific percentage. This percentage reflects the relative performance or condition of that dimension in the area.

The Final CHUI Score is then 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:

$$\mathrm{CHUI} = \frac{R_{\%} + E_{\%} + G_{\%} + A_{\%}}{4}$$

The resulting final score (0% to 100%) is 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%].

2.6. Index visualisation and formal analysis

The four CHUI dimension scores and the composite CHUI score for the ten case studies (CS) were spatially mapped in QGIS v4.0.0 (Nyall 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 (R, E, G, and A) characterising the ten CS. All variables were mean-centred and unit-variance scaled prior to 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). 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, but was superimposed as a supplementary variable using a continuous colour gradient. This allowed us 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.

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 & 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.

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 3).

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.

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 4).

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

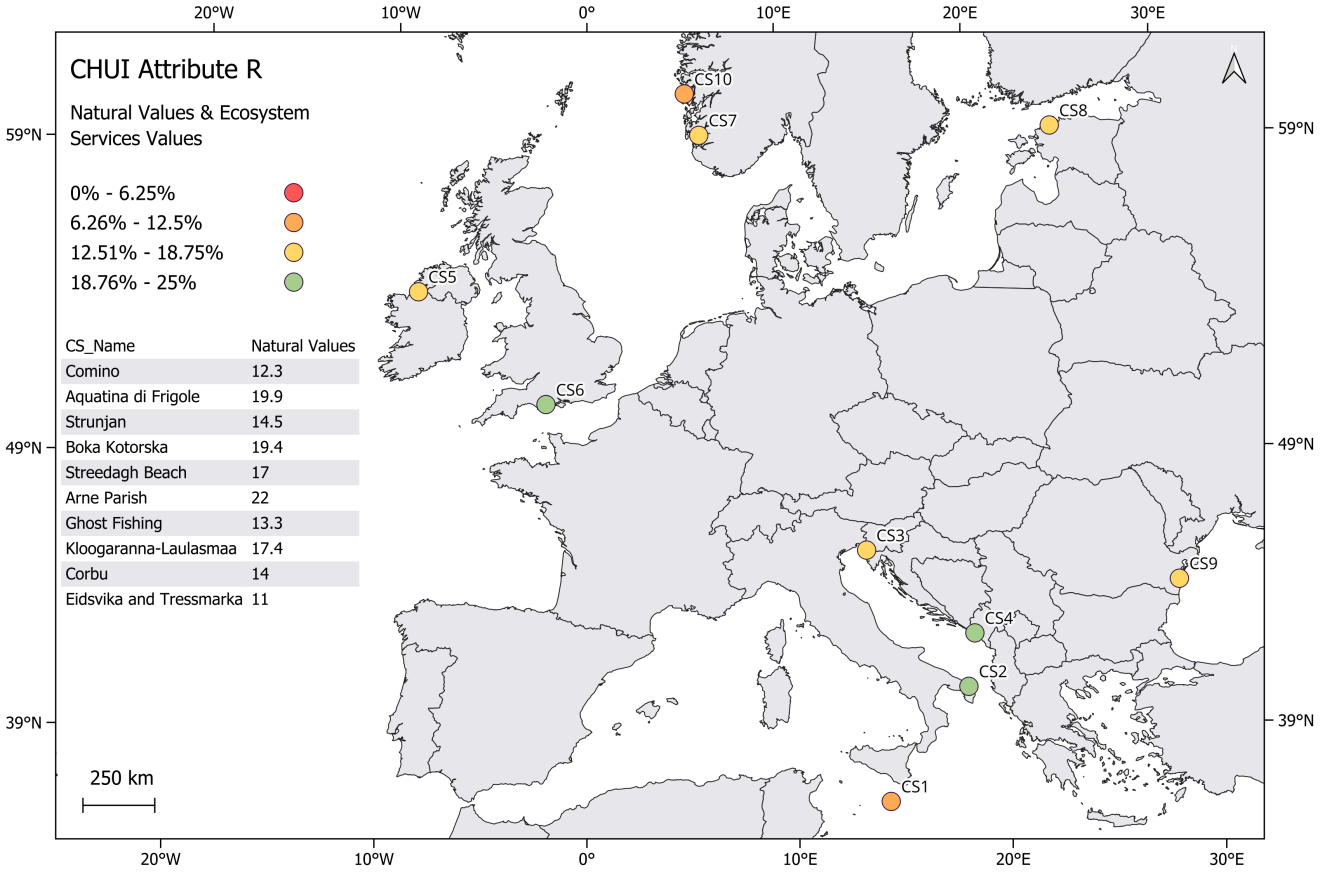


Figure 3. Spatial distribution of the Resource System (R) scores across the ten Case Study areas. Higher values indicate areas with relatively intact natural landscapes, protected species, and strong ecosystem service provision, while lower values highlight systems with degraded habitats, reduced ecological significance, or diminished ecosystem service delivery.

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 strongly reinforces the CHUI 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 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

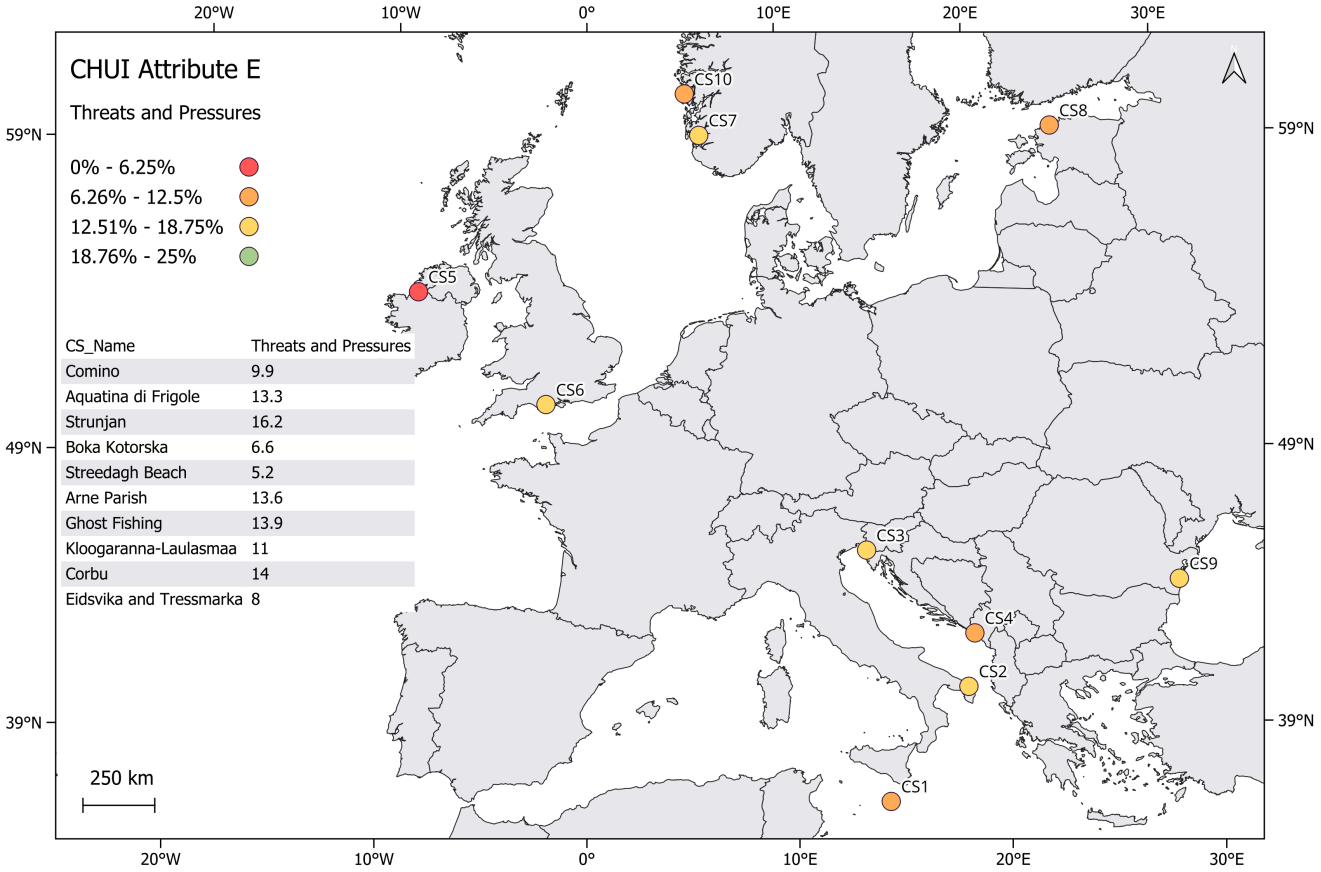


Figure 4. Map illustrating the magnitude of human-mediated and environmental pressures affecting each Case Study. Higher scores represent sites where pressures remain moderate or well-mitigated, whereas lower scores reveal hotspots of ecological stress.

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. The spatial governance map underscores these contrasts and demonstrates how institutional conditions are as geographically variable as ecological ones.

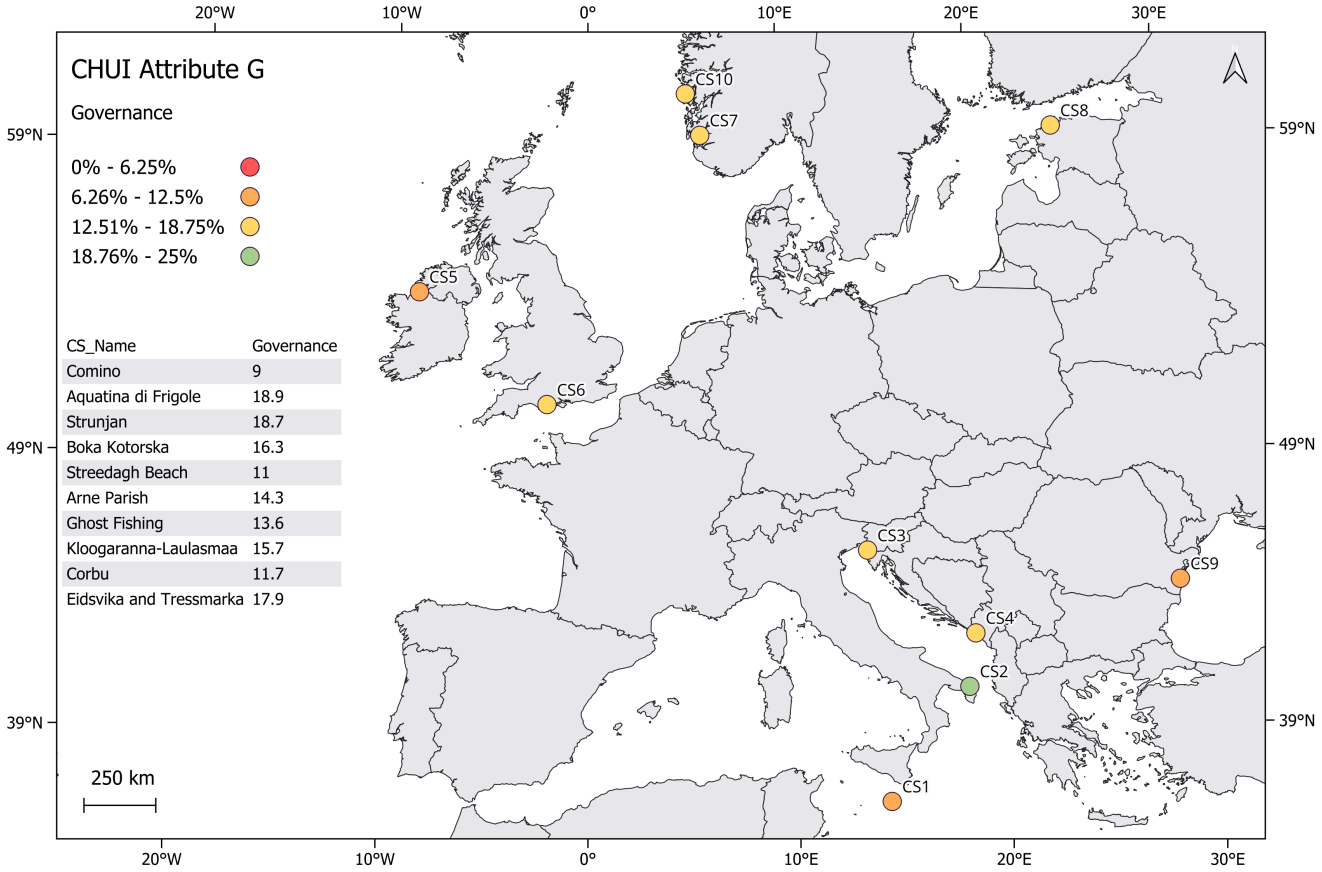


Figure 5. Spatial representation of governance performance across sites. Higher scoring areas exhibit characteristics such as implemented management plans, monitoring programmes, legal recognition of authorities, and transparent decision-making, while lower scoring sites indicate governance gaps, limited enforcement capacity, or fragmented coordination.

3.4. Social Perceptions (A): Engagement, Trust, 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 6).

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

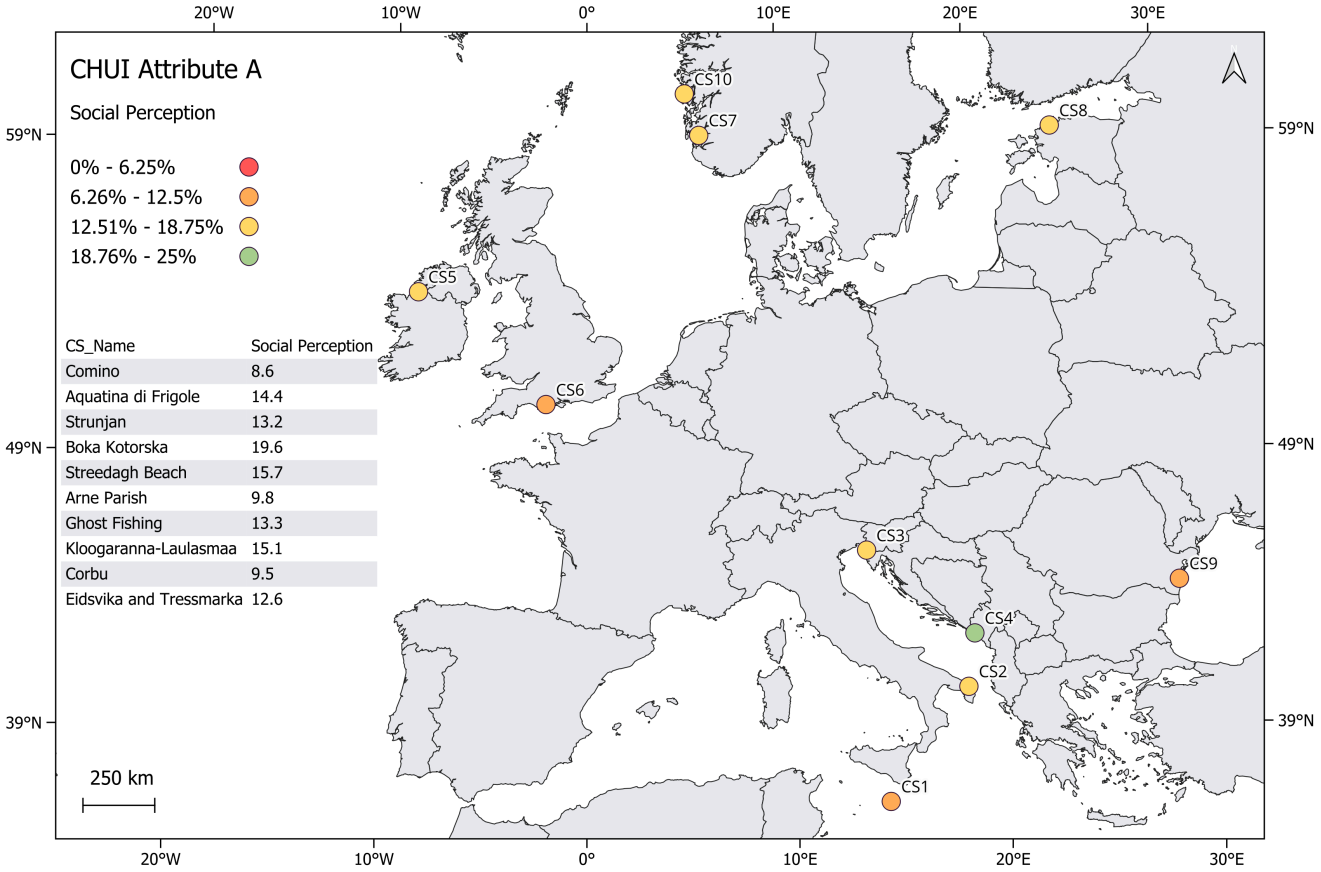


Figure 6. Spatial visualisation of stakeholder perceptions regarding fairness, participation, trust in management, and perceived benefits or burdens associated with the Case Study area. Higher scores reflect positive social relationships and local management support, whereas lower scores indicate mistrust, conflict, perceived inequity, or limited community engagement.

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. Overall 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 7).

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

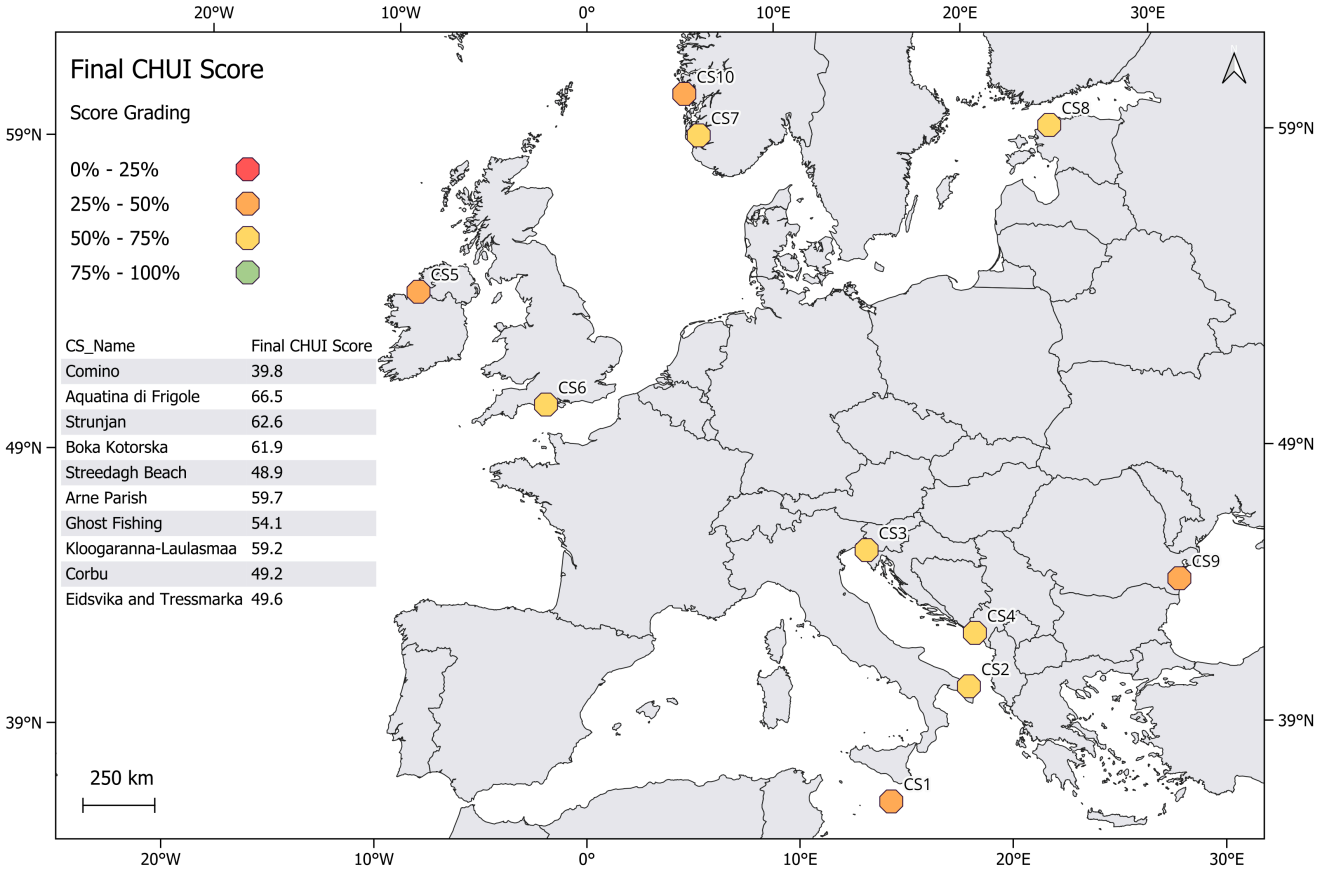


Figure 7. Composite map showing the overall sustainability performance of each Case Study area, derived from the average of the four CHUI dimensions. Higher values reflect more balanced SES configurations, where ecological, institutional, environmental, and social components reinforce one another. Lower values indicate systems where multiple stressors or cross-subsystem mismatches constrain resilience.

to strong governance capacity, and engaged local communities, underpinning higher overall resilience.

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 7) 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.

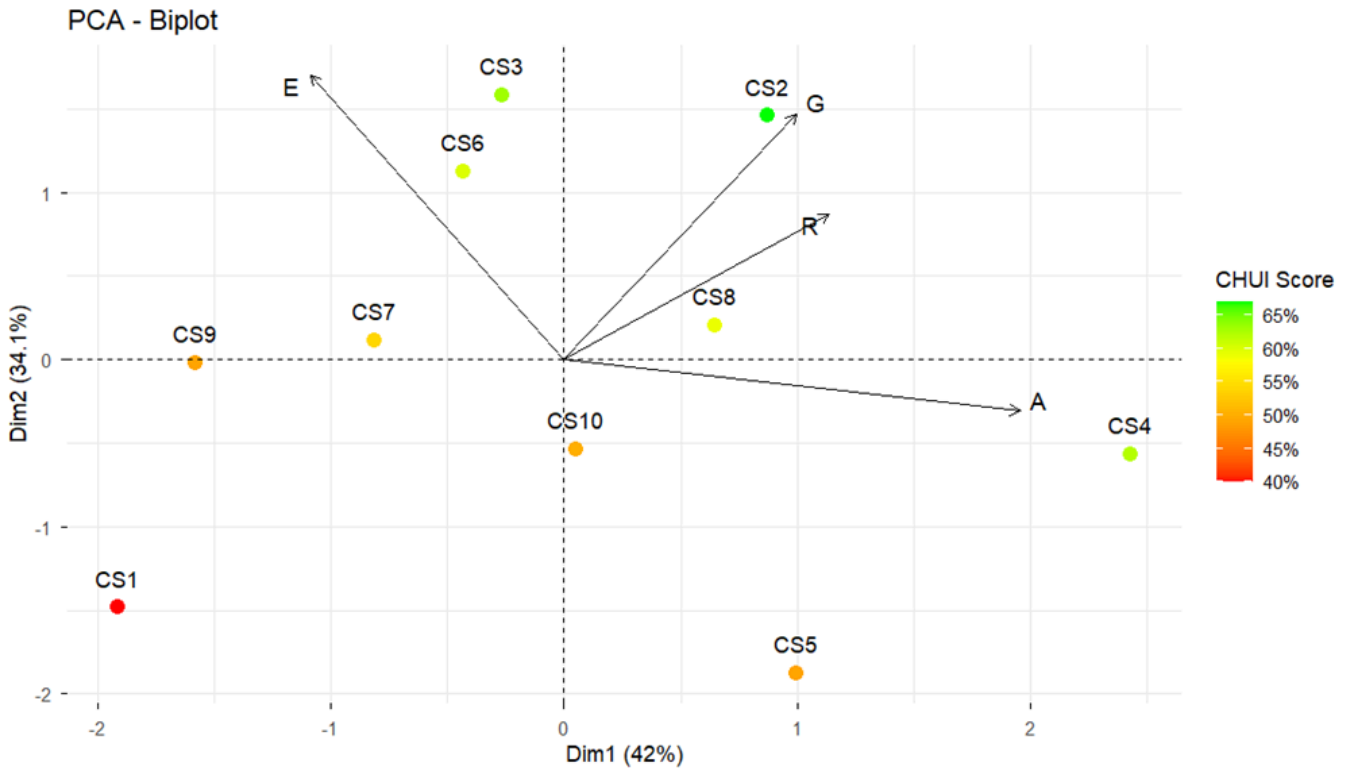


Figure 8. Principal Component Analysis (PCA) biplot of the ten case studies based on the four standardised SES indicators of the CHUI (R, E, G, A). Arrows represent variable loadings on the first two principal components, reflecting the direction and relative magnitude of each indicator's contribution to the ordination space. Points correspond to individual case studies and are coloured along a continuous gradient according to their composite CHUI score.

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 8) 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, 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 strengthened these findings. The first latent component accounted for 98.1% of variance in the composite CHUI score and was predominantly structured by the governance (G) and resource (R) dimensions, with secondary contributions from actors (A) and a comparatively minor influence of ecological conditions (E). The second latent component revealed a directional trade-off between the ecological and actor-related dimensions, indicating that comparable aggregate performance can be achieved through structurally compensatory configurations, a pattern consistent with the multivariate heterogeneity observed in the PCA.

Collectively, these analyses demonstrate 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.

4. Discussion

The application of the Conservation & 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 backbone, 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. 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. 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. The intensity appears highest at Comino Island, where up to 5000 daily summer visitors descend on a 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. A pattern shared by most is institutional fragmentation, described as the coexistence of multiple overlapping authorities (municipal, regional, national, and EU-level) that brings 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 local community play a vital but often informal role, and citizen science is consistently identified as both an underutilised resource and a key opportunity. 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 of the coastal ecosystem (PRO-COAST, 2023).

Accordingly, PCA and PLS analyses 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, characterized 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.

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 trainings 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, and ecological resilience 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 resilience 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).

The SES approach emphasises that improving system resilience 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 requires the co-evolution of all four subsystems (Berkes and Folke, 2002; Carpenter et al., 2006; Ostrom, 2009; Intergovernmental Panel On Climate Change (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.

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 of coastal Social-Ecological Systems.

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