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European coastal wetlands datasets and their use in decision-support tools for policy restoration objectives

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ABSTRACT

Ecosystem restoration is a paramount policy priority for this decade, with ambitious global and European targets requiring unprecedented levels of data-driven implementation. Achieving effective and equitable restoration, particularly for coastal wetlands, hinges on spatially explicit socio-ecological information - maps that integrate habitats, ecosystem services, human activities, and pressures to guide prioritization, stakeholder negotiation, and adaptive management. This study, grounded in the RESTORE4Cs initiative, introduces an innovative multi-layered dataset that bridges science and policy for six emblematic European coastal wetlands: Ria de Aveiro (Portugal), Valencian Wetlands (Spain), Camargue (France), Southwest Dutch Delta (Netherlands), Curonian Lagoon (Lithuania), and the Danube Delta (Romania). The dataset consolidates ecological mapping (EUNIS 2021, 2022), human activity and pressure documentation (aligned with EU Habitats Directive, Water Framework Directive, Marine Strategy Framework Directive), comprehensive ecosystem services mapping (CICES v5.1), alongside robust participatory community and stakeholder data. Altogether, the database encapsulates 97 habitat records, 23,160 activity-pressure associations, and 1,668 ecosystem service records—enabling robust cross-regional analyses and direct integration into evidence-based decision support tools. By illustrating practical pathways for participatory engagement, trade-off negotiation, and cross-scale integration, this research equips scientists, policymakers, practitioners, and communities with the scientific foundation to propel the Nature Restoration Regulation and Biodiversity Strategy 2030 objectives, fortifying Europe's climate adaptation trajectory. The approach showcased signals a new era for restoration science – where spatially explicit, multi-actor data supports policy, mobilizes citizen stewardship, and accelerates the transformative ambitions of Europe's restoration decade.

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1. Introduction

European coastal wetlands cover roughly 84,500 km^2, representing only one percent of EU27+UK wetland coverage, yet their contribution to climate mitigation and biodiversity far surpasses their extent (Otero et al., 2024). Coastal wetlands, when in good ecological status, provide essential ecosystem services, including climate regulation (carbon pathways), shoreline stabilization, wave attenuation, biogeochemical regulation (nutrient cycling and water quality), and high taxonomic and functional diversity (complex trophic networks). The diversity of European coastal wetland habitats, as classified by EUNIS - a reference framework for EU habitat classification - encompasses subtidal seagrass beds and shallow marine sediments; intertidal flats, saltmarshes, and saline lagoons; and transitional waters, including estuaries and deltas. These habitats, shaped by regional biogeographical and hydrological regimes, span all biogeographical regions of Europe, reflecting varied climatic, geomorphological, and anthropogenic contexts.

IPBES (Intergovernmental Panel for Biodiversity and Ecosystem Services) notes that up to 50 percent of global coastal wetlands have been lost since 1900, with local losses exceeding 80 percent in some regions. Remaining wetlands face increasing vulnerability to: sea-level rise, coastal erosion, sediment deficits, droughts, altered hydrology, and land-use change pressures (IPBES, 2019). Wetlands face intensifying pressures from land reclamation, urban expansion, agricultural runoff, and hydrological and geomorphological modifications (e.g., activities that alter sediment supply, shorelines introduce pollutants, disrupt natural water flow). These anthropogenic activities and associated pressures compromise habitat status, decrease ecosystem service delivery, and increase vulnerability to climate extremes (persistent deviations in climate variables). Without habitat-specific pressure mapping, management efforts risk misallocating resources, as pressures like pollution, invasive species, and infrastructure development disproportionately affect some habitats (IPBES, 2019). This diagnosis has made the current decade the momentum for ecosystem, particularly coastal wetland, conservation and restoration. Relevant examples are UN Ocean Decade (United Nations, 2017), UN Decade on Restoration (United Nations, 2019), EU Biodiversity Strategy (European commission, 2020), and the EU Nature Restoration Regulation (NRR) (European Parliament and Council, 2024), all with specific restoration targets for 2030. Wetland Restoration includes actions (active or passive) to return a wetland to a previous or improved ecological status, enhancing carbon storage, biodiversity, and ecosystem services (European Parliament and Council, 2024). Active restoration removes the pressure source followed by measures to enhance recovery, while passive restoration allows natural regeneration after pressure removal.

Wetlands' role on carbon pathways towards a net removal of carbon, namely CO_2 from the atmosphere and soil/sediment organic matter, encompass three major pathways: i) carbon pool in plant living biomass (% or g C g^{-1} dry weight) closely linked to photosynthesis, as energy source for biomass building blocks (in coastal wetlands this represents a dynamic and smaller amount but ecologically important); ii) carbon sequestration (g C m^{-2} yr^{-1} or t CO_2e ha^{-1} yr^{-1}) refer to the annual net balance of added carbon per unit area; and iii) carbon stock (Mg C ha^{-1}), which correspond to the long-term storage of carbon mostly in sediments (plants rhizosphere) but also carbon accumulated in biomass (above- and belowground) per unit area. These pathways represent meaningful means to offset global carbon emissions (CO_2, CH_4) (McLeod et al., 2011; Pendleton et al., 2012).

To effectively evaluate restoration potential in recovering ecosystem functions and services, accurate, high-resolution mapping of European coastal habitats, ecosystem services, human activities, and pressures is essential. Such mapping underpins evidence-based conservation and restoration planning aligned with global and EU policy targets. At the EU level, detailed habitat maps are critical for meeting reporting requirements under the EU Habitats Directive (The Council of the European Union, 1992), the EU Water Framework Directive (WFD) (European Parliament and the Council, 2000), and the Marine Strategy Framework Directive (MSFD) (European Parliament and the Council, 2008). These maps ensure standardized habitat classification and cross-border comparability across Member States, supporting the integrated marine and terrestrial management across EU coastal zones.

Consistent mapping also supports monitoring habitat transitions, adaptive management, and the integration of local restoration into EU-wide strategies. Maps also function as communication tools for assessing policy options, identifying potential co-benefits, and recognizing trade-offs (Maes et al., 2012). As European coastal wetlands increasingly face pressures from global environmental change (Newton et al., 2020), robust habitat mapping provides a scientific foundation for implementing policy targets. Because coastal wetlands are complex socio-ecological systems, mapping should not solely focus on biophysical aspects (supply side of ecosystem services). It must also include the stakeholders, land uses, and activities that shape the demand for ecosystem benefits. This integrated, spatially explicit approach allows for more comprehensive policy-relevant analyses (Borgwardt et al., 2019). Spatially explicit datasets encompass biophysical and ecological information from remote sensing and field surveys, ecological status indicators (consistent with EU Habitats and WFD Directives), carbon stocks, and greenhouse gas (GHG) fluxes. Thus, mapping European coastal wetlands must integrate three dimensions: (1) habitats, (2) ecosystem services, and (3) activities and pressures. This triad is a scientific necessity and a policy requirement. For each wetland type, three conditions were initially identified: well-preserved, impacted, and restored. The datasets also include geospatial information from satellite imagery on land cover, vegetation condition, and wetland extent. Remote layers further support mapping of land use, activities, and pressures. These layers are complemented by social datasets capturing perceptions, attitudes, and preferences of stakeholders, landowners, and local communities toward wetland restoration. Such spatially explicit social datasets may be enriched by qualitative information on social acceptability, barriers, motivations, and co-creation processes developed within a Community of Practice (CoP). A CoP is a self-organized group of experts, policymakers, and practitioners working collaboratively to enhance shared knowledge and access to expertise on a specific topic or focus area (Kampa et al., 2025). A CoP for Wetland Restoration represents a strategic knowledge mobilization framework for scaling coastal wetland restoration, reflecting a deliberate, multi-methodological approach to synthesizing lessons and entrenching them within a functional network (IPBES, 2021).

This integrated and harmonized spatial information underpins the NRR ambitions, ensures compliance with multiple directives, and provides the decision-support required to safeguard coastal wetlands of Europe for current and future generations. This information is of high added value when ingested and used in decision support tools that aim at supporting wetland managers and policy makers to prioritize restoration actions (Kampa et al., 2025). Standardized nomenclatures and classifications allow for the development and application of standardized methods to map and assess habitat extent, potential ecosystem service delivery, and estimate the impact of restoration actions.

In this context, RESTORE4CS, a Horizon-funded project, establishes an integrative socio-ecological framework for European coastal wetlands management and restoration. It involves active participatory methods to identify restoration pathways with stakeholders, uniting field surveys, expert validation, remote sensing, and policy frameworks. It underpins climate mitigation targets and the implementation of EU ecological legislation by delivering decision-support tools and standardizing interoperable, high-resolution habitat maps; quantifying and mapping the supply of multiple ecosystem services; and assessing human activities and pressures to prioritize restoration and inform policy implementation. To this end, six EU case pilots (CPs) were selected considering their broad geographical distribution and ecological representation. Each CP included three comparable conditions (well-preserved, impacted, and restored); and socio-ecological approaches with stakeholders mapping and engagement were already in place. Each selected CP brings added value to scale up at EU level: Ria de Aveiro (Atlantic) – Coastal lagoon, important for biodiversity and carbon storage. Supports understanding of Atlantic wetland restoration. Marjal dels Moros (Mediterranean) – Brackish marshes, offering a model for restoration and management under Mediterranean conditions. Camargue (Mediterranean) – Extensive wetland. Provides insights into restoration in large, complex deltaic systems. Southwest Dutch Delta (Atlantic) – Intertidal area, essential for flood mitigation and biodiversity. Represents restoration in highly managed coastal systems. Curonian Lagoon (Baltic) – Largest European lagoon. Exemplifies restoration challenges and opportunities for Baltic coastal wetlands. Danube Delta (Black Sea) – Europe's largest continuous marshland. Provides a unique perspective on large-scale restoration.

Grounded in RESTORE4Cs main objective to assess the restoration potential of coastal wetlands in recovering ecosystem functions and associated services related to carbon pathways, and other co-benefits, the main objective of this manuscript is to introduce and demonstrate an integrated transdisciplinary, spatially explicit framework that combines ecological vulnerability analysis, stakeholder-based multi-criteria and social acceptability assessment, and meta-analytic value transfer across six heterogeneous European coastal wetlands. As such, the emphasis is on the structure, internal consistency, and joint application of the four methodological components, rather than on providing an exhaustive cross-case evaluation of all site-specific patterns or a detailed account of implementation processes in each case. Specifically, it is described how to standardize cross-regional habitat mapping using the EUNIS classification system to enable continental-scale comparisons and compliance with EU environmental directives; how to systematically link ecological assessments with ecosystem service supply across CICES v5.1 frameworks to operationalize service cascades for restoration impact prediction; comprehensively document spatially explicit activity-pressure associations aligned with EU legislative requirements, creating explicit causal pathways between anthropogenic drivers and habitat degradation; and integrate participatory, multi-criteria stakeholder assessments to capture social acceptability, co-benefits recognition, and governance constraints. This paper showcases the added value of these six case pilots spanning Atlantic, Mediterranean, Baltic, and Black Sea biogeographical regions, demonstrating how integrated socio-ecological datasets and decision-support tools support the development of restoration strategies and policies grounded in real-world outcomes, thereby operationalizing the Nature Restoration Regulation and Biodiversity Strategy 2030.

2. Material and methods

This study builds on an integrated socio-ecological dataset that links biophysical, socio-economic, and governance dimensions across six European coastal wetland case pilots. Drawing on EUNIS habitat classifications and a structured catalogue of ecosystem services, we coupled information on local activities and pressures with EU policy frameworks, including water, marine, and nature legislation, to ensure that restoration options are assessed within a consistent regulatory context. Stakeholder engagement processes were used to co-produce criteria, indicators, and scenarios that reflect place-based values and management priorities, thereby complementing expert-based ecological and economic assessments. This integrated design supports the application of multiple, mutually informing tools – AquaLinks ecological vulnerability assessment, multi-criteria analysis and social acceptability – within a common decision-support and prioritization framework for coastal wetland restoration (Fig. 1).

2.1. Case pilots

The dataset covers six coastal wetlands (CPs) across European biogeographical regions (Table 1), representing specific wetland types.

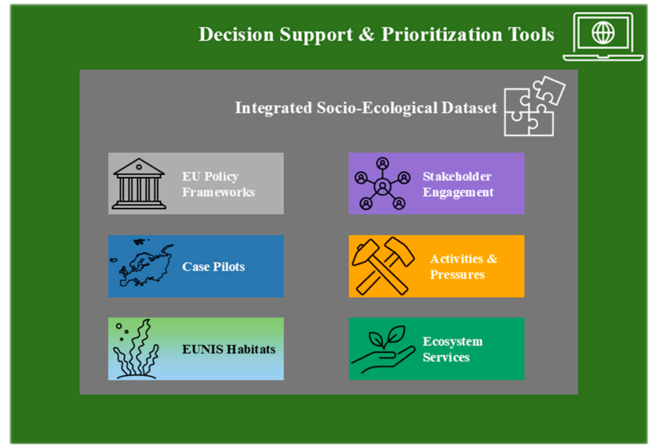

Fig. 1. Schematic overview of the workflow.

Their collective added value supports the integration and upscaling at the EU level. More details about the Case Pilots can be found in Supplementary Material 1.

2.2. Biophysical and ecological data

Habitat mapping was conducted using the hierarchical EUNIS habitat classification database. Initial habitat data were extracted from the EUNIS shapefiles available on the European Environment Agency's (EEA) EUNIS portal, which provides comprehensive spatial data for standardized European habitat types (European Environment Agency EEA, 2019). Subsequently, local experts refined the preliminary classifications by integrating regional databases and historical surveys to enhance accuracy and ecological relevance. The data was then harmonized and updated to EUNIS terrestrial 2021 (European Environment Agency EEA, 2021) and marine 2022 (European Environment Agency EEA, 2022), using the tabular datasets with crosswalks, and the local experts did a final validation, eliminating ambiguity caused by multiple matches. This multi-step approach assured methodological consistency and allowed integration of updated hierarchical habitat categories while maintaining coherence with prior nomenclatures and facilitating interoperability with European environmental reporting obligations.

2.3. Socio-ecological data

For each EUNIS landscape unit, ecosystem services were systematically assigned based on the Common International Classification of Ecosystem Services (CICES) version 5.1 framework (Haines-Young, 2023). The CICES nomenclature encompassed provisioning services, regulation and maintenance services, and cultural services, and the local experts were responsible to assign the ecosystem services provided by each habitat in their CP, ensuring ecological accuracy and contextual relevance.

The methodology proposed by Borgwardt et al. (2019) to categorize activities and pressures was followed. Anthropogenic activities and pressures were identified through satellite imagery for land cover, vegetation health, and wetland extent complemented with remote sensing layers and systematic field surveys, literature review, and expert consultation, aligned with Habitats Directive, WFD, MSFD, and the statistical classification of economic activities (NACE - *Nomenclature Statistique des Activités Économiques*) codes. The dataset captures a detailed record of direct and indirect effects of natural and anthropogenic activities and pressures on the wetland functionality.

2.4. Stakeholder and community data

A multi-layered participatory approach was followed to integrate

Table 1
Description of CPs and respective habitats of interest for restoration.

Case Pilot	Country	European Basin	River Basin	Coordinates	Interest for Restoration						References
					Wetland type	EUNIS Level 2	Area (ha)	Justification for Selection	Type of Disturbance	Type of Restoration	
Ria de Aveiro	Portugal	Atlantic Ocean	Vouga River	40.63°N–40.74°N; -8.72°E–-8.59°E	Intertidal seagrass beds (*Zostera noltii*)	A2.7	~11,000	Priority for seagrass recovery; nursery habitat; ongoing restoration actions; priority for local community	Morphological: Erosion of lagoon shoreline, sediment instability, trampling by humans, bioturbation from bait digging; increased turbidity and habitat fragmentation due to eco-hydrological changes.	Active: Transplantation of *Zostera noltii* and physical protection (coconut mats, structures). Passive: Removal of disturbance factors allowing natural sediment stabilization and recolonization.	(Sousa et al., 2019; Lillebø and Stålnacke, 2015; Costa et al., 2022; Crespo et al., 2023)
Marjal dels Moros	Spain	Mediterranean Sea	Jucar River	39.61°N–39.64°N; -0.28°E–-0.24°E	Coastal brackish marshes	A2.5	~620	Represents Mediterranean wetlands under peri-urban and industrial pressures	Hydrological: Drainage, groundwater extraction, artificial flooding. Trophic: Eutrophication from agricultural runoff and wastewater. Morphological: Soil degradation and land-use change.	Mixed: Soil reconstruction, hydrological improvements, active planting of native vegetation, and passive recolonization after pressure reduction. Periodic mowing for habitat heterogeneity.	(Rochera et al., 2025)
Camargue	France	Mediterranean Sea	Rhone River	43.32°N–43.67°N; 4.43°E–4.92°E	Freshwater marshes and ponds	C1	~190,000	Complements saline sites; freshwater restoration under agricultural pressures	Hydrological: Disconnection from natural flooding due to embankments. Land-use: Agricultural intensification (rice fields), irrigation, drainage, fertilizer use causing eutrophication.	Active: Hydrological reconnection, removal of drainage infrastructure, soil and vegetation recovery, topographic reshaping, adaptive management (seasonal flooding, organic farming).	(Davranche et al., 2024)
SW Dutch Delta	Netherlands	North Sea	Scheldt River	51.27°N–51.68°N; 3.99°E–4.40°E	Intertidal salt marshes	A2.5	Large delta system	Carbon-rich salt marsh; innovative restoration in engineered coastal landscapes	Morphological: Coastal squeeze due to fixed embankments, hard structures (stone breakwaters, wooden pales) altering hydrodynamics, preventing marsh migration, accelerating erosion.	Active: Managed realignment (breaching seawalls to create intertidal habitat), pioneer planting (Spartina anglica with coconut mats), restoring tidal patterns and sedimentation processes.	(Willemsen et al., 2022)
Curonian Lagoon	Lithuania	Baltic Sea	Nemunas River	54.87°N–55.71°N; 20.51°E–21.26°E	Submerged/ emergent plant beds	C1 / A2	~158,400	Large-scale lagoon; nutrient reduction and water quality recovery	Trophic: Severe eutrophication from nutrient loading (agriculture, wastewater), cyanobacterial blooms, internal phosphorus release under hypoxic conditions, sediment resuspension reducing light.	Passive: Reduction of external nutrient inputs (improved wastewater treatment, agricultural management), natural recolonization of submerged vegetation, sediment stabilization.	(Vybernaite-Lubiene et al., 2018; Bartoli et al., 2018; Petkuviene et al., 2016; Zilius et al., 2014; Sinkevičiene et al., 2017)
Danube Delta	Romania	Black Sea	Danube River	44.80°N–45.47°N; 28.28°E–29.74°E	Freshwater lakes with reed beds	C1	~580,000	Biodiversity hotspot; large-scale hydrological restoration potential	Hydrological: Disconnection from river flooding due to dikes, drainage for agriculture. Morphological: Soil alteration, reed bed destruction from heavy machinery, habitat loss.	Passive: Hydrological reconnection (dike removal, canal restoration), rewetting former agricultural land, natural recolonization of reed beds and aquatic vegetation.	(Lupu et al., 2025; Aivaz and Serbanescu, 2024)

stakeholder and community perspectives into coastal wetland restoration assessment across CPs. This participatory framework was designed to capture local stakeholder preferences, perceptions, and priorities regarding restoration actions, ecosystem services valuation, and decision-making processes - particularly focusing on carbon pathways and associated co-benefits. The participatory methodology relied on a structured multi-criteria analysis (MCA) framework that positioned stakeholders as active co-designers rather than passive information sources.

The MCA framework proceeded through three integrated steps: Step 1) contextual scoping through semi-structured interviews with CP leaders to characterize site boundaries, ecosystems, activities, pressures, and stakeholder networks, while simultaneously developing preliminary criteria lists. Step 2) engage workshop participants in structured criteria weighting exercises on a 1-9 importance scale, with 1-2 hours dedicated to weighting embedded within 3–4-hour sessions that included contextual briefings and moderated discussions, explicitly distinguishing between criterion importance in decision-making and projected impact magnitude. Steps 3) operationalized each criterion through quantitative, qualitative, or monetary indicators sourced from in-field measurements (GHG, habitat extent, hydrological assessments), administrative records (employment, tourism, agricultural data), stakeholder knowledge through expert elicitation, and custom survey instruments, subsequently enabling indicator evaluation under alternative management scenarios.

The knowledge base supporting the ECoP was built through multiple parallel data streams. The first phase involved a scoping review of scientific literature, examining fifty peer-reviewed publications from repositories including ResearchGate, Elsevier, and JSTOR. These sources were prioritized based on geographical scope (European focus), publication currency, and institutional links to European research programs (Horizon, LIFE, Interreg). This literature review identified both barriers and enablers of large-scale restoration, providing theoretical grounding for subsequent case study selection and comparative analysis. Thirty-seven interviews conducted with stakeholders from these pilot sites, providing insights into both historical restoration initiatives and contemporary adaptive management approaches within each coastal wetland system. Complementing these interviews, six participatory workshops (the same held for the MCA, to avoid stakeholder fatigue) were organized during the second semester of 2024 and early 2025.

The engagement at regional scale represents a critical strategic mechanism for extending methodologies and findings beyond the six pilot sites to broader geographical and administrative scales. To extend the community beyond CP boundaries, interviews were conducted with twenty partners representing civil society organizations, non-governmental organizations, international organizations, government agencies, private foundations, and research institutions engaged in large-scale wetland restoration across Europe. Simultaneously, the ECoP engaged with fourteen European projects working on wetland restoration, creating a distributed collaborative network distinct from formal institutional structures. The knowledge base supporting the ECoP recruitment was further strengthened through systematic literature review and grey literature analysis. This included fifty scientific publications sourced from academic repositories, and thirty-four additional publications encompassing national reports from local, subnational, and national authorities, Interreg project websites, Ramsar Convention materials, wetland-based solutions factsheets, and LIFE programme project entries. These multiple recruitment pathways - direct stakeholder engagement at pilot sites, extended network interviews, inter-project collaboration, and comprehensive literature synthesis- created a heterogeneous community representing diverse organizational types, biogeographical regions, wetland types, and restoration approaches across the European space.

3. Results and discussion

Decision support and prioritization tools are crucial for national/regional restoration plans. Effective, scalable tools require standardized, harmonized datasets for baseline mapping, pressure/threat analysis, and ecosystem service effects estimates. The described datasets largely meet these needs.

Applying the EUNIS habitat classification across CPs provides the standardization mechanism essential for effective continental-scale restoration planning. Standardized habitat mapping is vital as past assessments were hampered by heterogeneous classification systems, limiting synthesis of outcomes. Harmonization to EUNIS terrestrial 2021 and marine 2022 ensures compatibility with European environmental reporting obligations, facilitating integration with existing and coming regulatory frameworks. EUNIS's hierarchical structure, from broad habitat groups to fine-scale ecological units, offers analytical flexibility for multi-scale questions, from site-specific work to continental policy (Chytrý et al., 2020). This multi-scale analytical capacity responds to policy demands emerging from the NRR, which requires Member States to submit detailed national restoration plans with prioritization strategies for diverse coastal wetland ecosystems (European Parliament and Council, 2024).

A total of 38 distinct habitats at EUNIS level 2 were identified in the six CPs (Fig. 2), covering diverse natural and human-shaped coastal wetland ecosystems such as intertidal salt marshes, seagrass meadows, coastal lagoons, freshwater marshes, inland water bodies, saltpans, and rice fields. Notable habitats include extensive littoral sediments in the Camargue (France), Southwest Dutch Delta (Netherlands) and Curonian Lagoon (Lithuania) sites (relative cover up to 85-95%), intertidal seagrass beds and coastal dunes in Ria de Aveiro (Portugal), freshwater marshes and reedbeds in the Danube Delta (Romania), and arable land in Valencian Wetlands (Spain) (Oliveira et al., 2025). The legal protection status and policy instruments such as Natura 2000 and EU Habitats Directive Annex I apply variably across habitats and pilots.

Recent advances demonstrate that ensemble machine learning models combined with high-resolution satellite imagery and ecologically meaningful environmental variables can produce European habitat maps with independent validation and uncertainty analyses, significantly improving both thematic and spatial resolution compared to traditional manual classification approaches. Integrating the hierarchical nature of EUNIS classifications through deep learning frameworks substantially improves classification accuracy for Level 3 habitat types across heterogeneous European ecosystems. This technological integration with standardized habitat frameworks provides an operational pathway to scale point-scale habitat data from CPs to continental assessments, ensuring that fine-scale ecological knowledge can inform landscape-level policy implementation (Janowski et al., 2025; Si-Moussi et al., 2025).

For the socio-ecological data, the successful linkage between EUNIS habitat types and CICES v5.1 ecosystem service categories operationalizes the ecosystem service cascade model, enabling quantitative estimation of service supply from spatial habitat maps. The direct crosswalk between habitat classification and ecosystem service frameworks is a key advancement for restoration prioritization, allowing managers to predict how habitat-specific restoration actions translate into changes in provisioning, regulating, and cultural services. Previous studies demonstrate that ecosystem services vary substantially among coastal wetland habitat types, emphasizing the importance of habitat-level service assessments over aggregated valuations (Grizzetti et al., 2019; Teixeira et al., 2019).

The dataset encompasses 1,612 records linking habitats to ecosystem service classes under the CICES v5.1, providing comprehensive coverage of provisioning services (including biomass production for nutrition, materials, and energy; genetic materials; and non-aqueous abiotic outputs such as wind and solar energy), regulation and maintenance services (water quality regulation, erosion control, atmospheric composition regulation, and lifecycle maintenance including habitat and gene pool protection), and cultural services (intellectual and representational interactions including scientific investigation and

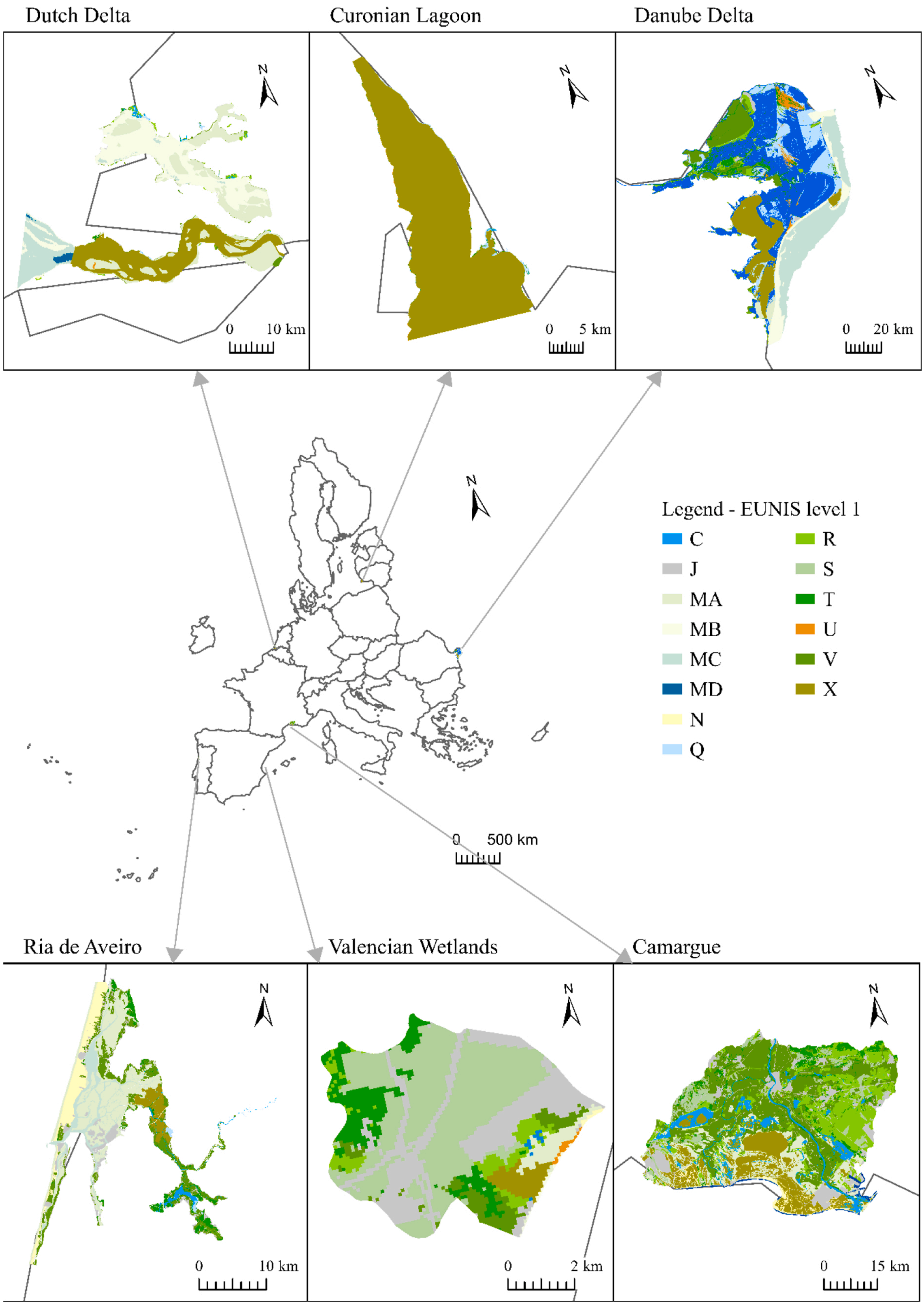

Fig. 2. Case Pilot location and EUNIS level 1 coastal wetlands habitats. Spatial data were projected in WGS 1984 geographic coordinate system (EPSG:4326). Country administrative areas from GISCO, European Commission.

education; physical and experiential interactions including recreation and health; and non-use values linked to biodiversity and landscape appreciation) (Oliveira et al., 2025). This spatially explicit ecosystem service cascade recognizes that service provision (supply side) must be evaluated in relation to human needs and benefits requests (demand side), addressing a critical analytical gap in restoration planning. Studies show supply and demand are frequently spatially mismatched, with supply concentrated in rural and less-developed areas while demand is concentrated in urban and economically developed zones (O'Higgins et al., 2020). By mapping both supply (habitat mapping) and demand (stakeholder engagement), the RESTORE4Cs approach identifies priority zones where restoration can simultaneously address ecological degradation and unmet service demands. This integration supports identifying co-benefits and trade-offs, enabling transparent multi-objective decision-making (demand side) (O'Higgins et al., 2020).

The ecosystem services flow is mediated by human activities establishing activity-pressure associations that impact the ecological status of habitats and compromise service provisioning. The extensive compilation of 23,064 habitat - ecosystem services – activity - pressure associations detail the anthropogenic activities taking place in the pilots. These are categorized using harmonized groupings derived from European legislative frameworks including Habitats Directive, WFD, and MSFD, supplemented by NACE codes (Borgwardt et al., 2019). The dataset distinguishes direct and indirect pressures such as habitat modification, pollution, eutrophication, hydrological alterations, invasive species, and infrastructure development. Explicitly associating these pressures with EUNIS habitats and CICES groups enables targeted impact and restoration priority assessments (Borgwardt et al., 2019). This significantly advances conventional planning, which often lacks explicit documentation of causal pathways linking activities to degradation and outcomes.

Regarding stakeholders and community data, across the CPs, workshops assembled between 7 and 29 participants, with individual surveys collecting 7 to 21 valid answers per site. Participants included governmental environmental agencies, municipalities, NGOs, research institutions, traditional resource users, cultural heritage practitioners, tourism operators, and civil society. This diverse engagement reflects the critical principle that coastal wetland restoration decisions involve trade-offs among competing objectives, requiring comprehensive stakeholder input to reach socially acceptable strategies. A key finding was the need for significant linguistic and conceptual adaptation across contexts, stressing that participatory methodologies must be iteratively adapted to local discourses and frameworks for genuine co-production of knowledge. This adaptive approach aligns with contemporary best practices in participatory research, which emphasize that meaningful stakeholder engagement requires not only structured elicitation mechanisms but also recognition and accommodation of how different communities understand and conceptualize environmental problems (Sella et al., 2025; Anglada et al., 2025). Participatory multi-criteria analysis literature confirms that stakeholders are rarely involved throughout entire decision-making processes, yet studies on nature-based solutions show that when stakeholders participate across problem definition, criteria development, and prioritization stages, implementation success rates increase substantially (Marttunen et al., 2015). The hierarchical integration of scoping, participatory preference elicitation, and scenario-based assessment creates a transparent, replicable methodology for systematic evaluation of restoration actions' multidimensional impacts across geographically diverse coastal wetland contexts. Coastal wetland restoration decisions inherently involve trade-offs among competing environmental, social, and economic objectives, and decision-makers require comprehensive stakeholder input reflecting diverse values and knowledge systems to reach acceptable and robust restoration (Lillebø and Stålnacke, 2015).

Managers involved in national roadmaps form Communities of Practice (CoP) at regional and EU levels (ECoP), engaging in strategic planning and effective implementation of the Regulation. Initiatives with the ECoP included a workshop at each pilot, an online European workshop, and an autumn school for sixteen policymakers. The ECoP is explicitly designed to capitalize on project learnings and promote their dissemination and replication at regional scales, including scaling application from pilot sites to catchments, national zones, and pan-European levels. This scalability is achieved by standardizing monitoring and prioritization tools developed at pilot sites. The ECoP structure exemplifies how learning networks translate local innovations into regional/EU policy. This approach addresses a gap in restoration science by embedding participatory processes within formal institutional frameworks, creating scaffolding for deeper learning processes (double-loop/triple-loop learning) to emerge and influence policy. As end-users, their feedback was paramount for the usability and pertinence of the technological interface. The participatory methodology demonstrated that rigorous integration requires: (1) structured yet adaptive frameworks accommodating local contexts; (2) multi-layered data integration (ecological, economic, preferences); (3) transparent documentation of indicators/methods; and (4) recognition of subjectivity/power dynamics. These principles ensure replicability while maintaining contextual relevance, crucial for upscaling.

Supported by the integrated datasets, impact and restoration priority assessments can be conducted in a more integrative and holistic manner using spatial decision support systems, which assist in solving spatial problems (e.g., land use decisions) by consider co-benefits and trade-offs between ecosystem services and activity-pressure associations. These systems operationalize spatially distributed data into decision environments by integrating biophysical parameters (habitat condition, degradation pressures, restoration potential), socio-ecological parameters (ecosystem service supply and demand, stakeholder preferences), and governance considerations (regulatory requirements, implementation feasibility, equity concerns). Beyond data integration, the RESTORE4Cs Spatial Prioritization Toolbox operationalize these datasets into a decision-support environment that helps identify and rank potential restoration areas across European coastal wetlands, highly demanded by national and subnational entities to prepare the restoration plans in the context of the NRR. The Toolbox combines harmonized spatial layers on habitats, degradation pressures, and potential ecosystem service supply to compute multi-criteria indices of restorability and restoration relevance, enabling users to visualize where restoration actions can maximize co-benefits for climate mitigation, biodiversity conservation, and water cycle regulation. At the pilot level, the Toolbox ingests fine-scale spatial data to identify priority zones where interventions are most likely to restore functions or reconnect degraded areas. Harmonization and standardization of spatial data ensures seamless visualization and comparison in the RESTORE4Cs data platform.

The combined use of ecological vulnerability assessment, stakeholder-based multi-criteria and social acceptability analysis, and economic valuation is designed to support authorities and stakeholders in screening and prioritizing restoration options under existing EU policy frameworks, for example by identifying habitats and ecosystem services most at risk, clarifying which criteria different stakeholder groups consider most important, and approximating the magnitude of associated co-benefits. In practice, the framework can be applied iteratively: ecological and social information narrows the set of feasible and socially legitimate interventions, while value-transfer results help compare their expected benefits relative to costs and funding constraints, thus guiding the construction of restoration portfolios that are both ecologically effective and socially acceptable. By documenting the standardized data structures, indicator definitions, and methodological choices used in CPs, the RESTORE4Cs approach adaptable to coastal regions lacking detailed baseline data., where structured expert knowledge and partial monitoring can be progressively incorporated. In such contexts, machine-learning techniques, including transfer learning, offer pathways to extrapolate pilot-level insights to broader European coastal zones, while remote sensing enables systematic temporal monitoring of restoration effectiveness over large areas, supporting adaptive management. Taken together, the integrated dataset and tools address a critical need: effective restoration prioritization requires not only rigorous ecological assessment, but also explicit integration of ecosystem service valuation, stakeholder preferences, regulatory requirements, and transparent documentation to ensure that decisions are both evidence-based and socially robust.

4. Conclusions

The comprehensive dataset developed through the RESTORE4Cs project, offers a robust, interoperable foundation for advancing European coastal wetland habitat conservation and restoration. These data sets include biophysical and ecological data, socio-ecological data, and data and information on stakeholders and communities' engagement, that is spatial explicit at the level of habitats, as land scape unit. By systematically mapping habitat distributions using updated EUNIS classifications alongside detailed ecosystem service assessments through the CICES framework, the dataset enables a nuanced understanding of the diverse biogeographical and ecological contexts defining these wetlands across Europe. Furthermore, the integration of anthropogenic activities and associated pressures following EU wetlands-related directives standards, provides critical insights into the spatially explicit drivers impacting wetlands ecosystems functions and provided services. This triad of habitat, ecosystem services, and activities and pressures mapping is also essential for stakeholders and citizens engagement, enabling evidence-based decision-making, following a participatory process. This transdisciplinary approach, foster social acceptance of restoration options, allowing for targeted restoration interventions, cross-regional comparisons, and compliance with evolving EU environmental legislation such as the Nature Restoration Law and Biodiversity Strategy 2030.

Beyond its immediate application in site-specific restoration planning, these datasets serve the RESTORE4Cs toolbox to address broader environmental challenges including climate change mitigation, biodiversity loss, and sustainable land management. Ultimately, RESTORE4Cs contributes significantly to advancing science-policy interfaces by sharing spatial explicit data, following FAIR principles, as well as two technological interfaces, Toolbox and Decision Support Tool, that underpin sustainable coastal wetland management and restoration to safeguard these ecosystems for future generations.

The 6 CPs were selected for ecological representation and socio-political readiness but still can be considered geographically discrete sites. The extrapolation to broader European coastal zones depends critically on machine learning techniques and transfer learning methodologies - pathways that require validation and uncertainty quantification before continental-scale application. Adding to this, the datasets generated capture conditions at discrete temporal snapshots (four seasons for well-preserved, altered, and restored states) and lacks continuous temporal monitoring of restoration trajectory recovery curves. Another potential limitation is the number of valid stakeholders in the participatory moments since variable participation rates across biogeographical regions might introduce potential heterogeneity in stakeholder preference elicitation.

Overall, while the RESTORE4Cs framework represents a significant advance in operationalizing transdisciplinary, spatially explicit restoration science, its full potential requires: (1) temporal depth through long-term monitoring; (2) rigorous uncertainty quantification in scaling procedures; (3) expanded stakeholder engagement grounded in equity and governance analysis; (4) explicit climate resilience assessment; and (5) implementation-focused research interrogating feasibility, financing, and institutional barriers. These complementary research streams would transform the framework from into a genuinely adaptive, evidence-based decision-support system capable of guiding European restoration at continental scale.

CRediT authorship contribution statement

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2026.104386.

Data availability

The data is published and cited in the article.

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