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Studies in support of the implementation of the Mission – Wetlands and Blue Carbon

Blue Carbon Roadmap for EU Member States

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Contact: *CINEA HORIZON EUROPE*

E-mail: *CINEA-HE-CLIMATE@ec.europa.eu*

European Commission
B-1049 Brussels
BELGIUM

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Author affiliations:

[1] Blue Carbon Lab, Melbourne, Australia

[2] Centro de Estudios Avanzados de Blanes, Consejo Superior de Investigaciones Científicas, Blanes, Spain

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Contents

1. Executive Summary

The **Blue Carbon Roadmap for EU Member States** outlines a framework to enhance the mapping, monitoring, and management of coastal wetland ecosystems—such as seagrasses, tidal marshes, and mangroves—across the European Union (EU). This roadmap aims to guide policymakers, stakeholders, and the scientific community in improving blue carbon stewardship to support climate mitigation, biodiversity conservation, and the EU's long-term sustainability goals. It offers targeted actions and objectives to address key knowledge gaps, strengthen data collection, and facilitate the inclusion of blue carbon ecosystems in carbon and nature markets. The roadmap aligns with the EU's overarching climate strategies, including the European Green Deal and the Biodiversity Strategy for 2030.

The roadmap is structured around three main objectives:

Objective 1: Map the Distribution of Coastal Wetland Ecosystems and Monitor Changes in Extent and Condition

This objective focuses on establishing a consistent baseline for coastal wetland ecosystems across the EU and its outermost regions, using high-resolution maps and standardised monitoring protocols. It stresses the use of advanced technologies, such as satellite imagery, drones, and other remote sensing tools, to track changes in ecosystem extent and health. The goal is to provide essential data for informed management, conservation, and restoration actions.

Objective 2: Enhance the Monitoring of Blue Carbon and Other Ecosystem Services within Coastal Wetland Ecosystems

This objective aims to improve the accuracy of monitoring blue carbon stocks and greenhouse gas fluxes, while also assessing broader ecosystem services like biodiversity enhancement, coastal protection, and water purification. It focuses on standardising methodologies and developing regional-specific emission factors, alongside creating baseline maps of blue carbon storage and establishing greenhouse gas inventory systems. Enhanced monitoring will enable the integration of coastal wetlands into carbon and nature markets, contributing to the EU's climate and nature objectives.

Objective 3: Strengthen Collaboration and Support Improved Data Accessibility and Integration for Decision-Making

This objective enhances cooperation among EU Member States, promoting data integration into national and regional climate, biodiversity, and conservation strategies. It calls for the creation of a centralised platform for blue carbon data and the development of decision support tools for policymakers. It also advocates for greater collaboration between scientists, policymakers, and local communities, ensuring that monitoring results are used effectively in planning and management.

The roadmap provides a phased, action-oriented approach, breaking down each objective into clear, achievable steps over short-, medium-, and long-term timelines. The **Blue Carbon Roadmap** provides a strategic guide to enhancing the management of coastal wetland ecosystems across the EU. By improving mapping, monitoring, and data sharing, the roadmap will enable Member States to better assess and manage these ecosystems, helping to meet EU climate and biodiversity goals while promoting innovative environmental management.

Graphical Abstract

2. Introduction

Purpose and Scope

This roadmap is designed to improve the monitoring of coastal wetland ecosystems, including tidal marshes, seagrasses and mangroves, and manage their carbon storage capacities within European Union (EU) Member States, supporting climate mitigation, biodiversity conservation, nature repair, and sustainable development goals.

Building on insights from coastal wetland distribution mapping (Sub-Task 2.1) and the analysis of changes in wetland extent (Sub-Task 2.2), the **Blue Carbon Roadmap** (Roadmap) offers targeted recommendations to strengthen coastal wetland monitoring across the EU.

Key components of the Roadmap include:

- **Addressing knowledge gaps:** Identify and address critical gaps in the distribution of coastal wetland ecosystems within the EU, as highlighted by findings from Task 2.

- **Enhancing Mapping Accuracy:** Propose advanced methods and systematic protocols for accurately mapping and monitoring changes in coastal wetland extent, integrating technologies like satellite imagery, drones, and field validation.

- **Harmonising Monitoring Systems:** Establish consistent, interoperable monitoring systems across Member States to enable collaboration, data sharing, and alignment with EU-wide objectives.

- **Integration into Policy Frameworks:** Align monitoring efforts with the EU's climate and biodiversity strategies, including the European Green Deal, Biodiversity Strategy 2030, and Marine Strategy Framework Directive (MSFD).

- **Establishing objectives and actions:** Define short-, medium-, and long-term objectives and actionable recommendations to address monitoring challenges, ensuring progress over time.

This Roadmap aims to guide policymakers and stakeholders in enhancing and coordinating blue carbon monitoring efforts across the EU. It seeks to standardise monitoring systems, address critical knowledge gaps, and align with the EU's climate and biodiversity objectives.

Importance of Coastal Wetlands

Coastal wetlands, also known as blue carbon ecosystems, namely seagrass meadows, tidal marshes, and mangroves[1], are critical natural assets for mitigating and adapting to climate change[2,3]. These ecosystems sequester and store significant amounts of carbon, while offering co-benefits such as coastal protection, biodiversity enhancement, and fisheries productivity[4,56], among others. However, coastal wetlands face significant threats[7,8], including habitat loss, pollution, and climate impacts and thereby, there is a need to develop and implement robust monitoring frameworks to facilitate conservation and restoration actions at scale towards achieving climate change mitigation and sustainable development goals.

Coastal Wetland Mapping

For *Sub-Task 2.1- coastal wetland distribution mapping* we used existing spatial datasets (Appendix-Table S1) to understand the distribution of coastal wetlands

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[1] Lovelock, C. E., & Duarte, C. M. (2019). Dimensions of blue carbon and emerging perspectives. *Biology Letters*, 15(3), Article 20180781. https://doi.org/10.1098/rsbl.2018.0781

[2] Macreadie, P. I., Costa, M. D. P., Atwood, T. B., Friess, D. A., Kelleway, J. J., Kennedy, H., Lovelock, C. E., Serrano, O., & Duarte, C. M. (2021). Blue carbon as a natural climate solution. *Nature Reviews Earth & Environment*, 2(12), 826–839. https://doi.org/10.1038/s43017-021-00224-1

[3] Serrano, O., Kelleway, J. J., Lovelock, C. E., & Lavery, P. S. (2019). Conservation of blue carbon ecosystems for climate change mitigation and adaptation. In G. M. E. Perillo, E. Wolanski, D. R. Cahoon, & C. S. Hopkinson (Eds.), *Coastal Wetlands: An Integrated Ecosystem Approach* (2nd ed., pp. 965–996). Elsevier. https://doi.org/10.1016/B978-0-444-63893-9.00028-9

[4] Bertram, C., Quaas, M., Reusch, T. B. H., Vafeidis, A. T., Wolff, C., & Rickels, W. (2021). The blue carbon wealth of nations. *Nature Climate Change*, 11(8), 704–709. https://doi.org/10.1038/s41558-021-01089-4

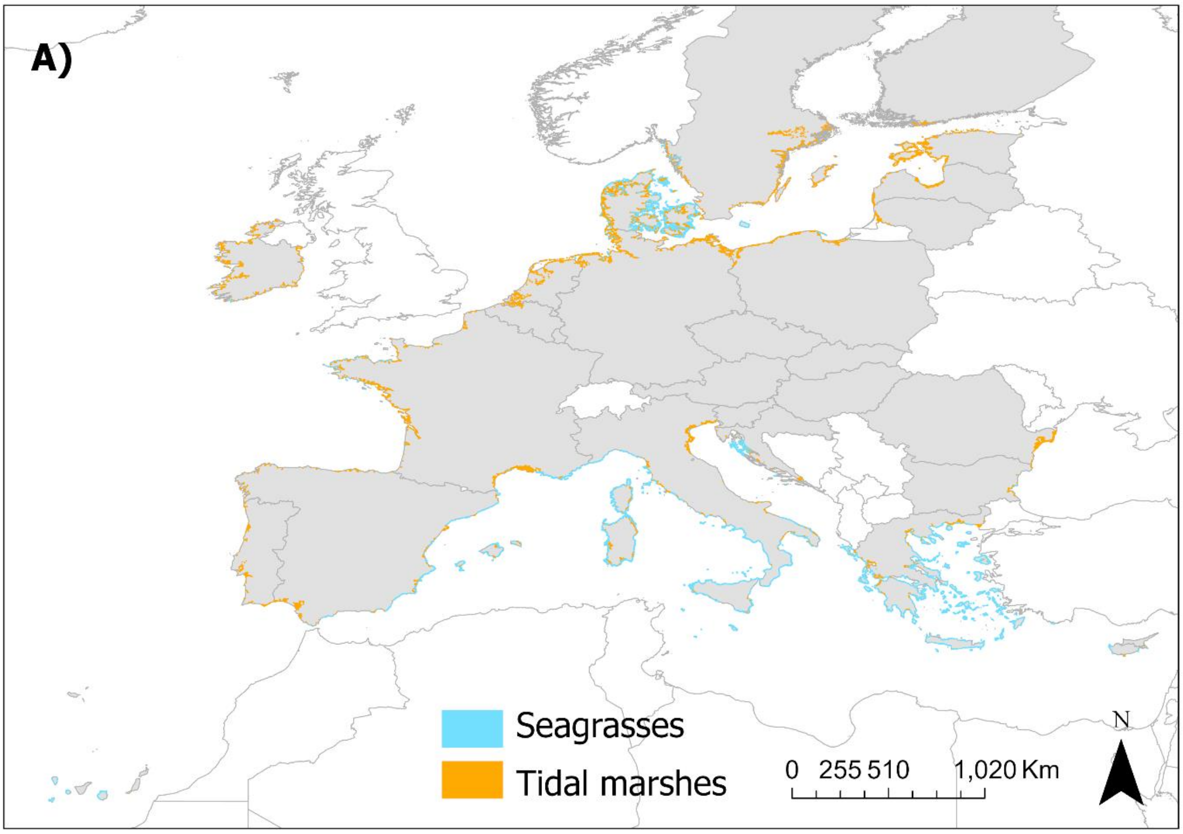
[5] Davidson, N. C., van Dam, A. A., Finlayson, C. M., & McInnes, R. J. (2019). Worth of wetlands: Revised global monetary values of coastal and inland wetland ecosystem services. *Marine and Freshwater Research, 70*(8), 1189–1194. https://doi.org/10.1071/MF18391

[6] Himes-Cornell, A., Pendleton, L., & Atiyah, P. (2018). Valuing ecosystem services from blue forests: A systematic review of the valuation of salt marshes, seagrass beds, and mangrove forests. *Ecosystem Services*, 30, 36–48. https://doi.org/10.1016/j.ecoser.2018.01.006

[7] Newton, A., Icely, J., Cristina, S., Perillo, G. M. E., Turner, R. E., Ashan, D., Cragg, S., Luo, Y., Tu, C., et al. (2020). Anthropogenic, direct pressures on coastal wetlands. *Frontiers in Ecology and Evolution*, 8, 144. https://doi.org/10.3389/fevo.2020.00144

[8] Ballut-Dajud, G. A., Sandoval Herazo, L. C., Fernández-Lambert, G., Marín-Muñiz, J. L., López Méndez, M. C., & Betanzo-Torres, E. A. (2022). Factors affecting wetland loss: A review. *Land, 11*(3), 434. https://doi.org/10.3390/land11030434

within the EU Member States and outermost regions. Based on our analysis, we estimated that coastal wetlands are distributed within more than 2 million hectares across the EU and their outermost regions (Figure 1, Table 1). From this total, mangroves are distributed within the outermost regions only (i.e., approximately 93,400 ha), with French Guiana holding ~94% of the extent. Tidal marshes are widely distributed across the EU Member States, totaling over 400,000 ha (Table 1), with Romania and France holding the largest areas of the mapped tidal marshes (Table 1). We estimate that seagrass is the blue carbon ecosystem with the largest distribution in the EU, encompassing more than 1.4 million ha, with Denmark and Italy holding the largest mapped distribution (Table 1).



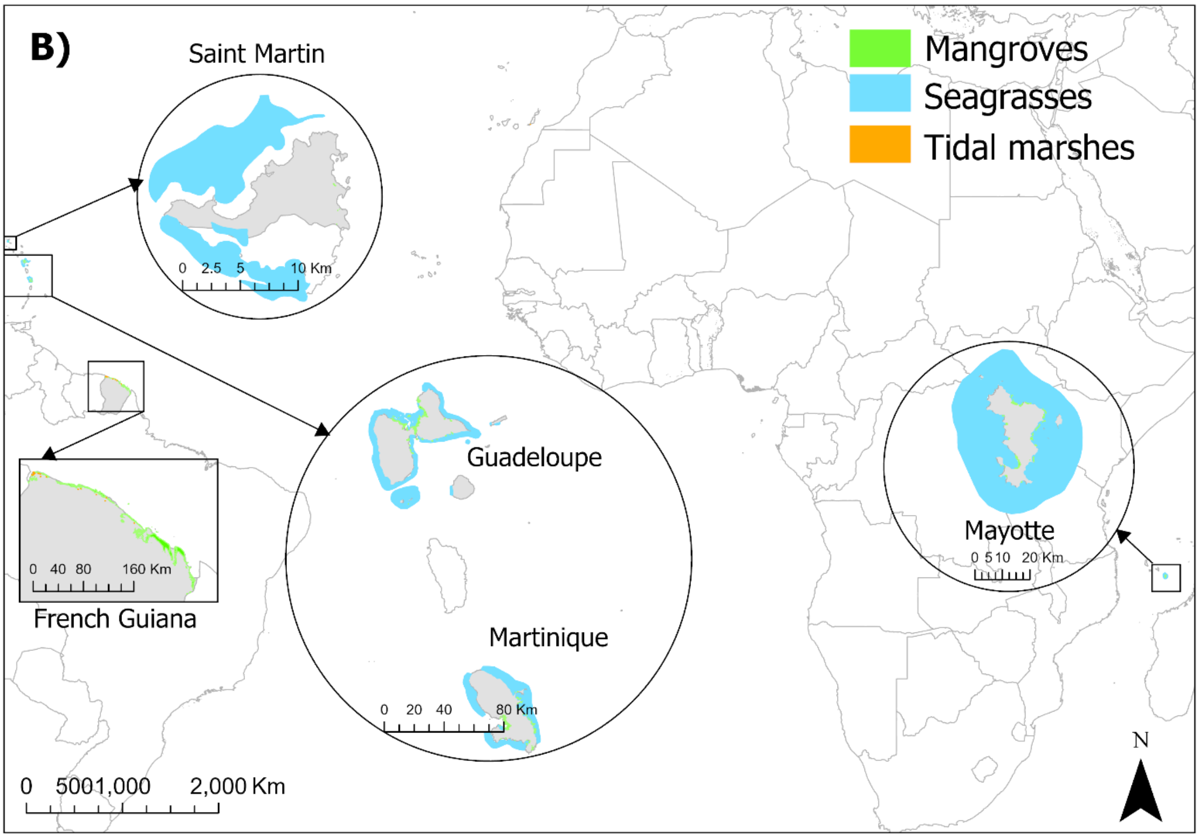


Figure 1: Mapped distribution of mangroves, tidal marshes and seagrasses within the EU region (A), including their outermost regions (B). The spatial layers used to map the distribution of blue carbon ecosystems in this study are available on Table 1. The buffers around the polygons were increased for representation purposes. Here, we did not include maps of the outermost regions with smaller areas, or none mapped blue carbon systems.

Table 1: Distribution (ha) of different blue carbon ecosystems within each EU Member State and Outermost regions. The spatial layers used to map the distribution of blue carbon ecosystems in this study are available in Appendix Table S1. Portugal and Spain include their outermost regions of Azores and Madeira, and Canary Islands, respectively. Values were rounded to the nearest integer.

EU Member State	Area (ha)		
	Mangroves	Tidal Marshes	Seagrasses
Austria			
Belgium		784	
Bulgaria		1,954	934
Croatia		5,162	29,794
Cyprus		220	6,986
Czechia			
Denmark		26,331	413,831
Estonia		26,954	9
Finland		731	
France		66,971	123,272
Germany		34,534	98,440
Greece		21,350	294,922
Hungary			
Ireland		13,067	358
Italy		22,860	386,872
Latvia		16,344	1,140
Lithuania		3,944	726
Luxembourg			
Malta			
Netherlands		18,115	
Poland		16,116	3,134
Portugal		15,763	4

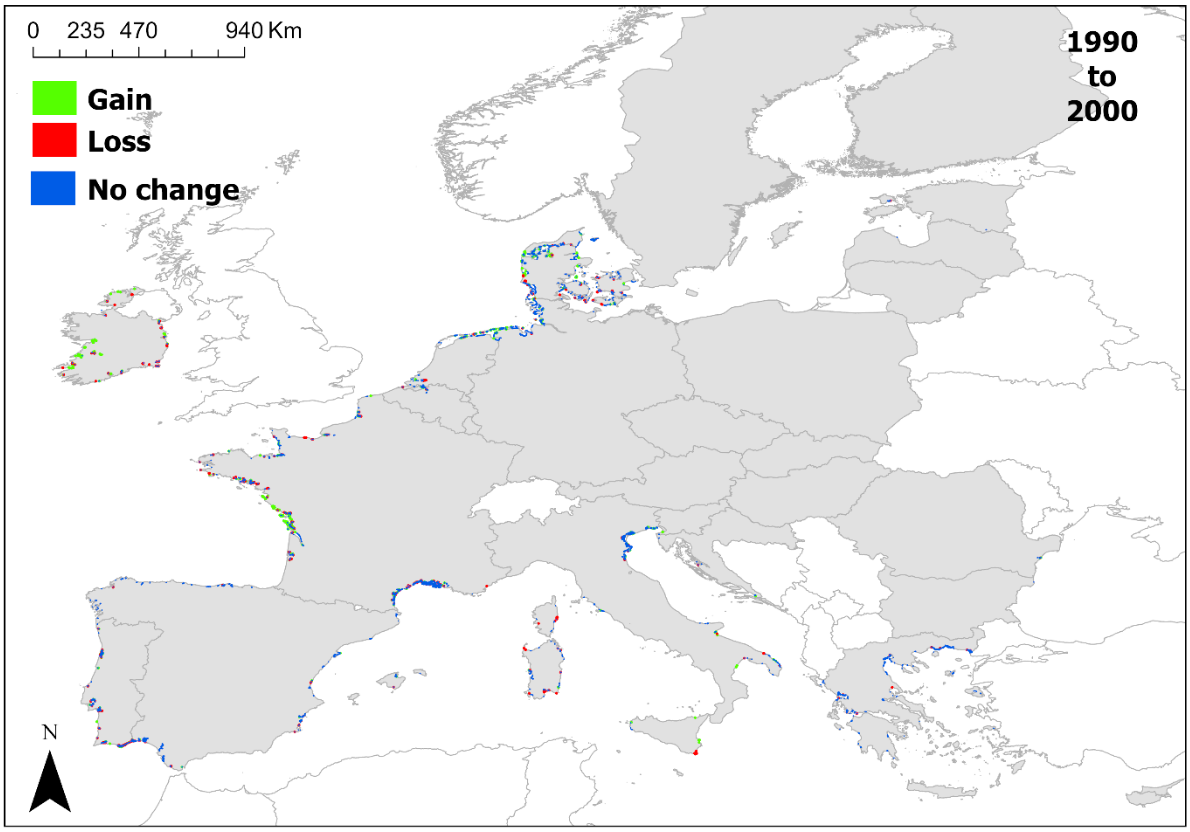
EU Member State	Area (ha)		
	Mangroves	Tidal Marshes	Seagrasses
Romania		71,466	8
Slovakia			
Slovenia		142	
Spain		34,137	115,869
Sweden		11,695	4,285
Outermost regions			
Guadeloupe	3,152		76,033
French Guiana	87,968	478	
Martinique	1,698		55,842
Mayotte	579		148,437
Réunion	*	19	*
Saint Martin	1		10,696

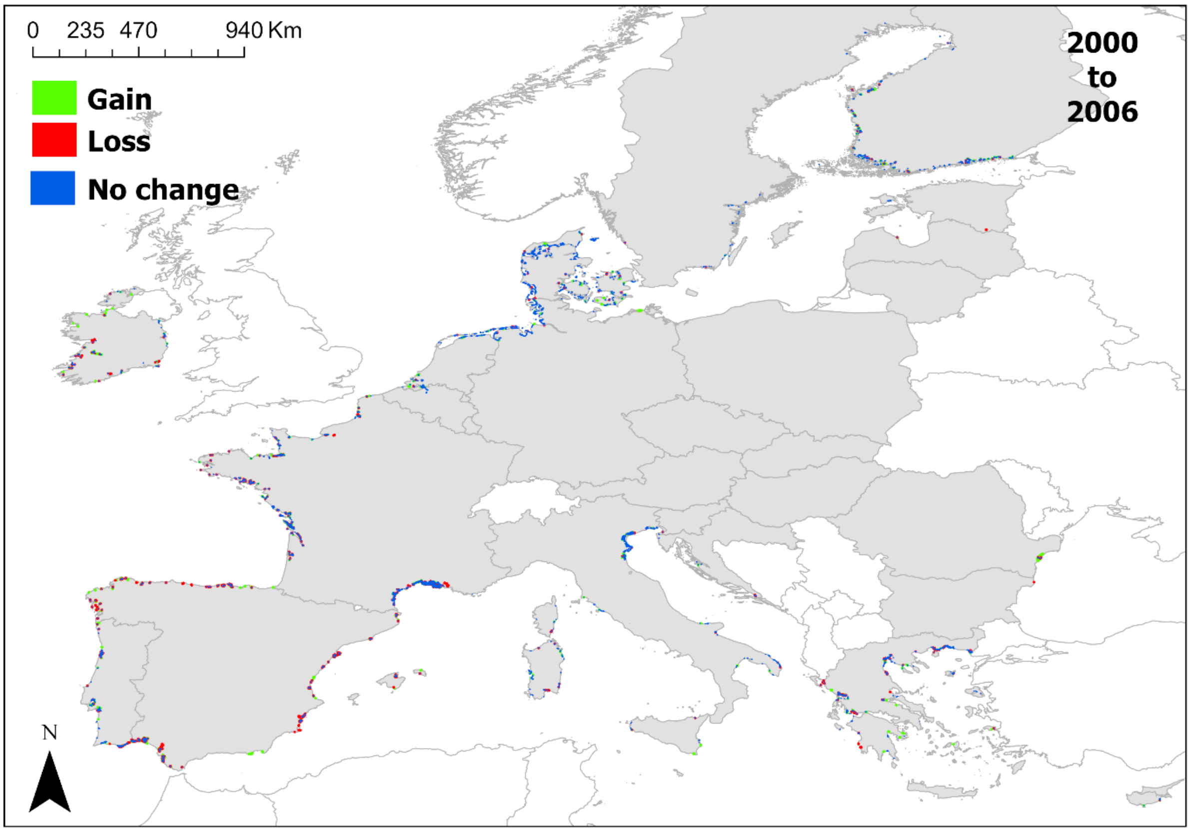
* Territories that are known to have mangroves according to the literature, but existing maps included in this study do not cover them.

Coastal Wetland Land-use Change

For *Sub-Task 2.2 - Mapping the distribution change of coastal wetlands*, we used existing data to estimate distribution change of coastal wetlands across the EU and outermost regions. Due to data availability, the focus of the analysis was tidal marshes. In the EU region, tidal marsh dynamics from 2006 to 2018 showed a substantial decrease in loss rates—from over 24,000 ha lost between 2006–2012 to just over 2,000 ha lost between 2012–2018—. Indeed, tidal marshes experienced the greatest expansion (>67,000 ha) between 2006– 2012 (Figure 2). The 2012–2018 period marked higher stability, with around 337,000 ha of marshes showing no distribution change. Changes in extent were largely linked to transitions with other vegetation types and agriculture (Figure 3). Spatial trends varied across Member States, with tidal marsh expansion observed in Denmark, France, Germany, Romania, and Spain, and losses in Greece and Italy. In the outermost regions (French Guiana and Mayotte), tidal marsh changes were minor and spatially limited, with overall greater losses than gains. Despite CORINE data indicating a net gain in tidal marshes between 1990 and 2018, alternate datasets suggest a net loss for the

EU. Overall, tidal flats were the most dynamic wetland type, and discrepancies across datasets highlight the need for improved and standardised coastal wetland monitoring methodologies in the EU.





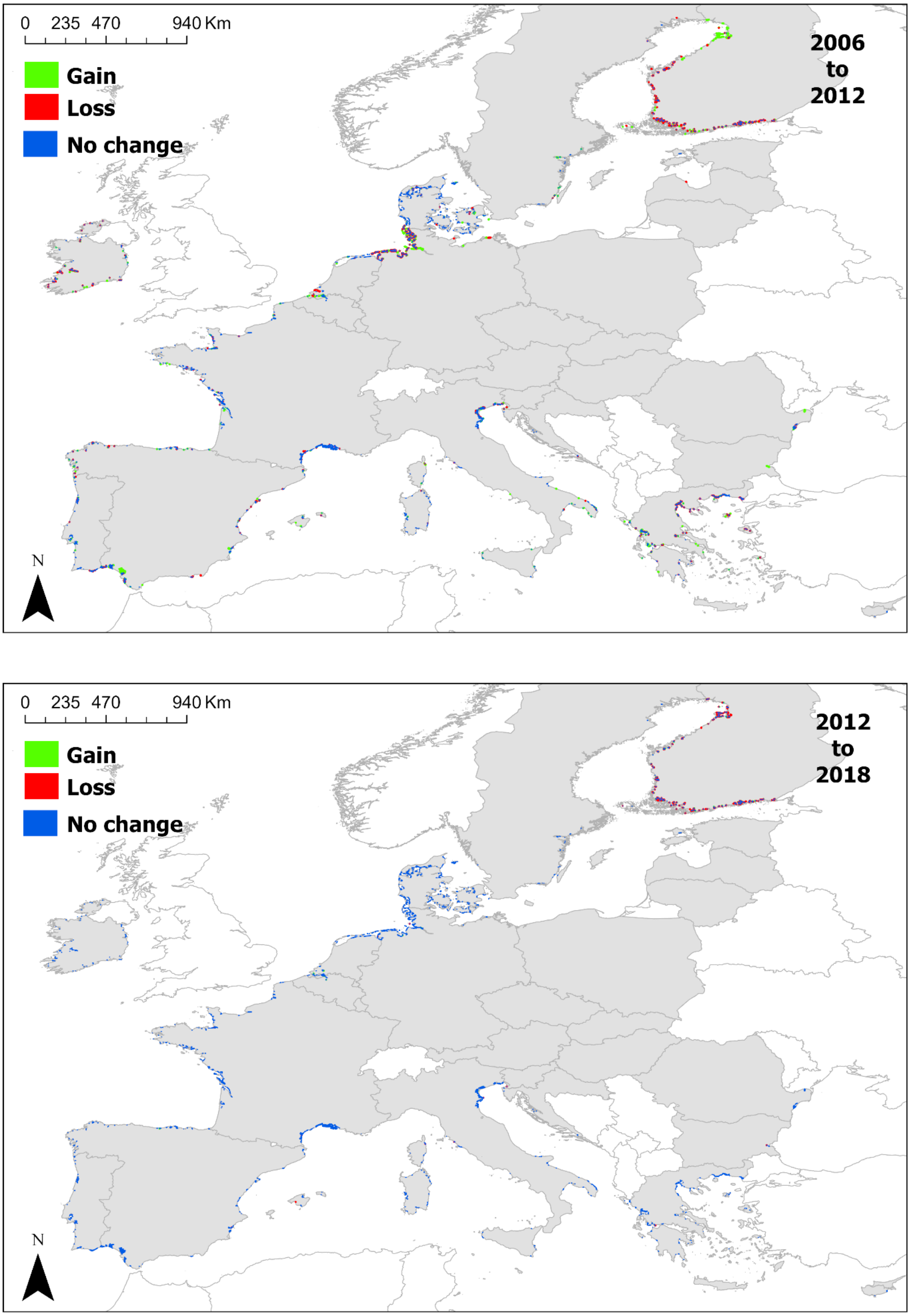


Figure 2. Spatial patterns in tidal marsh extent change between 1990 and 2018 across the EU. Here, we estimated extent change in tidal marshes using the long-term CORINE Land Cover inventory

dataset which includes data from 1990, 2000, 2006, 2012, and 2018. The buffers around the polygons were increased for representation purposes.

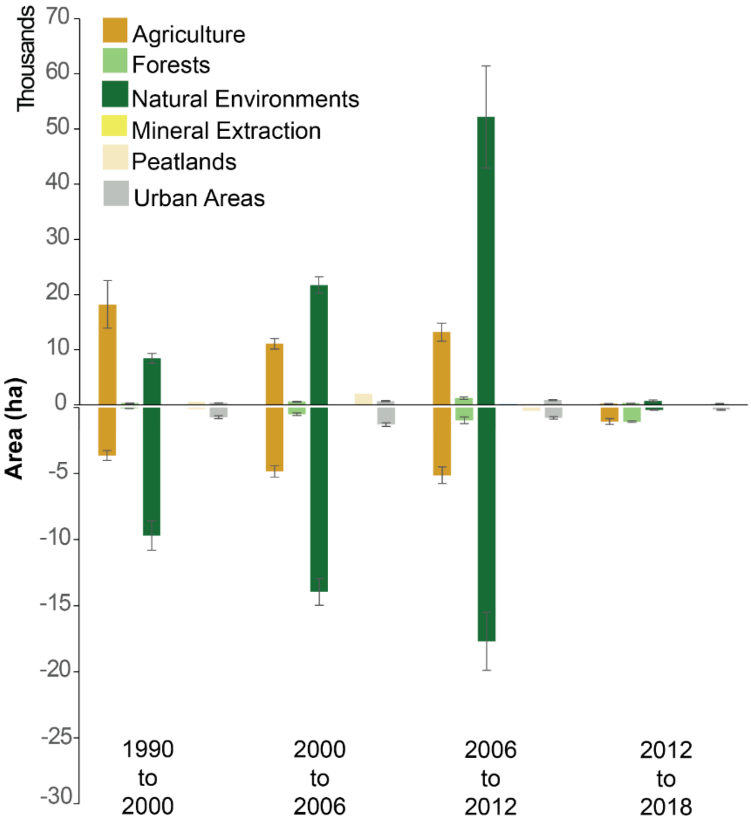


Figure 3: Changes in the distribution of tidal marshes (±SE) across the EU detailing the land use changes and its magnitude over time. We estimated extent change in tidal marshes over four periods using the long-term CORINE Land Cover inventory dataset which includes data from 1990, 2000, 2006, 2012, and 2018.

Gaps and Challenges in Coastal Wetland Mapping and Monitoring

Mapping Data Gaps

Accurate and up-to-date spatial data on coastal wetland ecosystems remains a major barrier to effective monitoring and decision-making across the EU. Most existing spatial datasets are global in scope and lack the detail required at national or regional scales. Many maps are outdated, incomplete, or inconsistent in resolution and classification methods. Critical ecosystems such as seagrasses and small tidal marsh areas are frequently underrepresented or misclassified in commonly used datasets like CORINE Land Cover, which has known limitations in spatial resolution (30 m) and thematic accuracy. These issues undermine accurate habitat delineation and carbon stock estimation.

Fragmented Monitoring Systems

Monitoring efforts across Member States are highly variable, with no coordinated EU-wide systems in place. Distribution maps often vary in time span and resolution, limiting comparability and integration. Many monitoring programmes are conducted sporadically or lack the consistency needed to track long-term ecosystem trends. These temporal gaps hinder the ability to detect early degradation or assess restoration outcomes effectively.

Carbon-Specific Data Limitations

There are substantial deficiencies in the collection and standardisation of carbon-related data. Many Member States lack uniform protocols for assessing carbon sequestration, greenhouse gas (GHG) fluxes, and baseline carbon inventories. Data on emissions and removals following restoration or loss of coastal wetlands is often incomplete or entirely absent. The IPCC 2013 Wetlands Supplement provides methodologies for accounting for wetland-related emissions, but the document is over 10 years old and scientifically outdated, and its implementation across the EU remains inconsistent, contributing to underreporting and reduced credibility of national GHG inventories.

Insufficient Understanding of Land-Use Change Drivers

Tracking the drivers of coastal wetland change is hampered by limited data on land tenure, land-use history, and management regimes. CORINE Land Cover data is often used to estimate land-use change but may lead to misclassification or overestimation, particularly where seagrasses are excluded or tidal marshes are misclassified as other habitat types. Large-scale, high-accuracy mapping efforts are needed to better understand how human activities are affecting wetland distribution and function.

Institutional and Policy Challenges

A range of structural and institutional challenges continue to limit effective coastal wetland monitoring across the EU. A key issue is the lack of standardised methodologies among Member States, with differing classification systems, indicators, and monitoring timelines complicating EU-wide data aggregation and comparison. Coordination between national agencies, and between national and EU levels, remains fragmented. Moreover, monitoring efforts are often dependent on short-term, project-based funding, leading to gaps in continuity once EU-funded initiatives conclude. Despite growing scientific evidence, blue carbon and coastal wetland data are still not consistently integrated into national climate policy instruments like Nationally Determined Contributions (NDCs). Wetland monitoring often remains siloed within environmental agencies, rather than being embedded within broader climate adaptation and mitigation frameworks or national accounting systems such as greenhouse gas inventories or Land Use, Land-Use Change and Forestry (LULUCF) reporting.

3. Structure of the Roadmap

This Blue Carbon Monitoring Roadmap is designed to enhance the mapping, monitoring, and integration of blue carbon ecosystems across EU Member States. It is structured around three key objectives, each addressing a crucial aspect of blue carbon monitoring: mapping and assessing ecosystem changes, enhancing monitoring of carbon and ecosystem services, and strengthening collaboration and data accessibility.

Each objective is further broken down into four or five actions, with specific sub-actions providing clear steps for implementation. These actions are designed to be implemented in a phased approach with short-term (1–3 years), medium-term (3–5 years), and long-term (5+ years) timelines. This structured approach ensures that efforts are practical, scalable, and aligned with EU climate, biodiversity, and marine conservation policies.

Objective 1: Map the distribution of coastal wetland ecosystems and monitor changes in extent and condition

Mapping the distribution of coastal wetland ecosystems is fundamental to understanding their current state, carbon storage potential, and vulnerability to climate change and human impacts. This objective seeks to establish a robust spatial baseline map for coastal wetland ecosystems—including mangroves, tidal marshes, and seagrasses—across EU Member States and Outermost Regions. By leveraging advanced remote sensing, field surveys, and high-resolution mapping techniques, we can accurately delineate these vital habitats.

In addition to mapping, ongoing monitoring of changes in wetland extent and ecological condition is essential. Regular assessments will help to identify trends, such as habitat degradation or expansion, and provide critical data to inform conservation and restoration efforts. This comprehensive approach ensures that coastal wetlands are effectively managed and integrated into EU climate and biodiversity strategies.

Action 1.1	Develop spatially explicit baseline distribution maps of coastal wetland ecosystems
Action 1.2	Track changes in coastal wetland extent
Action 1.3	Monitor changes in coastal wetland ecological condition
Action 1.4	Utilise advanced technologies and cost-effective approaches to enhance monitoring and reporting capabilities

Action 1.1 Develop spatially explicit baseline distribution maps of coastal wetland ecosystems

1.1.1 Develop baseline distribution mapping of coastal wetlands including tidal marshes, seagrasses, and mangroves for EU Member States and Outermost regions

Implementation timeline: Short Term

Creating spatially-explicit baseline distribution maps of coastal wetland ecosystems, including mangroves, tidal marshes, and seagrasses, is essential for tracking ecosystem changes, informing conservation planning, and improving carbon accounting. Establishing high-resolution baseline maps will provide a foundational dataset to monitor wetland extent, degradation, and restoration efforts, supporting climate mitigation, biodiversity protection, and sustainable land-use management.

Key actions:

- Develop ecosystem distribution maps for coastal wetlands, refining where possible to the species or community level to distinguish between different mangrove, tidal marsh, and seagrass species or functional groups, improving habitat classification and ecological assessments. Update the maps regularly, possibly through machine learning or artificial inteligence engines.

- Ensure coastal wetland maps are open to users, consistent, comparable, and interoperable across EU Member States and Outermost Regions by using standardised classification systems, spatial resolutions, and data formats.

- Enhance the mapping of seagrass ecosystems across all EU Member States and Outermost regions by improving the detection of small seagrass species (e.g., *Zostera marina*, *Zostera noltii*, *Cymodocea nodosa*, and the invasive *Halophila* in the Mediterranean) and refining the mapping of deep-water *Posidonia oceanica* and *C. nodosa* habitats.

Key initiatives to build upon:

- Wet Horizons European Wetland Map - a comprehensive map of Europe's peatlands, floodplains, and coastal wetlands (tidal marshes only), compiled from around 200 data sources (released in 2025).

- Studies in Support to the Implementation of the Ocean Mission - Wetlands and Blue Carbon project used existing spatial datasets to map the distribution of coastal wetlands (tidal marshes, seagrasses and manrgoves) within the EU Member States and outermost regions.

- The distribution of global tidal marshes from Earth observation data – Worthington et al., 2024 developed a global 10-m resolution tidal marsh map using a random forest model trained on Earth observation data from 2020. The model achieved 85% accuracy in mapping tidal marsh distribution between 60°N and 60°S.

1.1.2 Improve spatial mapping and data accuracy for coastal wetland monitoring

Implementation timeline: Short Term

Accurate and high-resolution spatial mapping is essential for effectively monitoring coastal wetland ecosystems, tracking habitat changes, and ensuring coastal wetland ecosystems are integrated into climate and conservation strategies. Current mapping efforts often face challenges due to low spatial resolution, inconsistent classification methods, and a lack of standardised data across EU Member States. By improving mapping precision, data consistency, and integration of remote sensing technologies, this action will strengthen long-term monitoring, conservation planning, and carbon stock assessments.

Key actions:

- Improve spatial resolution and classification accuracy by employing high-resolution remote sensing technologies (e.g., Sentinel-2, LiDAR, Synthetic Aperture Radar) to enhance wetland delineation and habitat mapping.
- Ensure consistency in spatial resolution across coastal wetland distribution maps, using high-resolution mapping for smaller areas (e.g., Outermost Regions and islands) and lower-resolution data for larger regions to balance accuracy and coverage.
- Establish standardised mapping protocols across all EU Member States and Outermost Regions.
- Adopt a unified wetland classification system across the EU to prevent misclassification of coastal wetlands (e.g., mangroves misclassified as forests, tidal marshes as grasslands, and seagrass meadows as macroalgae), ensuring accurate carbon accounting and land-use reporting.
- Increase mapping accuracy through ground-truthing efforts by integrating field data with very high-resolution remote sensing imagery, improving classification validation and reducing errors.

Relevant projects and resources:

- EOMAP COASTS Project (EU-funded) applies multispectral satellite and drone data to enhance the mapping of shallow water and wetland habitats across Europe.

- ESA Coastal Blue Carbon Project is a consortium of experts, led by the European Space Agency (ESA), that aim to develop novel tools and indicators for Earth Observations related to blue carbon ecosystems.

- Implications of improved remote sensing capabilities on blue carbon quantification: Canty at al., 2025 showed that higher spatial resolution improves land cover estimates, which led to improved mangrove distribution maps and associated carbon stocks[9].

- The Nature Conservancy and Planet: The Earth Genome Seagrass Mapping Project, in collaboration with The Nature Conservancy, aims to develop scalable methodologies for accurately mapping and monitoring global seagrass ecosystems by utilising advancements in artificial intelligence and remote sensing technologies.

Action 1.2 Track changes in coastal wetland extent

1.2.1 Monitor shifts in coastal wetland extent over time

Implementation timeline: Ongoing

To effectively manage and conserve coastal wetland ecosystems, it is essential to track changes in wetland extent over time, identifying areas experiencing loss, degradation, or expansion. Regular monitoring will provide critical insights into habitat trends, inform restoration efforts, and support EU climate and biodiversity strategies. Improved tracking will also ensure that wetlands are accurately represented in land-use classifications and climate reporting frameworks, such as the LULUCF Regulation and the EU Biodiversity Strategy 2030.

Key actions:

- Member States should adopt the IPCC guidelines (Wetlands Supplement) for measuring and reporting changes in coastal wetlands extent.

[9] Canty, S. W. J., Cifuentes-Jara, M., Herrera-Silveira, J., Morrissette, H. K., Cissell, J. R., Acosta-Velázquez, J., Cherrington, E., Feller, I. C., Friess, D. A., Lefcheck, J. S., Simpson, L. T., & Teutli-Hernandez, C. (2025). Implications of improved remote sensing capabilities on blue carbon quantification. *Estuarine, Coastal and Shelf Science*, 319, 109275. https://doi.org/10.1016/j.ecss.2025.109275

- Review and update national habitat classification schemes to ensure coastal wetland ecosystems—such as mangroves, tidal marshes, and seagrasses—are consistently classified across all EU Member States. This will support standardised monitoring and reporting, and enable alignment with the IPCC Wetlands Supplement, greenhouse gas inventory requirements and NDCs. This principle can also be extended to freshwater wetlands where appropriate.

- Leverage historical datasets and time-series analysis to assess long-term wetland trends.

- Integrate coastal wetland extent mapping into large-scale land cover monitoring systems such as the CORINE Land Cover programme, while advocating for refinement of categories to better reflect coastal wetland habitats.

Related resources:

- CORINE Land Cover - The dataset, part of the EU's Copernicus Land Monitoring Service, provides consistent and comparable information on land cover and land use across Europe. It includes detailed maps updated every six years, enabling the monitoring of land cover changes over time to support environmental policy, spatial planning, and sustainable land management. While the dataset includes coastal wetlands, they are currently represented in a generalised and broad land cover classification, rather than with detailed ecosystem specific resolution.

- High-resolution mapping of losses and gains of Earth's tidal wetlands – Murray et al., 2022 conducted a global analysis using satellite data from 1999 to 2019 to simultaneously monitor changes in three intertidal ecosystems—tidal flats, tidal marshes, and mangroves—demonstrating the effectiveness of Earth Observation (EO) methods in tracking both losses and gains in tidal wetlands at a global scale[10].

- The Mapping and Assessment of Ecosystems and their Services (MAES) initiative developed an EU-wide ecosystem typology and mapping protocol which many countries now use to report ecosystem extent and condition. However, coastal wetlands are often underrepresented or inconsistently assessed in its implementation.

- Digital Earth Australia Mangrove Canopy Cover track changes in the extent and canopy density of mangroves providing a sequence of 25 m resolution

[10] Murray, N. J., Worthington, T. A., Bunting, P., Duce, S., Hagger, V., Lovelock, C. E., Lucas, R., Saunders, M. I., Sheaves, M., Spalding, M., Waltham, N. J., & Lyons, M. B. (2022). High-resolution mapping of losses and gains of Earth's tidal wetlands. *Science*, 376(6594), 744–749. https://doi.org/10.1126/science.abm9583

annual maps using Landsat. Lymburner et al., 2020 undertook a 30-year analysis of Landsat mangrove data to track mangrove dynamics[11].

- Changing landscapes: habitat monitoring and land transformation in a long-time used Mediterranean coastal wetland – This study by Tomaselli et al., 2022 highlights how land use pressures such as agriculture and altered water flow have transformed saltmarshes and coastal dune systems in one of Italy's largest coastal wetlands, using habitat mapping, transition matrices, and landscape metrics to assess changes over a 10-year period and inform conservation strategies[12].

1.2.2 Map coastal wetlands restoration opportunities and assess the effectiveness of protection and restoration efforts through monitoring

Implementation timeline: Medium Term

Mapping coastal wetland restoration opportunities and assessing the cost-effectiveness of conservation and restoration efforts are essential for sustaining coastal wetlands and maximising their climate mitigation potential. Strengthening monitoring frameworks will enable the identification of degraded or at-risk wetlands, track changes in ecosystem condition, and evaluate the success of restoration interventions. Robust monitoring systems will ensure that past and ongoing restoration projects deliver long-term ecological benefits, enhance carbon sequestration, and contribute to EU climate and biodiversity objectives.

Key actions:

- Identify and map priority areas for coastal wetland restoration using high-resolution remote sensing and in-situ surveys to locate degraded coastal wetlands with high restoration potential.
- Develop spatial models integrating hydrology, land-use history, and ecosystem health to assess restoration feasibility.
- Conduct comparative analyses of protected vs. non-protected wetlands to determine the success of conservation and restoration policies.

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[11] Lymburner, L., Bunting, P., Lucas, R., Scarth, P., Alam, I., Phillips, C., Ticehurst, C., & Held, A. (2020). Mapping the multi-decadal mangrove dynamics of the Australian coastline. *Remote Sensing of Environment*, 238, 111185. https://doi.org/10.1016/j.rse.2019.05.004

[12] Tomaselli, V., Mantino, F., Tarantino, C., Albanese, G., & Adamo, M. (2023). Changing landscapes: habitat monitoring and land transformation in a long-time used Mediterranean coastal wetland. *Wetlands Ecology and Management*, 31(1), 31–58. https://doi.org/10.1007/s11273-022-09900-5

- Establish long-term monitoring frameworks to evaluate the effectiveness of protection and restoration activities.

Example programs and research initiatives:

- RESTORE4Cs project – The Horizon Europe project aims to assess how wetland restoration actions can enhance climate change mitigation and adaptation, improve ecosystem services, and support biodiversity conservation.

- ALFAwetlands – Work Package 1 aims to enhance geospatial knowledge on European wetlands by developing multi-scale spatial data and identifying priority areas for restoration and conservation, with a focus on peatlands, to support climate, biodiversity, and ecosystem service goals.

- Modelling blue carbon farming opportunities at different spatial scales – Costa et al., 2022 used existing data on the past and present distribution of coastal wetlands, land cover and land use data to identify restoration opportunities in Queensland, Australia, under different restoration scenarios[13].

- Mapping tidal restrictions to support blue carbon restoration – Nuyts et al., 2024 used high-resolution LiDAR, geospatial analysis, and a multi-criteria scoring system to identify tidal restrictions in Victoria, Australia, assessing their potential for tidal restoration to support blue carbon ecosystems and their ecosystem services[14].

- Spatially explicit ecosystem accounts for coastal wetland restoration – Costa et al., 2024 used existing data on coastal wetlands (e.g., distribution, condition) to identify potential areas for restoration and conservation and their potential benefits based on an environmental economic accounting framework[15]. This work was undertaken in collaboration with the Victoria's Department for Energy, Environment and Climate Action in Australia, and used to support the State's Blue Carbon Initiative.

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[13] De Paula Costa, M. D., Lovelock, C. E., Waltham, N. J., Moritsch, M. M., Butler, D., & Macreadie, P. I. (2022). Modelling blue carbon farming opportunities at different spatial scales. *Journal of Environmental Management*, 301, 113813. https://doi.org/10.1016/j.jenvman.2021.113813

[14] Nuyts, S., Wartman, M., Macreadie, P. I., & De Paula Costa, M. D. (2024). Mapping tidal restrictions to support blue carbon restoration. *Science of The Total Environment*, 949, 175085. https://doi.org/10.1016/j.scitotenv.2024.175085

[15] Costa, M. D. P., Wartman, M., Macreadie, P. I., Ferns, L. W., Holden, R. L., Ierodiaconou, D., MacDonald, K. J., Mazor, T. K., Morris, R., Nicholson, E., Pomeroy, A., Zavadil, E. A., Young, M., Snartt, R., & Carnell, P. (2024). Spatially explicit ecosystem accounts for coastal wetland restoration. *Ecosystem Services*, 65, 101574. https://doi.org/10.1016/j.ecoser.2023.101574

Action 1.3 Monitor changes in coastal wetland ecological condition

1.3.1 Classify coastal wetland ecosystems within the EU based on their conservation status and ecological health

Implementation timeline: Short Term

A standardised classification system for coastal wetlands—including mangroves, tidal marshes, and seagrasses—is essential for assessing their conservation status, ecological health, and restoration priorities. Aligning coastal wetland ecological health classification with the EU Habitats Directive will improve monitoring consistency, facilitate policy integration, and support compliance with EU biodiversity and climate targets.

Key actions:

- Assess coastal wetland ecological health using the EU Habitats Directive framework (Favourable, unfavourable-inadequate, unfavourable-bad, or unknown), applying Article 17 reporting requirements every six years and evaluating coastal wetlands based on range, area/population, structure and functions, and future prospects.

- Categorise coastal wetlands based on protection status by distinguishing protected coastal wetlands (e.g., those within Marine Protected Areas) from non-protected coastal wetlands and prioritise at-risk ecosystems for restoration and conservation planning.

- Enhance reporting and data accessibility by integrating coastal wetland classification and health assessments into EU-wide platforms (Action 3.2) and ensuring transparent, open data sharing to improve collaboration across Member States.

Relevant policies and reporting mechanisms

- EU-wide methodology to map and assess ecosystem condition developed under the EU Biodiversity Strategy for 2030, adopts the System of Environmental Economic Accounting - Ecosystem Accounting (SEEA EA) as its reference framework. This spatially-integrated method organises biophysical ecosystem data, aligning with global statistical standards to ensure standardised mapping and assessment across Member States.

- Article 17 Reporting – Requires EU Member States to submit conservation status assessments every six years.

- EU Biodiversity Strategy 2030 – Calls for the strict protection of high-carbon ecosystems, including coastal wetland ecosystems.

1.3.2 Establish early warning systems and standardised ecosystem health indicators

Implementation timeline: Medium Term

Monitoring both short-term environmental disturbances and long-term ecosystem health is essential for identifying risks, enabling timely interventions, and ensuring the resilience of coastal wetland ecosystems. The development of early warning systems will facilitate the detection of immediate impacts resulting from coastal development, pollution, and land-use changes, while standardised ecosystem health indicators will support long-term assessments of ecosystem condition. Aligning these efforts with EU environmental policies will strengthen wetland management, conservation planning, and climate adaptation strategies across Member States.

Key actions:

- Deploy real-time monitoring technologies, including remote sensing, water quality sensors, and satellite imagery, to detect or predict sudden coastal wetland degradation.
- Establish risk assessment frameworks to evaluate the impact of anthropogenic stressors (e.g. industrial runoff, dredging, or land reclamation) on coastal wetlands.
- Integrate early warning systems data into EU-wide environmental monitoring platforms to support rapid policy responses and adaptive management measures.
- Define consistent metrics for assessing coastal wetland health, including vegetation cover, carbon sequestration rates, hydrological stability, and biodiversity trends.
- Ensure long-term monitoring of coastal wetlands using ground-based surveys, remote sensing, and predictive ecological models.

Relevant examples:

- Global Mangrove Watch: Monthly Alerts of Mangrove Loss for Africa – Bunting et al., 2023 developed a prototype mangrove loss alert system to provide monthly updates on mangrove deforestation, enhancing real-time management beyond annual mapping efforts like Global Mangrove Watch. Using Sentinel-2 imagery (2018–2022) and NDVI-based detection, the system achieved 92.1% accuracy and identified significant losses in Nigeria, Guinea-Bissau, Madagascar, Mozambique, and Guinea due to agriculture, infrastructure, and climate impacts. The alerts will be published monthly on Global Mangrove Watch and expanded to other regions.

- DETER-B: The New Amazon Near Real-Time Deforestation Detection System – The Brazilian Legal Amazon (BLA) is monitored by INPE's DETER system, which provides near real-time deforestation alerts. This study by Diniz et al., 2015 introduces DETER-B, an improved version using higher-resolution AWIFS imagery (56 m) to enhance detection of small-scale deforestation (<25 ha) and identify logging and degradation patterns missed by the original system[16].

Action 1.4 Utilise advanced technologies and cost-effective approaches to enhance monitoring capabilities

1.4.1 Trial emerging technologies for coastal wetland monitoring

Implementation timeline: Medium Term

Advancements in remote sensing, Artificial Intelligence (AI), and cost-effective monitoring technologies are transforming the way coastal wetland ecosystems are mapped and monitored. By leveraging satellite imagery, drone-based mapping, and machine learning, EU Member States can improve spatial resolution, data consistency, and efficiency in tracking changes in coastal wetland extent and condition. Emerging technologies, such as drone-based mapping and satellite remote sensing, provide high-resolution, scalable solutions for monitoring coastal wetlands, detecting changes in habitat extent, and assessing ecosystem health. These technologies improve cost-efficiency, accuracy, and frequency of data collection, ensuring robust long-term monitoring, with large potential particularly for tidal marsh, mangrove and shallow seagrass ecosystems.

Key actions:

- Expand the use of satellite remote sensing by leveraging Copernicus Sentinel satellites (Sentinel-1 SAR, Sentinel-2 optical imaging, Sentinel-3 multi-instrument monitoring), CHIME hyperspectral imaging, and CO2M carbon dioxide monitoring to enhance wetland mapping, detect habitat changes, and assess carbon stocks.

[16] Diniz, C. G., Souza, A. A. de A., Santos, D. C., Dias, M. C., Luz, N. C. da, Moraes, D. R. V. de, Maia, J. S. A., Gomes, A. R., Narvaes, I. da S., Valeriano, D. M., Maurano, L. E. P., & Adami, M. (2015). DETER-B: The New Amazon Near Real-Time Deforestation Detection System. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, 8(7), 3619–3628. https://doi.org/10.1109/JSTARS.2015.2437075

- Utilise drone-mounted LiDAR, multispectral, and thermal sensors to improve spatial resolution, detect small-scale habitat changes, and monitor hard-to-access coastal wetlands.

- Trial cost-effective innovative monitoring methods such as hyperspectral imaging, acoustic sensors for biodiversity assessments, and in-situ water quality sensors to assess wetland health in real time.

- Invest in cloud-based data processing and storage infrastructure to manage large datasets generated by remote sensing and drone technologies, ensuring timely data integration, analysis, and accessibility for EU-wide monitoring and decision-support systems.

Example program and research initiatives:

- The European Union's Copernicus Programme supports coastal wetland monitoring through satellites like Sentinel-1 (SAR imagery for wetlands and land use), Sentinel-2 (high-resolution optical imaging for vegetation health), and Sentinel-3 (multi-instrument monitoring for ocean color, temperature, and coastal water quality).

- The Copernicus Hyperspectral Imaging Mission for the Environment (CHIME) is an upcoming initiative under the EU's Copernicus Programme, designed to enhance environmental monitoring through advanced hyperspectral imaging. CHIME will consist of two satellites, CHIME-A and CHIME-B, each equipped with a state-of-the-art hyperspectral imager (HSI). These instruments will capture data across more than 200 spectral bands, covering wavelengths from 400 nm to 2500 nm in the visible to shortwave infrared spectrum. This capability will provide detailed information on vegetation health, soil properties, and land cover changes. The mission is currently in development, with the first satellite, CHIME-A, expected to launch in 2029.

- CREODIAS is a cloud-based platform developed under the European Union’s Copernicus programme that provides fast and easy access to Earth Observation (EO) data, including Sentinel satellite imagery. It offers users integrated processing, storage, and analysis tools in one environment, enabling efficient data handling for environmental monitoring, research, and decision-making.

- The use of Earth Observation for wetland inventory, assessment and monitoring - This Ramsar Technical Report explores the advantages and limitations of Earth Observation (EO) for wetland inventory, assessment, and monitoring through case studies on tools and workflows, global datasets, and scalable national approaches.

- A nested drone-satellite approach to monitoring the ecological conditions of wetlands - A study in Ireland by Bhatnagar et al., 2021 integrates drone imagery, Sentinel-2 satellite data, and machine learning to automate wetland monitoring, reducing the need for manual field surveys and enabling seasonal vegetation mapping for long-term ecological assessment[17].

- A Review of Unoccupied Aerial Vehicle Use in Wetland Applications: Emerging Opportunities in Approach, Technology, and Data – Dronova et al., 2021 undertook a review of 122 case studies from 29 countries highlighting the growing role of UAVs in wetland monitoring, showcasing their potential to bridge gaps between field surveys and satellite data, enhance ecosystem management, and support long-term conservation efforts[18].

- Remote Sensing and Machine Learning Tools to Support Wetland Monitoring: A Meta-Analysis of Three Decades of Research - Remote sensing and machine learning are increasingly used for wetland monitoring, Jafarzadeh et al., 2022 undertook a meta-analysis of 344 studies highlighting best practices, data selection, and future research opportunities to support conservation, restoration, and policy development[19].
- Remote sensing for cost-effective blue carbon accounting – This review by Malerba et al., 2023 outlines a roadmap for using remote sensing technologies to develop cost-effective blue carbon inventories, summarising standard guidelines, mapping methods, carbon estimation techniques, and a decision tree for selecting the most suitable approach based on scale, budget, and accuracy needs[20].

1.4.2 Integrate artificial intelligence (AI) and machine learning for coastal wetland monitoring

Implementation timeline: Medium Term

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[17] Bhatnagar, S., Gill, L., Regan, S., Waldren, S., & Ghosh, B. (2021). A nested drone-satellite approach to monitoring the ecological conditions of wetlands. *ISPRS Journal of Photogrammetry and Remote Sensing*, 174, 151–165. https://doi.org/10.1016/j.isprsjprs.2021.01.012

[18] Dronova, I., Kislik, C., Dinh, Z., & Kelly, M. (2021). A review of unoccupied aerial vehicle use in wetland applications: Emerging opportunities in approach, technology, and data. *Drones, 5*(2), 45. https://doi.org/10.3390/drones5020045

[19] Jafarzadeh, H., Mahdianpari, M., Gill, E. W., Brisco, B., & Mohammadimanesh, F. (2022). Remote sensing and machine learning tools to support wetland monitoring: A meta-analysis of three decades of research. *Remote Sensing, 14*(23), 6104. https://doi.org/10.3390/rs14236104

[20] Malerba, M. E., Costa, M. D. P., Friess, D. A., Schuster, L., Young, M. A., Lagomasino, D., Serrano, O., Hickey, S. M., York, P. H., Rasheed, M., Lefcheck, J. S., Radford, B., Atwood, T. B., Ierodiaconou, D., & Macreadie, P. (2023). Remote sensing for cost-effective blue carbon accounting. *Earth-Science Reviews*, 238, 104337. https://doi.org/10.1016/j.earscirev.2023.104337

The application of artificial intelligence (AI) and machine learning (ML) offers transformative potential for improving the efficiency, accuracy, and scalability of coastal wetland monitoring. These technologies enable the processing of large and complex datasets, automated detection of ecosystem changes, and predictive modelling of carbon sequestration and wetland health. AI-powered tools can reduce reliance on manual interpretation, enhance classification accuracy, and provide early warnings for ecosystem degradation, thereby supporting adaptive management and decision-making processes.

Key actions:

- Automate wetland classification and condition assessments using AI-driven analysis of Sentinel-2, LiDAR, and drone imagery to reduce processing time and increase mapping accuracy.
- Develop and train machine learning algorithms for mapping, change detection, and monitoring of seagrass, tidal marsh, and mangrove degradation.
- Ensure access to adequate computing infrastructure and cloud-based platforms to support real-time processing and large-scale AI modelling.
- Apply deep learning techniques to improve detection of subtle changes in wetland condition and classify degradation indicators across habitat types.
- Deploy real-time AI processing tools to support the integration of early warning systems for ecosystem disturbance and risk detection.
- Use machine learning models to forecast carbon accumulation trends and enhance the accuracy of carbon stock estimates by refining emission factor calculations.
- Develop AI-powered decision support tools to visualise real-time monitoring data, identify high-priority restoration areas based on erosion risk, biodiversity value, and carbon sequestration potential, and simulate the impacts of land-use change, sea-level rise, and climate variability.

Relevant examples:

- AI4Copernicus – This Horizon 2020 project bridges AI and Earth Observation (EO) by integrating Copernicus data into the AI4EU platform, enabling users to access computing power, training, and tools for high-impact applications across sectors like agriculture, energy, and environment.
- Destination Earth (DestinE) – A European Commission initiative to build digital twins of the Earth system using high-performance computing, AI, and data analytics. It supports predictive environmental modelling, including climate and ecosystem dynamics.

- Current and future carbon stocks in coastal wetlands within the Great Barrier Reef catchments - Costa et al., 2021 estimated SOC stocks and their drivers within coastal wetlands of GBR catchments using boosted regression trees (i.e. a machine learning approach and ensemble method for modelling the relationship between response and explanatory variables) and identified the potential changes in future carbon stocks due to sea level rise[21].

- Novel approach to large-scale monitoring of submerged aquatic vegetation: A nationwide example from Sweden- Huber et al., 2021 demonstrated the feasibility of combining Copernicus Sentinel-2 imagery, machine learning, and cloud-based data processing for large-scale, high-resolution mapping of submerged aquatic vegetation (SAV) along the Swedish coast, resulting in a semi-automated tool that enables non-experts to monitor SAV distribution and detect changes over time in shallow coastal areas[22].

[21] Costa, M. D. P., Lovelock, C. E., Waltham, N. J., Young, M., Adame, M. F., Bryant, C. V., Butler, D., Green, D., Rasheed, M. A., *et al.* (2021). Current and future carbon stocks in coastal wetlands within the Great Barrier Reef catchments. *Global Change Biology*, 27(17), 4062–4075. https://doi.org/10.1111/gcb.15642

[22] Huber, S., Hansen, L. B., Nielsen, L. T., Rasmussen, M. L., Sølvsteen, J., Berglund, J., Paz von Friesen, C., Danbolt, M., Envall, M., Infantes, E., *et al.* (2022). Novel approach to large-scale monitoring of submerged aquatic vegetation: A nationwide example from Sweden. *Integrated Environmental Assessment and Management*, 18(4), 909–920. https://doi.org/10.1002/ieam.4493

Objective 2: Enhance the monitoring of blue carbon and other ecosystem services within coastal wetland ecosystems

Accurate monitoring of blue carbon and related ecosystem services is essential for effective coastal wetland management, improved policy-making, and robust climate action. By refining measurement techniques, developing comprehensive spatial datasets, and integrating monitoring data into national and EU-level reporting systems, this objective seeks to provide decision-makers with reliable, high-quality data. Enhanced monitoring will inform conservation strategies, enable accurate carbon accounting, and support the integration of blue carbon projects into carbon markets and NDCs, thereby aligning with the EU's climate and biodiversity objectives.

Action 2.1	Implement standardised methods for measuring or estimating change in carbon stocks, carbon sequestration, and greenhouse gas fluxes
Action 2.2	Develop baseline spatially explicit maps of blue carbon storage
Action 2.3	Establish a comprehensive GHG inventory system to monitor and report changes for coastal wetlands
Action 2.4	Strengthen blue carbon monitoring to support integration into carbon markets
Action 2.5	Quantify and monitor the ecosystem services provided by coastal wetlands

Action 2.1	Implement standardised blue carbon methods for measuring or estimating change in carbon stocks, carbon sequestration, and greenhouse gas fluxes

2.1.1 Align blue carbon monitoring methods with best practices in blue carbon science

Implementation timeline: Short Term

Ensuring that blue carbon monitoring methods align with best practices in blue carbon science is essential for consistency, comparability, and integration into national and international carbon accounting and climate policy frameworks. Standardised methodologies will enhance carbon stock assessments, facilitate inclusion in carbon markets, and improve policy decision-making across EU Member States.

Key actions:

- Adopt or reframe internationally recognised blue carbon monitoring protocols for measuring carbon stocks, sequestration rates, and greenhouse gas fluxes (CO_2, CH_4, N_2O emissions and removals)**.**
- Ensure quality control for blue carbon data.

Key information guides:

- IPCC Wetlands Supplement (2013) – Establishes best practices for integrating coastal wetlands into national GHG inventories ensuring wetland carbon sequestration and emissions are accounted for under the Land Use, Land-Use Change, and Forestry (LULUCF) sector[23].

- Blue Carbon Field Manual – Howard et al., 2014 outlines best practices for measuring, reporting, and verifying blue carbon stocks and emissions, offering practical guidance on producing robust carbon data[24].

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[23] Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M., & Troxler, T. G. (Eds.). (2014). *2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. IPCC, Switzerland. Retrieved from https://www.ipcc-nggip.iges.or.jp/public/wetlands/

[24] Howard, J., Hoyt, S., Isensee, K., Pidgeon, E., Telszewski, M. (eds.) (2014). Coastal Blue Carbon: Methods for assessing carbon stocks and emissions factors in mangroves, tidal salt marshes, and seagrass meadows. Conservation International, Intergovernmental Oceanographic Commission of UNESCO, International Union for Conservation of Nature. Arlington, Virginia, USA.

- Verra VM0033 Methodology for Tidal Wetland and Seagrass Restoration – This methodology outlines procedures to quantify net greenhouse gas emission reductions and removals resulting from project activities implemented to restore tidal wetlands[25].

- Recommendations for strengthening blue carbon science – Dahl et al., 2025 synthesized existing blue carbon data to assess uncertainties in differing methodologies and identified 14 key research practices for improvement to enhance biophysical assessments[26].

2.1.2 Develop regional-specific emission factors for blue carbon ecosystems

Implementation timeline: Short to Medium-Term

Establishing standardised regional emission factors for mangroves, tidal marshes, and seagrasses is essential to improve the accuracy of carbon flux estimates across diverse environmental conditions. These factors provide science-based estimations of carbon removals and emissions where direct field measurements are unavailable or impractical. By developing regionally specific values, EU Member States can enhance the reliability of national greenhouse gas inventories, carbon crediting schemes and NDCs, and climate mitigation strategies.

Key actions:

- Utilise existing datasets and international frameworks to generate or refine region-specific emission factors

- Ensure emission factors reflect variations in ecosystem conditions, degradation, and restoration potential

- Account for regional climate influences (e.g., temperature, salinity, hydrology) that impact carbon sequestration rates.

Key information guides:

[25] Verra. (2023). *VM0033 Methodology for Tidal Wetland and Seagrass Restoration, v2.1*. Verra. https://verra.org/methodologies/vm0033-methodology-for-tidal-wetland-and-seagrass-restoration-v2-1/

[26] Dahl, M., Lavery, P. S., Mazarrasa, I., Samper-Villarreal, J., Adame, M. F., Crooks, S., Duarte, C. M., Friess, D. A., Krause-Jensen, D., Leiva-Dueñas, C., Lovelock, C. E., Macreadie, P. I., Masqué, P., Mateo, M. A., & Serrano, O. (2025). Recommendations for strengthening blue carbon science. *One Earth*, 6(2), 101175. https://doi.org/10.1016/j.oneear.2025.101175

- IPCC Wetlands Supplement (2013) – Provides methodologies and emissions factors for estimating greenhouse gas (GHG) emissions and removals from various wetland types[22]

- BlueCAM Model – Lovelock et al., 2022 developed a conservative model using Australian region-specific data to estimate abatement from carbon and greenhouse gas sources and sinks arising from coastal wetland restoration (via tidal restoration) and aligns with the Intergovernmental Panel for Climate Change guidelines for national greenhouse gas inventories[27].

- Ranking the risk of CO_2 emissions from seagrass soil carbon stocks under global change threats – Dahl et al., 2023 assessed the vulnerability of seagrass soil carbon stocks to various global change threats, identifying climate change as the primary factor influencing potential CO_2 emissions from these ecosystems.[28]

2.1.3 Provide training programs for practitioners on standardised methods and advanced monitoring technologies

Implementation timeline: Short Term

Building technical capacity among practitioners is essential to ensure accurate, consistent, and scalable monitoring of blue carbon ecosystems across EU Member States. Effective implementation of standardized carbon accounting methods and the use of advanced monitoring technologies—such as remote sensing, LiDAR, drones, and AI-driven data analysis—requires specialised training for scientists, policymakers, conservation practitioners, and carbon market developers. By equipping stakeholders with the necessary skills and tools, training programs will improve data quality, comparability, and integration of blue carbon into climate mitigation and carbon market frameworks.

Key actions:

[27] Lovelock, C. E., Adame, M. F., Bradley, J., Dittmann, S., Hagger, V., Hickey, S. M., Hutley, L. B., Jones, A., Kelleway, J. J., Lavery, P. S., Macreadie, P. I., Maher, D. T., McGinley, S., Mosley, L. M., Rogers, K., & Sippo, J. Z. (2022). An Australian blue carbon method to estimate climate change mitigation benefits of coastal wetland restoration. *Restoration Ecology*, 30(5), e13739. https://doi.org/10.1111/rec.13739

[28] Dahl, M., McMahon, K., Lavery, P. S., Hamilton, S. H., Lovelock, C. E., & Serrano, O. (2023). Ranking the risk of CO_2 emissions from seagrass soil carbon stocks under global change threats. *Global Environmental Change*, 78, 102632. https://doi.org/10.1016/j.gloenvcha.2022.102632

- Develop hands-on and digital training programs covering topics such as carbon stock assessments, greenhouse gas flux measurements, use of satellite and drone imagery for wetland mapping, and data interpretation.

- Establish an EU-wide capacity building network for blue carbon monitoring and leverage international training programs (linked to Action 3.1.1)

Example training initiatives:

- The IORA Indian Ocean Blue Carbon Hub has YouTube channel with a range of training videos on how to take and process cores from seagrass ecosystems.

- Blue Carbon Foundations Course is a free course that builds the knowledge and skills to understand blue carbon, and covers topics such as blue carbon science, policy, economics, and other concepts including livelihoods, adaptation, resilience, and communications.

- The Grupo Español de Expertos en Ecosistemas de Carbono Azul (G3ECA) is a collective of Spanish experts dedicated to enhancing collaboration among national and international research groups specializing in blue carbon ecosystems, aiming to inform various sectors about the significance of these ecosystems and to develop solutions for their conservation to mitigate climate change while promoting economic growth and societal well-being

Action 2.2 Develop baseline spatially-explicit maps of blue carbon storage

2.2.1 Generate high-resolution EU blue carbon storage maps

Implementation timeline: Short Term

Developing spatially explicit, high-resolution maps of blue carbon storage is critical for accurate estimation of aboveground and belowground biomass, soil carbon stocks, and carbon accumulation rates in mangroves, tidal marshes, and seagrasses. These maps will support carbon accounting, inform restoration efforts, and facilitate the integration of blue carbon into climate mitigation strategies and carbon markets, including NDCs.

Key actions:

- Apply standardised methodologies to quantify blue carbon storage across different carbon pools, including aboveground and belowground biomass, soil carbon stocks, and carbon accumulation rates in coastal wetland ecosystems (linked to Action 2.1.1).

- Use statistical modelling to estimate and map blue carbon storage at large spatial scales, improving accuracy and coverage.

- Analyse key environmental and anthropogenic factors influencing carbon stocks to understand variability and enhance predictive modelling.

Relevant research:

- MPA Europe WP4 Blue Carbon – This project collated soil carbon data from coastal wetlands across the EU from available literature and existing databases. The project will generate an EU wide map of carbon storage capacity.

- Drivers of variability in Blue Carbon stocks and burial rates across European estuarine habitats – Mazarrasa et al., 2023 examined the variability of soil organic carbon storage and burial rates across different intertidal estuarine habitats along the Atlantic European coast, highlighting the influence of biotic and abiotic factors[29].

- Quantifying blue carbon stocks and the role of protected areas to conserve coastal wetlands –A study in Queensland, Australia by Costa et al., 2023, assessed sedimentary organic carbon stocks in mangroves, tidal marshes, and seagrasses using existing data and boosted regression tree models, providing spatially explicit blue carbon estimates[30].

Action 2.3	Establish a comprehensive GHG inventory system to monitor and report changes for coastal wetlands

[29] Mazarrasa, I., Neto, J. M., Bouma, T. J., Grandjean, T., Garcia-Orellana, J., Masqué, P., Recio, M., Serrano, Ó., Puente, A., & Juanes, J. A. (2023). Drivers of variability in Blue Carbon stocks and burial rates across European estuarine habitats. *Science of The Total Environment*, 163957. https://doi.org/10.1016/j.scitotenv.2023.163957

[30] Costa, M. D. P., Adame, M. F., Bryant, C. V., Hill, J., Kelleway, J. J., Lovelock, C. E., Ola, A., Rasheed, M. A., Salinas, C., Serrano, O., Waltham, N., York, P. H., Young, M., & Macreadie, P. (2023). Quantifying blue carbon stocks and the role of protected areas to conserve coastal wetlands. *Science of The Total Environment*, 865, 162518. https://doi.org/10.1016/j.scitotenv.2023.162518

2.3.1 Enhance coastal wetland monitoring to improve data integration into LULUCF accounting and ensure alignment with the 2013 IPCC Wetlands Supplement

Implementation timeline: Medium Term

A robust and standardised greenhouse gas (GHG) inventory system is essential for accurately tracking carbon emissions and removals from coastal wetland ecosystems across EU Member States. Currently, mangroves, tidal marshes, and seagrasses are often underrepresented or inconsistently accounted for in national GHG inventories, limiting their recognition in climate mitigation policies. Effective monitoring of coastal wetland ecosystems is essential for ensuring their accurate representation in Land Use, Land-Use Change, and Forestry (LULUCF) accounting and aligning with the 2013 IPCC Wetlands Supplement. Gaps in spatial data, inconsistent classification, and limited long-term carbon flux monitoring reduce the reliability of coastal wetland reporting in national greenhouse gas inventories. By enhancing monitoring efforts, EU Member States can generate robust, verifiable data on carbon sequestration, emissions, and removals, ensuring coastal wetlands are fully integrated into LULUCF and climate mitigation strategies.

Key actions:

- Establish EU-standard protocols for assessing changes in wetland extent and land-use transition, integrating remote sensing, field surveys, and geospatial data analysis. Ensure alignment with IPCC 2013 Wetlands Supplement and LULUCF Regulation.
- Assist Member States in transitioning from default (Tier 1) IPCC emission factors to more accurate, site-specific (Tier 2) or measured (Tier 3) data to improve data accuracy and policy impact (linked to Action 2.1.2).
- Expand existing platforms (e.g., EMODnet, Copernicus, and Euro Blue Carbon Database) to integrate wetland monitoring data into a single, interoperable system across all EU member states.

2.3.2 Align coastal wetland reporting with UNFCCC and NDC requirements

Implementation timeline: Medium Term

Ensuring coastal wetland monitoring aligns with UNFCCC reporting frameworks and Nationally Determined Contributions (NDCs) will improve transparency, accountability, and policy coherence across EU Member States. Many countries currently lack standardized procedures for reporting blue carbon stocks, emissions, and removals, limiting the effectiveness of blue carbon in climate mitigation strategies. Strengthening technical capacity and improving data consistency will enhance the integration of blue carbon into National Greenhouse Gas Inventories (NGGIs) and UNFCCC reporting mechanisms.

Key actions:

- Develop an EU standardised and centralised reporting framework, aligned with UNFCCC and NDC reporting requirements.
- Ensure BCE data is fully integrated into Biennial Transparency Reports (BTRs) submitted to the UNFCCC.
- Support Member States in incorporating blue carbon into NDCs, enhancing recognition of coastal wetlands as nature-based climate solutions.
- Provide training and technical support for national environmental agencies and stakeholders undertaking reporting for NGGI and NDCs

Relevant reports:

- Coastal Wetlands in National Greenhouse Gas Inventories Report provides advice on reporting emissions and removal from management of coastal wetland ecosystems[31].
- Blue Carbon and NDCs Guidelines: Second Edition provides guidance on how countries can incorporate blue carbon into their Nationally Determined Contributions (NDCs). It introduces a "tiered approach," similar to the IPCC framework, outlining multiple pathways for integrating coastal blue carbon ecosystems based on different national priorities and starting points[32].

Action 2.4 Strengthen blue carbon monitoring to support integration into carbon markets

[31] Green, C., Lovelock, C. E., Sasmito, S., Hagger, V., & Crooks, S. (2021). *Coastal wetlands in national greenhouse gas inventories: Advice on reporting emissions and removal from management of blue carbon ecosystems* (Revision 2). International Partnership for Blue Carbon. https://bluecarbonpartnership.org/wp-content/uploads/2021/11/Coastal-Wetlands-in-National-Greenhouse-Gas-Inventories.pdf

[32] Hamilton, J., Kasprzyk, K., Cifuentes-Jara, M., Granziera, B., Gil, L., Wolf, S., Starling, G., Zimmer, A., & Hickey, T. (2023). *Blue carbon and nationally determined contributions: Guidelines on enhanced action* (2nd ed.). Conservation International, The Nature Conservancy, NDC Partnership, MCC Sustainable Futures, The Pew Charitable Trusts. https://www.thebluecarboninitiative.org/policy-guidance

2.4.1 Align monitoring approaches with voluntary carbon market standards or an EU-wide blue carbon credit standards

Implementation timeline: Medium Term

Establishing robust monitoring, reporting, and verification (MRV) approaches is critical to ensuring the credibility, transparency, and marketability of blue carbon credits. Standardising MRV methods will enable project developers to generate high-integrity carbon credits that align with internationally recognised voluntary carbon schemes such as Verra, Gold Standard, and Plan Vivo. This alignment will enhance investor confidence, streamline project validation, and support the long-term integration of blue carbon projects into carbon markets. Additionally, assessing the need for an EU-wide blue carbon credit standard could provide a standardised framework for crediting and ensure alignment with EU climate policies, including the Carbon Removals and Carbon Farming Regulation (CRCF), the EU Biodiversity Strategy 2030, and the EU Sustainable Finance Taxonomy. A common standard would facilitate cross-border project comparability, enhance market confidence, and improve access to carbon finance for coastal wetland restoration and conservation efforts across Europe.

Key actions:

- Align monitoring approaches for blue carbon restoration projects with internationally recognised voluntary carbon schemes (e.g., Verra, Gold Standard, Plan Vivo).
- Assess the feasibility of an EU-wide blue carbon credit standard that covers multiple project activities and explore the integration of model-based approaches for estimating carbon sequestration.
- Utilise remote sensing, drone-based techniques, and AI-driven monitoring tools where appropriate to verify and track carbon storage and fluxes in blue carbon projects.

Relevant resources:

- Manual for the Creation of Blue Carbon Projects in Europe and the Mediterranean provides guidance on using carbon finance mechanisms to support blue carbon restoration and conservation in Europe and the Mediterranean, offering methodologies for project-based interventions, carbon stock quantification, and integration into national greenhouse gas inventories[33].

[33] IUCN (2021). Manual for the creation of Blue Carbon projects in Europe and the Mediterranean. Otero, M. (Ed)., 144 pages.

- Verra VM0033 Methodology for Tidal Wetland and Seagrass Restoration, v2.1 outlines procedures to quantify net greenhouse gas emission reductions and removals resulting from project activities implemented to restore tidal wetlands. Such activities include creating and/or managing the conditions required for healthy, sustainable wetland ecosystems[24].

- Gold Standard's Blue Carbon and Freshwater wetlands activity requirements provides a framework for certifying climate benefits from wetland restoration and conservation projects, ensuring robust measurement, reporting, and verification[34].

- New Mangrove Methodology featuring Remote-sensing - Gold Standard has introduced its first methodology for mangrove projects, incorporating innovative remote-sensing techniques for measurement and impact assessment.

- Modeled approaches to estimating blue carbon accumulation with mangrove restoration to support a blue carbon accounting method for Australia – Lovelock et al., 2022 developed a strategy for estimating organic carbon accumulation in biomass and soils during mangrove restoration in Australia by assessing global carbon accumulation data, modeling biomass growth using regional chronosequence studies, and stratifying soil carbon estimates by site elevation to support the development of a blue carbon method under Australia's ACCU Scheme[35].

Action 2.5	Quantify and monitor the ecosystem services provided by coastal wetlands

2.5.1 Standardise methods and indicators for ecosystem services quantification and monitoring

Implementation timeline: Medium Term

[34] Gold Standard Foundation. (2024). *Blue Carbon and Freshwater Wetlands Activity Requirements* (Version 1.0). https://globalgoals.goldstandard.org/204-ar-bcfw-blue-carbon-and-freshwater-wetlands-activity-requirements/

[35] Lovelock, C. E., Adame, M. F., Butler, D. W., Kelleway, J. J., Dittmann, S., Fest, B., King, K. J., Macreadie, P. I., Mitchell, K., Newnham, M., Ola, A., Owers, C. J., & Welti, N. (2022). Modeled approaches to estimating blue carbon accumulation with mangrove restoration to support a blue carbon accounting method for Australia. *Limnology and Oceanography*, 67(S2), S50–S60. https://doi.org/10.1002/lno.12014

Establishing a framework for assessing the ecosystem services of coastal wetlands is critical for ensuring consistent and comparable data collection across EU Member States. Currently, variations in monitoring approaches, data quality, and reporting standards hinder the ability to systematically evaluate the full range of ecosystem services provided by coastal wetland ecosystems. In addition to carbon sequestration and storage, coastal wetlands offer biodiversity support, water purification, coastal protection, flood mitigation, fisheries enhancement, and sediment stabilisation. Accurately quantifying these services is essential for informing conservation policies, integrating ecosystem services into environmental markets, and strengthening climate adaptation strategies. The recently announced 'nature credits' in the EU[36] could provide an opportunity to capitalise on the ecosystem services provided by blue carbon ecosystems beyond carbon, facilitating the financing of conservation and restoration actions.

Key actions:

- Develop standardised indicators and assessment protocols to establish consistent metrics, data collection techniques, and reporting formats to ensure comparability across EU Member States.
- Align protocols with existing EU and international frameworks, such as the EU Biodiversity Strategy 2030, Nature Restoration Law, European Green Deal, Marine Strategy Framework Directive (MSFD), The Kunming-Montreal Global Biodiversity Framework (GBF).
- Provide technical guidance and capacity-building programs for practitioners on ecosystem service quantification methodologies.

Example programs:

- OBAMA-NEXT aims to strengthen Europe's ability to monitor biodiversity and habitats by developing a toolbox for generating accurate, precise and relevant information characterising marine ecosystems and their biodiversity.
- A guide to measuring and accounting for the benefits of restoring blue carbon ecosystems – A guide to measure an account for the benefits of restoring blue carbon ecosystems in Australia[37].

[36] European Commission. (2024). President von der Leyen at the DLD Conference. *Press corner*. https://ec.europa.eu/commission/presscorner/detail/en/ac_24_4704

[37] Carnell, P., Whiteoak, K., Raoult, V., Vardon, M., Adame, M. F., Burton, M., Connolly, R. M., Glamore, W., Harrison, A., Kelleway, J., Lovelock, C. E., Nicholson, E., Nursey-Bray, M., Hill, C., Wootton, N., Mundraby, D., Mundraby, D., Owers, C. J., Pocklington, J. B., Rogers, A., Estifanos, T., Taye, F., Rogers, K., Taylor, M. D., Asbridge, E., Hewitt, D. E., & Macreadie, P. I. (2023). *A guide to measuring and accounting for the benefits of restoring coastal blue carbon ecosystems* (Version 1). Department of Climate Change, Energy, the Environment and Water.

- Biodiversity of the Coastal Ocean: Monitoring with Earth Observation (BiCOME) project develops innovative tools and methodologies to enhance the monitoring, assessment, and conservation of biodiversity and ecosystem services across terrestrial, freshwater, and marine environments, utilising remote sensing technologies to improve data collection and ecosystem mapping.

2.5.2 Integrate ecosystem services monitoring into nature markets

Implementation timeline: Medium Term

Quantifying and monetising the ecosystem services of coastal wetlands can unlock new financing mechanisms for conservation and restoration efforts. By developing robust quantification methods, ecosystem service benefits—such as biodiversity conservation, coastal resilience, and water quality improvements—can be assigned economic value and included in biodiversity and nature credit markets. These markets offer financial incentives for maintaining healthy wetlands, complementing the carbon crediting mechanisms already in place for blue carbon projects.

Key actions:

- Develop nature credits that recognise biodiversity conservation, coastal resilience, and water quality improvements for coastal wetland ecosystems.

- Assess whether nature credits are better suited for compliance or voluntary markets.

- Facilitate the incorporation of ecosystem service data into EU-wide geospatial platforms and environmental monitoring initiatives.

Key reports:

- Climate Biodiversity Nexus project, funded by the EU, explores how voluntary carbon markets can support biodiversity conservation by implementing biodiversity-linked carbon credit requirements. It also examines the development of standalone biodiversity credits, focusing on market demand and the policies needed to expand and enhance their quality.

- Building towards Nature Markets for the European Union- This paper outlines the case for establishing a common, EU-wide framework to enable the development of credible, effective, and regulated Nature Markets in Europe[38].

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https://www.dcceew.gov.au/sites/default/files/documents/eea-guide-accounting-benefits-coastal-restoration_1.pdf

[38] Aronson, J., Lee, S., Celik, A., Krolopp, A., & Yafai-Stroband, N. (2024). *Building towards nature markets for the European Union: A case for an EU-wide certification framework*. The Nature

Conservancy.
https://www.nature.org/content/dam/tnc/nature/en/documents/TNC_Report_BiDi_Markets.pdf

Objective 3: Strengthen collaboration and support improved data accessibility and integration for decision-making

Effective blue carbon monitoring requires not only robust data collection but also seamless collaboration and data sharing among EU Member States. By enhancing cooperation and centralising information, this objective seeks to ensure that policymakers, researchers, and stakeholders can access high-quality, harmonised data to inform decision-making. This will help align monitoring efforts with EU climate, biodiversity, and conservation goals while facilitating timely interventions and effective management of coastal wetland ecosystems.

By strengthening collaboration (Action 3.1), centralizing data (Action 3.2), and developing decision-support tools (Action 3.3), Member States can ensure blue carbon data is effectively used to inform climate policies and conservation strategies (Action 3.4). Promoting open data policies and public awareness (Action 3.5) will further enhance engagement, transparency, and the integration of local knowledge into blue carbon monitoring.

Action 3.1	Foster collaboration among EU Member States and outermost regions to share best practices, tools, and data for coastal wetland mapping and monitoring
Action 3.2	Build a centralised EU-level database for the storage and sharing of coastal wetland mapping, carbon, and monitoring data across EU Member States
Action 3.3	Develop tools and guidance for policymakers to incorporate monitoring results into decision-making processes
Action 3.4	Integrate coastal wetland ecosystem monitoring with national climate, biodiversity, and conservation strategies to inform long-term management goals
Action 3.5	Raise awareness of coastal wetlands' role in climate action and encourage community involvement in their monitoring and conservation

Action 3.1	Foster collaboration among EU Member States and outermost regions to share best practices, tools, and data for coastal wetland mapping and monitoring

3.1.1 Establish a collaborative EU Blue Carbon Network for knowledge exchange

Implementation timeline: Short Term

Establishing a collaborative EU Blue Carbon Network- with representation from the 27 Member States with coastal wetlands and key stakeholders from academia, industry, government and policy sectors- would enhance coordination, knowledge exchange and capacity building in blue carbon monitoring, conservation, and policy integration. This network would serve as a central platform for sharing best practices, advancing research, and driving innovation in monitoring technology, ensuring a harmonised and science-driven approach to blue carbon across the EU.

Key actions:

- Coordinate regular meetings, workshops, newsletters, and conferences, to support collaboration on data harmonisation, policy alignment, and funding opportunities.
- Facilitate cross-border cooperation to strengthen standardised monitoring efforts and integrate blue carbon data into EU climate strategies.
- Establish exchange programs with international blue carbon initiatives to enhance monitoring, standardise methodologies, and provide training on best practices while avoiding common pitfalls.

Existing initiatives to build upon:

- The European Regional Hub for Blue Carbon (Euro-BC), embedded within the Global Ocean-Blue Carbon (GO-BC) initiative, connects European stakeholders with global blue carbon efforts, fostering collaborative research and policy development. This hub already engages with international collaborators and partners with the International Partnership for Blue Carbon.
- The JPI Oceans Joint Action on Blue Carbon functions as a knowledge hub, bringing together researchers, policymakers, and stakeholders to enhance spatial knowledge of blue carbon ecosystems. This initiative

supports carbon removal actions and ensures blue carbon's integration into EU and international climate strategies.

3.1.2 Encourage collaborative research projects between Member States to address shared challenges in blue carbon mapping and monitoring

Implementation timeline: Medium Term

Collaboration between EU Member States is essential for advancing blue carbon mapping and monitoring, ensuring that efforts are efficient, standardized, and mutually reinforcing. Given the transboundary nature of many coastal wetlands, joint research initiatives can improve data harmonization, technology sharing, and policy alignment while avoiding duplication of efforts. Collaborative projects should focus on addressing knowledge gaps, developing innovative monitoring techniques, and enhancing the integration of blue carbon data into climate reporting frameworks.

Key actions:

- Develop a database of past and current coastal wetland funded projects with key objectives, key outcomes, key contacts, funding body, and links to any data available.
- Ensure projects complement existing research and avoid duplication.
- Develop a collaborative scientific paper[39] outlining scientists' perspectives on the 10 key research areas in blue carbon monitoring and mapping that are currently unaddressed in the EU, identifying research priorities to improve data accuracy, standardization, and policy integration.
- Identify and leverage EU funding mechanisms, such as Horizon and LIFE Programme, to support collaborative blue carbon initiatives.
- Encourage co-financing agreements between Member States for large-scale mapping and monitoring programs.

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[39] Macreadie, P. I., Anton, A., Raven, J. A., Beaumont, N., Connolly, R. M., Friess, D. A., Kelleway, J. J., Kennedy, H., Kuwae, T., Lavery, P. S., Lovelock, C. E., Smale, D. A., Apostolaki, E. T., Atwood, T. B., Baldock, J., Bianchi, T. S., Chmura, G. L., Eyre, B. D., Fourqurean, J. W., Hall-Spencer, J. M., Huxham, M., Hendriks, I. E., Krause-Jensen, D., Laffoley, D., Luisetti, T., Marbà, N., Masque, P., McGlathery, K. J., Megonigal, J. P., Murdiyarso, D., Russell, B. D., Santos, R., Serrano, O., Silliman, B. R., Watanabe, K., & Duarte, C. M. (2019). The future of Blue Carbon science. *Nature Communications*, 10, 3998. https://doi.org/10.1038/s41467-019-11693-w

Existing initiatives:

- C-BLUES is a Horizon Europe project under the Joint EU-China Flagship Initiative on Climate Change & Biodiversity, aiming to enhance knowledge of coastal wetland ecosystems, including natural and farmed kelp systems. It seeks to improve the inclusion of coastal wetlands in national greenhouse gas inventories and UNFCCC reporting, advancing research, monitoring, and policy integration for blue carbon.

- WET HORIZONS project, funded by the European Union's Horizon Europe Programme, aims to develop innovative solutions for wetland restoration and climate resilience. By integrating advanced hydrological modeling, remote sensing, and stakeholder engagement, the project enhances understanding of wetland ecosystem functions, supports EU climate and biodiversity policies, and provides decision-making tools for sustainable wetland management.

- Wetland4Change – is an Interreg Euro-MED project focused on enhancing the resilience of Mediterranean wetlands to climate change. It aims to improve monitoring, management, and policy frameworks by integrating climate adaptation strategies, fostering transnational cooperation, and promoting nature-based solutions to protect wetland biodiversity and ecosystem services.

- OBAMA NEXT project funded by the European Union's Horizon Europe Programme, aims to develop advanced tools for assessing and monitoring marine biodiversity, ecosystem health, and blue carbon stocks to support EU environmental policies. By integrating Earth Observation data, AI, and in-situ monitoring, the project enhances marine ecosystem assessments and facilitates decision-making for conservation, climate mitigation, and sustainable management.

- MPA Europe is a project funded by the European Union's Horizon Europe Programme, aimed at strengthening the role of Marine Protected Areas (MPAs) in biodiversity conservation and climate change mitigation. It focuses on improving MPA management, governance, and monitoring, integrating blue carbon ecosystems into climate policies, and enhancing collaboration across European MPAs to safeguard marine biodiversity and ecosystem services.

Action 3.2	Build a centralised EU-level database for the storage and sharing of coastal wetland mapping, carbon, and monitoring data across EU Member States

3.2.1 Build national and EU-level databases to centralise blue carbon monitoring data for ease of access and analysis

Implementation timeline: Medium Term

Building national and EU-level databases for blue carbon monitoring is essential for centralising data, improving accessibility, and supporting cross-border collaboration on coastal wetland conservation and climate mitigation. A well-integrated database system will streamline data collection, analysis, and reporting, ensuring that habitat distribution maps and changes in extent, carbon stock assessments, greenhouse gas emissions, and carbon sequestration rates are easily accessible for scientists, policymakers, and conservation practitioners.

Key actions:

- Assess existing national and EU-level platforms detailing the strengths and weaknesses of current data platforms, and recommendations for integration or expansion to centralise blue carbon monitoring data.

- Establish standardised data formats, classification systems, and metadata requirements for blue carbon data to ensure consistency and comparability across EU Member States.

- Develop a centralised digital repository (blue carbon data hub) that consolidates habitat distribution maps, carbon stock assessments, GHG emissions, and carbon sequestration rates. This hub should be accessible to all stakeholders, including scientists, policymakers, and conservation practitioners.

- Ensure the database is interoperable with other major EU environmental databases (e.g., CORINE, Natura 2000) and supports cross-border data sharing. Develop APIs (Application Programming Interfaces) to facilitate data exchange between databases at the national and EU levels.

- Develop and integrate advanced data visualisation tools within the database to allow users to easily analyse and interpret blue carbon data. These tools should support the generation of custom reports, trend analysis, and geographic visualisations.

Existing data platforms to integrate:

- Blue Cloud – A collaborative project advancing FAIR and open data in marine research by integrating platforms like Copernicus and EMODnet. Over 42 months, it will expand data access, analytical tools, and computing services, supporting the EU Blue Economy, Green Deal, and UN Sustainable Development Goals. Coordinated by CNR, Trust-IT

Services, and MARIS, it unites 40 partners across 13 EU countries to enhance marine environmental observation and data integration.

- Coastal Carbon Atlas – part of the Coastal Carbon Network, is a centralised platform for accessing and analyzing coastal wetland carbon data. It provides curated public datasets, standardized using open-source R scripts, and interactive map tools.

- MPA Europe Project Work Package 4: Euro Blue Carbon Database – Database aggregating organic carbon stocks in marine sediments. An associated data paper is currently in development.

- The European Marine Observation and Data Network (EMODnet) – A marine data repository that could incorporate standardised blue carbon datasets. EMODnet aggregates data into Findable, Accessible, Interoperable, and Reusable (FAIR) pan-European data layers, with data and accompanying metadata harmonised according to EU e.g., INSPIRE and International e.g., ISO standards.

- CORINE Land Cover – an EU-wide land monitoring program under Copernicus, providing standardised, high-resolution datasets on land use and land cover changes, which can support blue carbon ecosystem mapping and integration into climate policies.

3.2.2 Encourage open data policies

Implementation timeline: Medium Term

Ensuring open access to blue carbon data will enhance transparency, collaboration, and data accessibility across EU Member States, supporting scientific research, policy development, and ecosystem management.

Key actions:

- Require publicly funded blue carbon research to be openly available and ensuring data is uploaded upon completion of project.

- Implement Findable, Accessible, Interoperable, Reusable (FAIR) data principles.

- Facilitate real-time data sharing through a centeralised EU-level database (Action 3.2.1).

Key resources:

- FAIR data principles

Action 3.3	Develop tools and guidance for policymakers to incorporate monitoring results into decision-making processes

3.3.1 Create user-friendly decision support tools for mapping and monitoring data

Implementation timeline: Medium Term

Developing user-friendly decision support tools is essential for improving blue carbon monitoring and mapping, enabling policymakers to visualise wetland extent, carbon sequestration, and ecosystem condition. Interactive dashboards, scenario models, and prioritisation frameworks can enhance spatial data accessibility, track ecosystem changes over time, and support conservation and restoration planning.

Key actions:

- Assess gaps in existing decision support tools through a structured review to determine unmet needs, improve tool functionality, and guide future development to address policy and conservation priorities.
- Develop interactive dashboards and data visualisation platforms to map and monitor key ecosystems indicators to enhance data accessibility for policymakers, conservation practitioners, and carbon market stakeholders, integrating real-time blue carbon monitoring, habitat condition, and restoration progress.
- Refine scenario modelling tools to simulate future trends in coastal wetland ecosystems under different climate change, land-use, and policy scenarios, supporting strategic planning and adaptive management.
- Create spatial prioritisation frameworks that identify optimal restoration and conservation sites by integrating carbon sequestration potential, biodiversity benefits, socio-economic factors, and coastal resilience.
- Improve interoperability with existing EU data platforms (e.g., EMODnet, Copernicus, Euro Blue Carbon Database) to standardise reporting, enhance cross-border collaboration, and support compliance with EU policies.

Example decision support tools:

- Interactive Dashboards – Global Mangrove Watch provides real-time mapping of mangrove extent and carbon stocks.

- Ocean Ledger a unique geospatial accounting platform to quantify blue carbon and biodiversity using satellite imagery analysis, open reference data and AI models

- Scenario Models –The Nature Conservancy's Coastal Resilience Tool, used for wetland adaptation planning.

- Prioritisation Tools – InVEST, software models used to map and value the good and services from nature.

3.3.2 Foster collaboration between scientist and policymakers

Implementation timeline: Ongoing

Strengthening collaboration between scientists and policymakers is essential for ensuring that blue carbon monitoring data directly informs decision-making, climate policy, and conservation strategies. Regular science-policy forums, interactive workshops, and targeted training sessions can bridge the gap between research and implementation, enabling policymakers to better interpret monitoring results, carbon stock assessments, and restoration impacts.

Key actions:

- Establish annual science-policy forums where researchers present blue carbon monitoring data and policy implications.

- Develop policy briefings and decision-support tools to translate complex scientific data into actionable insights.

- Facilitate cross-sector collaboration to align monitoring methodologies with EU climate policies, biodiversity strategies, and carbon markets.

Existing initiatives:

- Science-Policy Forum: Biodiversa+ held a science-policy forum that brought together scientists and policymakers to discuss current biodiversity monitoring challenges and align research efforts with policy needs.

- European Marine Board (EMB) facilitates science-policy dialogues by organising forums and producing policy briefs on marine issues, including blue carbon. These initiatives aim to bridge the gap between scientific research and policy development, ensuring that marine science effectively informs decision-making processes.

Action 3.4	Integrate coastal wetland ecosystem monitoring with national climate, biodiversity, and conservation strategies to inform long-term management goals

3.4.1 Integrate data into policy frameworks including land-use planning climate adaptation strategies and marine spatial planning

Implementation timeline: Long-term

Integrating coastal wetland monitoring data into land-use planning, climate adaptation strategies, and marine spatial planning is essential for ensuring evidence-based decision-making and enhancing long-term ecosystem resilience. By incorporating spatially explicit blue carbon and wetland health data into policy frameworks, Member States can prioritise conservation and restoration efforts, optimise coastal zone management, and strengthen the role of nature-based solutions in climate adaptation.

Key actions:

- Recognise mangroves, tidal marshes, and seagrasses as critical marine habitats within national and regional marine spatial planning (MSP) frameworks.
- Use monitoring data on wetland extent, condition, and carbon sequestration potential to designate high-priority conservation and restoration zones in MSP.
- Align wetland protection efforts with coastal development policies, ensuring sustainable land-use decisions that minimise habitat degradation.

3.4.2 Align coastal wetland monitoring with national climate plans and EU directives

Implementation timeline: Medium-term

To strengthen policy coherence and environmental accountability, coastal wetland monitoring must align with national climate action plans and key EU directives. Monitoring data should directly inform progress tracking, target setting, and policy implementation within these frameworks.

Key actions:

- Conduct a comprehensive review to identify all relevant EU and national plans, strategies, and directives related to coastal wetlands. Convert results into an interactive Blue Carbon Enabling Policy Conditions map.
- Ensure coastal wetland mapping and monitoring programs supports EU climate and biodiversity targets.
- Harmonise blue carbon data reporting with the LULUCF Regulation, UNFCCC, and NDCs (Actions 2.3.1 and 2.3.2)

Relevant policies and strategies:

- EU Biodiversity Strategy 2030 aims to protect 30% of the EU's land and sea area and restore ecosystem integrity. Relevance: Coastal wetland monitoring can track ecosystem health and habitat loss, ensuring wetlands contribute to biodiversity protection goals[40].
- Marine Strategy Framework Directive (MSFD) requires Member States to achieve Good Environmental Status (GES) of marine environments. Relevance: Monitoring coastal wetland extent, condition, and carbon sequestration supports MSFD Descriptors 1 (Biodiversity), 6 (Seafloor Integrity), and 8 (Contaminants)[41].
- Marine Spatial Planning Directive (MSP Directive) ensures sustainable use of marine resources by integrating environmental, economic, and social considerations[42]. Relevance: Coastal wetland monitoring can help identify priority areas for protection, restoration, and carbon crediting initiatives.
- European Green Deal is the EU's overarching strategy for climate neutrality by 2050, promoting nature-based solutions and stronger biodiversity protections[43]. Relevance: Coastal wetland monitoring

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[40] European Commission. (2020). *EU Biodiversity Strategy for 2030: Bringing nature back into our lives*. Publications Office of the European Union. https://environment.ec.europa.eu/strategy/biodiversity-strategy-2030_en

[41] European Parliament and Council. (2008). *Directive 2008/56/EC of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive)*. Official Journal of the European Union, L 164, 19–40. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32008L0056

[42] European Commission. (n.d.). *Maritime spatial planning*. https://oceans-and-fisheries.ec.europa.eu/ocean/blue-economy/maritime-spatial-planning_en

[43] European Commission. (n.d.). *The European Green Deal*. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

contributes to carbon neutrality goals, ecosystem resilience, and biodiversity restoration, supporting Green Deal objectives in climate action, land use, and marine protection.

3.4.3 Recommend a policy framework for rolling project boundaries, accommodating ecosystem migration due to sea level rise

Implementation timeline: Long-term

As climate change drives sea-level rise and shifting coastal conditions, many coastal wetland ecosystems will experience natural migration or inland retreat. Current conservation and restoration frameworks often do not account for these dynamic shifts, limiting long-term protection. A rolling boundary policy framework would allow for adaptive conservation planning, ensuring wetlands remain protected and continue providing climate mitigation and adaptation benefits despite spatial changes.

Key actions:

- Establish rolling conservation zones that adjust project boundaries based on long-term monitoring of wetland migration patterns.
- Integrate climate projection models into policy planning to anticipate future wetland shifts and incorporate adaptive management strategies.
- Ensure wetland restoration projects and carbon market methodologies allow for boundary adjustments over time, maintaining eligibility for conservation funding and carbon crediting.

Examples from other countries:

- Rolling covenants to protect coastal ecosystems in the face of sea-level rise – Bell-James et al., 2021 explore how rolling covenants, which adapt land use over time in response to sea-level rise, offer a legal mechanism to balance short-term land productivity with long-term coastal ecosystem migration, as demonstrated through legislative analysis and interviews in an Australian case study[44].

[44] Bell-James, J., Fitzsimons, J. A., Gillies, C. L., Shumway, N., & Lovelock, C. E. (2022). Rolling covenants to protect coastal ecosystems in the face of sea-level rise. *Conservation Science and Practice*, 4(1), e593. https://doi.org/10.1111/csp2.593

Action 3.5	Raise awareness of coastal wetlands' role in climate action and encourage community involvement in their monitoring and conservation

3.5.1 Develop training modules for local stakeholders and policymakers to implement monitoring protocols

Implementation timeline: Short to Medium-term

Ensuring consistent and high-quality monitoring practices requires capacity-building among local governments, conservation groups, and land managers. Training efforts should be linked to existing policy frameworks (Action 3.4) and decision-support tools (Action 3.3) to ensure that monitoring results inform conservation strategies.

Key actions:

- Deliver technical training (e.g., e-learning modules or in person workshops) to local relevant authorities on standardised monitoring methods (linked to Action 3.1 and 3.2), and how to integrate wetland monitoring into land-use planning and restoration efforts (Action 3.4).
- Provide policy-focused guidance for integrating monitoring data into decision-making (linked to Action 3.3 and 3.4)

Example training modules:

- Fair Carbon has developed the Blue Carbon Academy a structured e-learning program that guides participants through the fundamentals of blue carbon, project planning, governance, accreditation, and monitoring, with expert resources to support access to carbon markets for ecosystem restoration.

3.5.2 Promote citizen science initiatives to improve data collection and stakeholder awareness

Implementation timeline: Long-term

Engaging the public in coastal wetland monitoring through citizen science initiatives can significantly enhance data collection, increase awareness, and foster a sense of ownership among local communities.

Key actions:

- Develop user-friendly tools and mobile applications for citizen science participation.
- Encourage partnerships with schools, universities, NGOs, and coastal communities to organize hands-on field surveys, wetland restoration projects, and data collection campaigns.
- Leverage citizen-generated data to complement scientific datasets and improve spatial and temporal monitoring coverage of coastal wetland ecosystems.

Examples of citizen science initiatives:

- Restore4Life's Citizen Science program establishes local citizen scientist groups across European wetlands to monitor changes from restoration activities. Volunteers assess wetland species, monitor climate and water data, and utilise remote sensing tools like Copernicus and drones.
- Coastwatch Europe is an international network of environmental groups that monitors coastal and wetland environments across several European countries. Volunteers participate in annual surveys assessing coastal litter and pollution, contributing to environmental policy improvements and public awareness.
- More4nature is a European Union-funded project aimed at empowering citizens and communities to actively engage in environmental compliance through monitoring, reporting, and action.
- The #BlueCarbonArmy is an Australian-based citizen science initiative that engages corporate executives, community groups, Traditional Owners, and students in hands-on coastal wetland research to enhance climate literacy and promote sustainable practices. Participants swap business attire for gumboots, immersing themselves in activities like data collection and ecosystem monitoring.

3.5.3 Incorporate indigenous knowledge in monitoring frameworks

Implementation timeline: Medium to Long-term

Indigenous and Traditional Ecological Knowledge (TEK) offers centuries of expertise in wetland conservation and climate resilience strategies. Integrating Indigenous-led approaches into formal monitoring frameworks will improve data accuracy, support culturally appropriate conservation efforts, and foster long-term stewardship. These efforts should be linked to national climate strategies (Action 3.4) and policy engagement efforts (Action 3.3).

Key actions:

- Establishing co-management structures that enable Indigenous communities to contribute directly to wetland monitoring, restoration, and governance.
- Integrate traditional ecological indicators into blue carbon monitoring.

Examples:

- The Local Indicators of Climate Change Impacts (LICCI) project aim to incorporate Indigenous and local knowledge into climate change research, enhancing policy-making processes and international climate negotiations.
- Exchange for Local Observations and Knowledge of the Arctic (ELOKA) collaborates with Indigenous communities to document and share local observations of environmental changes, integrating traditional knowledge with scientific data to inform Arctic research and policy.

4. Conclusion

The **Blue Carbon Roadmap for EU Member States** offers a strategic and comprehensive approach to enhancing the management of coastal wetland ecosystems, such as seagrasses, tidal marshes, and mangroves, across the EU. By focusing on improved mapping, monitoring, and data integration, the roadmap provides the necessary framework to support the achievement of the EU's climate, biodiversity, and sustainability targets. The roadmap's phased approach ensures that each objective, from establishing baseline ecosystem data to integrating blue carbon into climate policies and carbon markets, is both actionable and scalable.

Through enhanced cooperation, standardisation of methodologies, and the application of advanced technologies, the roadmap addresses critical gaps in knowledge and monitoring capacity, empowering EU Member States to take effective action in managing coastal wetland ecosystems. It fosters long-term, evidence-based decision-making that can be integrated into national and EU-wide policy frameworks, supporting the restoration and conservation of vital coastal wetland ecosystems.

Ultimately, the successful implementation of this roadmap will not only contribute to the EU's environmental goals but also highlight the significant role that coastal wetlands can play in mitigating climate change, enhancing biodiversity, and supporting ecosystem services. By aligning scientific data with policy and market frameworks, the roadmap encourages coastal wetland ecosystems to be effectively managed and utilised for the benefit of both the environment and society.

5. Appendix

Table S1. Summary table of the spatial datasets included in this study for the spatial assessment of coastal and freshwater wetlands.

Layer (Source)	Original Format	Reference year	Scale/Region	Resolution	Sub-task	Tier
Source datasets						
High-resolution Global Mangrove Forests (Jia et al., 2023)	Polygon	2020	Global	10 m	2.1	1
Global Mangrove Watch (Bunting et al., 2022)	Polygon	1996, 2007-2010, 2015-2020	Global	25 m	2.1; 2.2	1
Global distribution of tidal marshes (Worthington et al., 2024)	Raster	2020	Global	10 m	2.1	1
Global Wetland Map (Zhang et al., 2023)	Raster	2020	Global	30 m	2.1	1
Global distribution of seagrasses (version 7.1; UNEP-WCMC, Short, 2021)	Vector	-	Global	-	2.1	3
Current distribution of *Zostera* seagrass meadows along the SW coast of the Black Sea, Bulgaria (Berov et al., 2022)	Vector	-	Bulgaria	-	2.1	1
Seagrass mapping in Greek territorial waters using Landsat-8 satellite images (Topouzelis et al., 2018)	Vector	-	Greece	-	2.1	1
Seagrass meadows region (Helsinki Commission, 2013)	Vector	-	Baltic Sea	-	2.1	3
Danish coastal submerged aquatic vegetation 2018 (DHI, 2024)	Raster	2018	Denmark	10 m	2.1	4
CORINE Land Cover (2020)	Raster	1990, 2000, 2006, 2012, 2018	Europe	100 m	2.2	1-2
de Los Santos et al. (2019)	csv	1860 to 2016	Europe	-	2.2	-

Layers used for comparison purposes

Global Mangrove Watch	Polygon	2020	Global	25 m	2.1	1
Extended wetland ecosystem layer (EEA, 2022)*	Raster	2018	Europe	100 m	2.1	2
Global Wetland Map (Zhang et al., 2023)	Raster	2020	Global	30 m	2.1	1
A modelled global distribution of the seagrass biome (Jayathilake & Costello, 2018)	Vector	-	Global	-	2.1	4
Global saltmarsh change, 2000-2019 (Campbell et al., 2022)	Raster	2000-2019	Global	30 m	2.2	1
High-resolution mapping of losses and gains of Earth's tidal wetlands (Murray et al., 2022)	Raster	1999-2019	Global	30 m	2.2	1

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