REWRITE

D2.1 - Selection and gap analysis report for each demonstrator, interim (carbon and biodiversity)

Project acronym: **REWRITE**

Project title: **Rewilding and Restoration of Intertidal Sediment Ecosystems for Carbon Sequestration, Climate Adaptation and Biodiversity Support**

Call: **HORIZON-CL-2022-D1-02-05**

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Author list

Name	Organisation
Vona Méléder	NANTESU
Koen Sabbe	UGent
Ana Sousa	UAveiro
Evangelia Drakou	HUA
Umberto Pernice	PER
Graham Underwood	UESSEX

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Executive Summary

This report presents a cross-Demonstrator synthesis of the foundational ecosystem functions of carbon sequestration and biodiversity within intertidal soft-sediment (ISS) seascapes, based on a pyramidal analytical approach involving all REWRITE Demonstrators (10 DMs). These two functions are central to the supply of multiple ecosystem services (ES), from climate regulation to food provision and cultural services.

Findings from the activities undertaken under task 2.1 "Establishing state-of-existing knowledge on intertidal coastal soft sediment seascapes" reveal that all project Demonstrators (DMs), despite their ecological and socio-political diversity, have a minimum knowledge (common background) on carbon sequestration and biodiversity, which is the necessary basis to emphasise the pivotal role of ISS in delivering nature-based solutions for climate adaptation and biodiversity conservation. However, the capacity to quantify and monitor these ES functions varies widely due to differences in data types, temporal coverage, spatial resolution, and disciplinary perspectives.

The analysis highlights:

- A strong reliance on *in situ* ecological data in some sites, while others depend more on remote sensing, modeling, or stakeholder knowledge.
- In few cases data are missing, and need to be acquired : missing data include mostly C origin (either allocthonous or autochtonous), sediment depth (1 m for Blue Carbon assement) and dating (for burial rate estimation); data sets for Biodiversity are almost complete, but gaps exist, mainly related to microbial groups (bacteria, microphytobenthos, meiobenthos) and metabarcoding.
- Gaps in harmonized protocols, long-term monitoring, and integration between biophysical and social data.

This synthesis underscores the need for a shared framework and coordinated strategies to better capture and support the multifunctionality of ISS seascapes. In this aim, several recommandations for WP3 and data collection efforts, but also for integrating this existing (and future) knowledge in strategies for stakeholder engagement are made. It advocates for transdisciplinary collaboration and long-term investment to unlock the full potential of these overlooked ecosystems in achieving EU biodiversity and climate targets.

Acronym	Description
BEF	Biodiversity–Ecosystem Functioning
C	Carbon
DCMI	Dublin Core Metadata Initiative
DM	Demonstrators
DwC	Darwin Core
DOC	Dissolved Organic Carbon
ES	Ecosystem Services
EU	European Union
FAIR	Findable, Accessible, Interoperable, Reusable
IPBES	Intergovernmental Science–Policy Platform on Biodiversity and Ecosystem Services
GIS	Geographical Information System
IPCC	Intergovernmental Panel on Climate Change
ISS	Intertidal Soft Sediment
MPB	Microphytobenthos
NbS	Nature-based Solution
POC	Particulate Organic Carbon
RBAC	Role-Based Access Control
TLS	Transport Layer Security
UK	United Kingdom
UN	United Nations
USA	United States of America
WP	Work Package

Contents

1 Introduction

The climate and biodiversity crisis are major global challenges of the 21st century. Without proper mitigation and adaptation, the consequences will be catastrophic for humanity and natural systems. We are already observing profound changes, including biodiversity loss, more frequent or extreme weather events, as well as sea level rise[1]. Within European coastal zones, intertidal areas consisting of soft sediment and emerging during each low tide, form seascapes (*i.e* spatially heterogeneous and dynamic marine spaces that can be delineated at a wide range of scales in time and space)[2], covering more than 10 000 km^2 along the 35 000 km of the tidal coastline. These habitats provide multiple ecosystem services (ES) with a great potential to cope with the biodiversity-climate crisis and thus to contribute to a number of UN and EU priorities[a] regarding carbon neutrality, climate resilience and biodiversity support[3,4]. Nevertheless, an alarming situation has emerged over recent years: these seascapes continue to disappear, to be fragmented and to be polluted, resulting in a decrease of their provision of goods and ES[5–7].

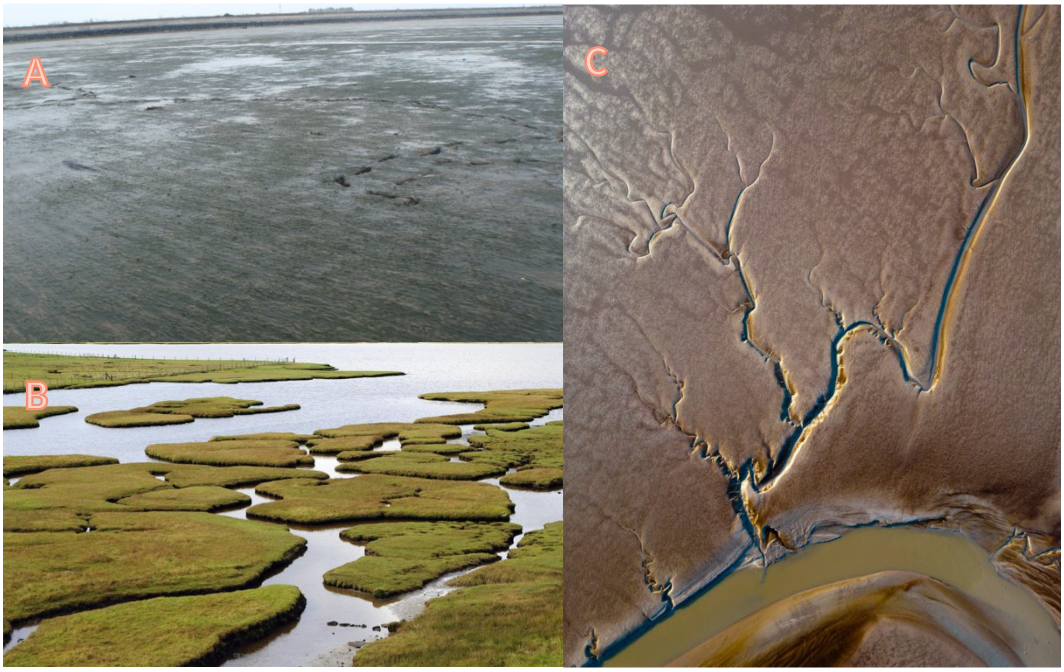

FIGURE 1. INTERTIDAL SOFT SEDIMENT SEASCAPES. A/ SEAGRASS MEADOWS; B/ SALTMARSHES; C/MUDFLATS DOMINATED BY MICROPHYTOBENTHOS.

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[a] e.g: EU Green Deal with the EU Biodiversity strategy for 2030 (https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en; https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/actions-being-taken-eu/EU-biodiversity-strategy-2030_en) - UN Sustainable Development Goals (13 to 15, but also 3, 6 and 17 SDGs: https://sdgs.un.org/goals) - UN Paris Agreements (https://unfccc.int/process-and-meetings/the-parisagreement/the-paris-agreement) - UN Decade of Ocean Science for Sustainable Development (https://en.unesco.org/ocean-decade) - UN Decade on Ecosystem restoration (https://www.decadeonrestoration.org/)

Within European coastal zones, seagrass meadows, saltmarshes and intertidal mudflats dominated by microphytobenthos[b] (MPB) (Figure 1), are three key habitats forming intertidal soft sediment (ISS) seascapes, playing critical roles in several ES and functions. They contribute to a safe coast by attenuating erosion and providing a natural buffer between the sea and land, the so-called 'accommodation space' – space available for dynamic coastal change as sea level rise and extreme events frequency increases[8–10]. They support socio-cultural activities as promoting health, recuperation or enjoyment, resonance in terms of culture or heritage[11,12]. Moreover, ISS seascapes support also high levels of biodiversity, providing niches for diverse set of taxa, from microorganisms[13,14], to shorebirds[15,16], fish and invertebrate nursery habitats[17,18], and biogenic habitat structures (*e.g* oyster and polychaete reefs, seagrass meadows, saltmarshes)[19–21]. Biodiversity contributes to ecosystem productivity and functions[3], supporting the wider metapopulations that underpin shallow water food webs[3], therefore playing a key role in the use of tidal areas (e.g. as nursery areas) by fish and other mobile species[15–18]. This productivity explains also their use by human society for aquaculture or cultural and recreational activities[12,22]. Supported by the three key habitats, i.e. seagrass meadows, saltmarshes and mudflats, this productivity plays significant roles in Carbon (C) sequestration and storage. Because vegetated mudflats (seagrasses and saltmarsh) and those dominated by MPB can sequester C from the atmosphere (CO_2 sequestration through photosynthesis) but also from internal and external riverine and oceanic sources (laterally imported C), ISS represent a C sink for a larger area and contribute to the C sequestration and storage (i.e. the Blue Carbon)[23].

But, at this point in our planet's history, ISS seascapes find themselves exposed to "a triple whammy"[3]: i) increasing fragmentation (e.g. industrialization and urbanization); ii) increasing loss of biological and physical resources (e.g. fish, water, energy, space); iii) and increasing warming climate and sea level rise. In the current situation, their contribution to UN and EU policies and priorities regarding carbon neutrality, climate resilience and biodiversity support is highly weakened.

In this context, Rewilding, a Nature-based Solution (NbS), is a new concept for seascapes to reverse this situation and to "let (again) Nature do the job" for a climate-resilient Europe[c] and to support a long-term prosperous, modern, competitive and climate-neutral economy[d]. Although rewilding practices were initially developed for terrestrial ecosystems, their implementation in marine and coastal environments has grown significantly over the past 10–15 years[24]. However, because coastal rewilding remains undefined in both academic research and official nature conservation frameworks, its understanding and implementation is still in its infancy[25]. But, an initial attempt to define coastal rewilding could be proposed as

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[b] microalgal and bacterial biofilms
[c] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52021DC0082&from=EN
[d] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52018DC0773&from=EN

the restoration of coastal ecosystems to their natural or wilder states, enabling natural processes to recover and thrive with minimal human intervention. This approach focuses on regenerating habitats such as saltmarshes, seagrass meadows, sand dunes, and tidal flats, which are essential for biodiversity support, climate resilience, and human well-being.

2 Objectives of REWRITE

The overall aim of REWRITE is to expand innovative approaches and nature-based solutions for rewilding intertidal soft sediment (ISS) seascapes, bridging environmental needs (carbon sequestration and storage, climate adaptation and biodiversity support) and societal expectations and uses. Within a network of ten demonstrators and 25 partners from the academic and private sector, representing eight EU tidal coastal member states, and as well as the UK, Canada and the USA, REWRITE will bring together for the first time in Europe, an interdisciplinary consortium constituted by internationally recognized experts in natural and coastal environment, in social sciences and humanities to rewild the European shores and ensure their climate resilience, biodiversity support and societal benefit.

To reach our main goal, three key challenges will be addressed:

- Reducing the uncertainty of the future trajectories of ISS seascapes. Due to a fragmented knowledge on their ecological and social functioning, the scientific community is currently unable to project accurately their trajectories by 2050. A deep understanding of the different restoration, rewilding and "do nothing" options, compared to a "business-as usual" option in the context of erratic and constant changes is urgently needed.
- Assessing the cascading effect. Understanding the propagation of the effect of the increase of CO_2, temperature, sea level rise, extreme weather events and the loss of biodiversity from the local to the global scale is a key factor to enhance local natural capital for a resilient European shoreline.
- Assessing how society engages to agree upon and / or overcome the trade-offs of rewilding, considering environmental benefits and societal pressures. Identifying the social, cultural and economic drivers and barriers is crucial to ensure local and national engagement and support, and place-based decisions responsive to local needs, particularly where space requirements for rewilding are a source of conflict.

To tackle these challenges, innovative actions of REWRITE will focus on the climate-biodiversity-society nexus, following the latest recommendations of the Intergovernmental Science–Policy Platform on Biodiversity and Ecosystem Services (IPBES) and the Intergovernmental Panel on Climate Change (IPCC)[26]. With the implementation of multi-actor co-designed scenarios as the core of our research program, we will exploit a collaborative and interdisciplinary multi-stakeholder approach for identifying possible ISS rewilding scenarios and the actions necessary to implement them. REWRITE will bridge natural and social sciences and humanities, engage varied categories of stakeholders, from both public and private sectors, aiming to take into account the complexity of these systems, including the specific local, regional and European constraints, to project the future of European rewilded ISS seascapes. To reach its goal, REWRITE will address the four specific objectives (SO) (Table 1), within the three WP-specific research/innovation and engagement activities (Figure 2).

TABLE 1. THE 4 SPECIFIC OBJECTIVES (SO) OF REWRITE

Strategic Objectives description	Related WP
SO1: Analyse the changes in ISS functioning within their past and current trajectories to identify environmental, social and cultural drivers or barrier parameters for the implementation of rewilding approaches in the context of climate change (i.e. increase of CO_2, temperature, sea level rise, extreme events and loss of biodiversity).	WP2, 3 and 4
SO2: Strongly engage stakeholders to achieve a step-change in their appreciation of the natural coastal function of ISS seascapes and integrate their interests within a collective learning, co-construction, and dissemination of knowledge framework.	WP4
SO3: Estimate and upscale trajectories of ISS seascape changes from the local to the European shoreline, within the context of climate change following rewilding, restoring, "business as usual" or "do nothing" options.	WP3 & 4
SO4: Establish protocols (i.e. tools and methods) for successful ISS seascape rewilding to ensure a high ecological and societal co-benefit / low-cost ratio.	WP2 & 4

All REWRITE tasks within the three WP-specific research/innovation and engagement activities converge for a collective learning, co-construction, and dissemination of knowledge about ISS seascapes, to produce desirable scenarios; and conversely, the analysis of each projected rewilding ecological trajectory within our demonstrator network, feeds back to the project objectives (Figure 2). Through the duration of the project, stakeholders will be engaged (SO2) with REWRITE partners, to integrate their expectations, needs and requirements and ensure the replicability of the REWRITE's outcomes. Stakeholder's engagement will consider the key role of social innovation for understanding how rewilding can address societal challenges and how social acceptance can be secured. A plan for engaging stakeholder will foresee the adoption of several tools to ensure inclusive participation, and in particular the powerful living laboratory methodology of Multi-Actor Laboratories (MALs). Stakeholder's engagement will therefore contribute to the analysis of changes (SO1) through which environmental, social, cultural and economic parameters and factors driving changes within ISS seascapes will be identified using existing databases and new acquisitions. To capture the "big picture" of the ISS seascapes changes (SO3), our understanding will be conducted at the European scale and beyond, and projected by 2050 using remote sensing, numerical modelling and 3D digital visualisation. To lead an efficient and robust cross-comparison between demonstrators (DM), we will develop protocols to cover gaps of knowledge and bring natural and social sciences to develop key performance indicators to assess costs and benefits for nature and society through the prism of plural and integrated valuation approaches (SO4).

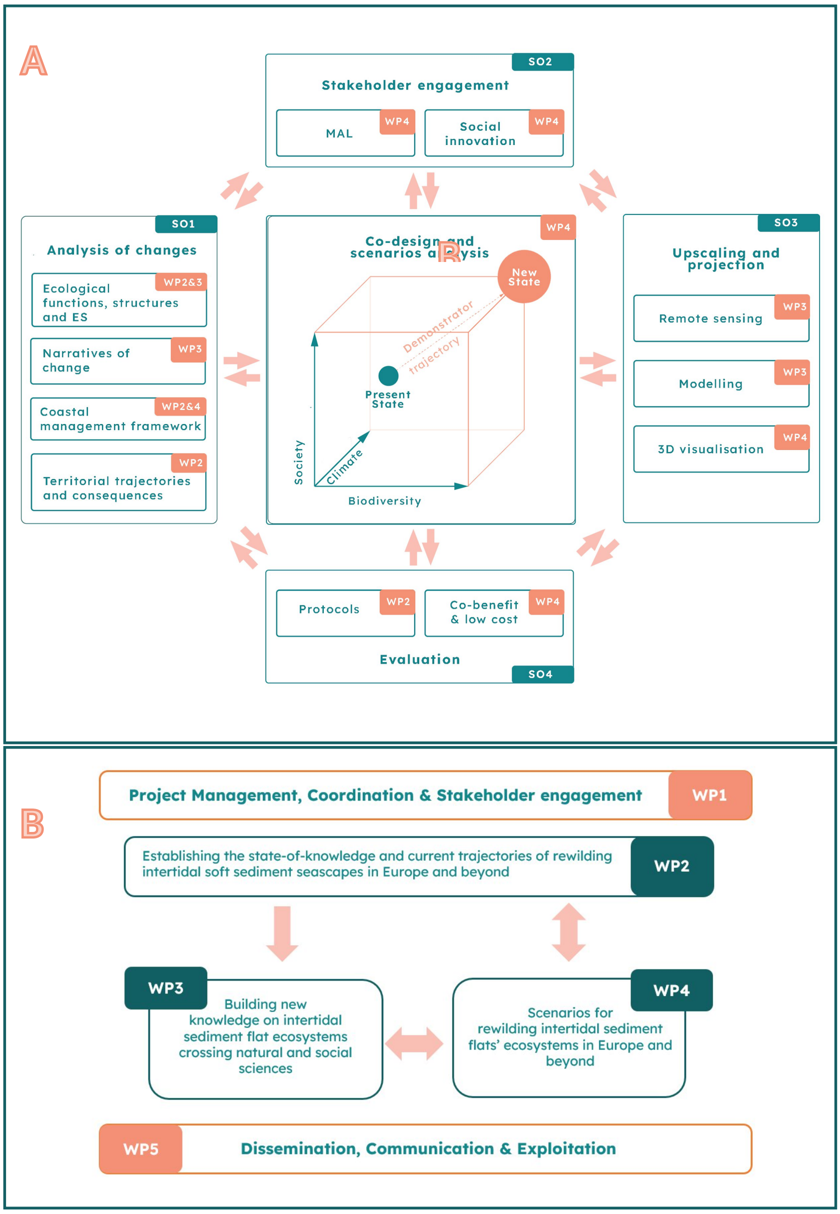


FIGURE 2. REWRITE OVERALL CONCEPT (A), WITH THE CO-DESIGN AND SCENARIOS ANALYSIS AS THE CORE OF THE PROJECT. REWRITE ACTIONS ARE LINKED TO EACH SPECIFIC OBJECTIVE (SO1 TO SO4, TABLE 1) AND WILL BE IMPLEMENTED WITHIN WORKPACKAGES (WP2 TO WP4, B).

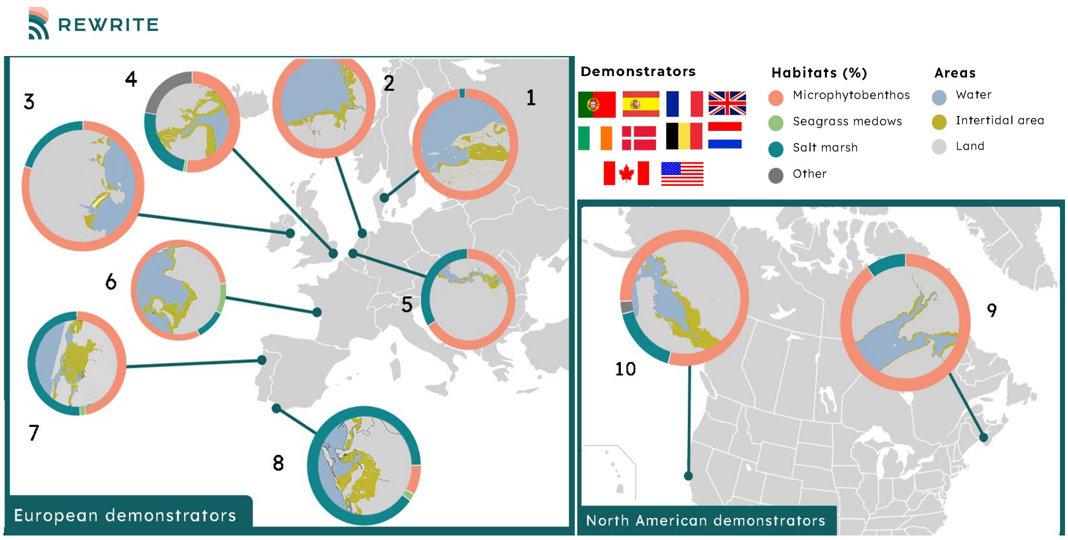


FIGURE 3. DEMONSTRATOR NETWORK TO IMPLEMENT THE "SPACE FOR TIME" APPROACH WITHIN REWRITE. COLOURS INSIDE THE CIRCLES ILLUSTRATE THE LAND, WATER AND THE INTERTIDAL AREAS; COLOURS SURROUNDING THE CIRCLES ILLUSTRATE THE PROPORTION OF THE THREE KEY ISS HABITATS: MICROPHYTOBENTHOS-DOMINATED MUDFLATS, SALTMARSH AND SEAGRASS MEADOWS. THE NUMBERS REFER TO THE NAME OF THE DEMONSTRATOR (TABLE 2).

The success of REWRITE is supported by the expertise of the partners covering a wide range of ISS seascapes ecological and social functioning along a latitudinal (Denmark to Spain) and longitudinal (from Europe to North America) climate gradient, along with a network of 10 demonstrators (DM) from 36.5 °N to 55.5 °N and from 122.0 °W to 10.0 °E, giving an exhaustive and representative panel of the functioning of ISS seascapes in Europe and beyond (Figure 3 and Table 2).

TABLE 2. PRESENTATION OF THE CURRENT AND EXPECTED SITUATION FOR THE 10 REWRITE'S DEMONSTRATORS (CONTINUE TO THE NEXT PAGE)

REWRITE Demonstrators	Designation					Shoreline modification				Restoration of habitats			
	Unesco	Ramsar	Nat2000	LTSER	NAT	MR	NB	NN	AB	ISS	SM	SG	OY
1. Gyldensteen Coastal Lagoon (DK)		●	●		●	●				●	●	●	
2. Wadden Sea (NL)	●Ö	●	●	●	●	●	●	●		●	●	●	●
3. Essex estuaries complex and Humber (UK)		●	●		●	●	●	●			●	●	●
4. Dublin Bay (IR)	●ÖÖ	●	●		●		●			●	●		
5. Scheldt estuary (NL/BE)		●	●		●	●				●	●		
6. Loire Estuary (FR)		●	●		●			●	●				
7. Ria de Aveiro (PT)		●	●	●	●		●	●	●	●		●	

8. Cadiz Bay (ES)		●	●		●		●	●	●	●	●
9. Fundy Bay (CA)	●Ö Ö	●			●	●	●			●	●
10. San Franscisco Bay (USA)	●Ö Ö	●			●	●				●	●

REWRITE Demonstrators	Resilience plans*		Community engagement			Surface (ha) to be restored/rewilded within and after REWRITE (year expected)			
	CC	BIO	H	M	L	ISS	SM	SG	OY
1. Gyldensteen Coastal Lagoon (DK)	●	●	●	●		**		>2[a] (by 2025)	>1[a] (by 2025)
2. Wadden Sea (NL)	●	●	●			> 100[b]	>25[c]	> 250[d] (by 2030)	>1000[e] (by 2030)
3. A/ Essex estuaries complex and B/ Humber (UK)		●	●			> 15%[f] (by 2043)		100[f] (by 2026)	
4. Dublin Bay (IR)		●		●		> 12 000[g]			
5. Scheldt estuary (NL/BE)	●	●	●			> 885[h,i]			
6. A/ Loire Estuary and B/ Bourgneuf bay (FR)	●		●	●		> 300[j] (by 2026)			
7. Ria de Aveiro (PT)	●	●	●	●		***	>1***	>1[k] ***	
8. Cadiz Bay (ES)	●			●	●	365[l]			
9. Fundy Bay (CA)	●		●			> 150[m]			
10. San Franscisco Bay (USA)	●		●			> 900[n]			

ÖUnesco-World Heritage; ÖÖUnesco-Biosphere; Nat2000: Natura 2000 site; LTSER: Long Term Socio-economic & Ecosystem Research platform; NAT: varied national designation; MR: managed realignment; NB: natural breach; NN: not modified; AB: abandoned area ; ISS: intertidal soft sediment ; SM: saltmarsh; SG: seagrass meadow; OY: oyster and other habitats; H: high (active participation); M: medium (interest, but for recreation); L: low (no participation at the moment). *adaptable coastal protection for climate adaptation and/or C sequestration (CC) and/or for biodiversity support (BIO).

Example of ongoing restoration projects:
a) https://www.avjf.dk/avjnf/naturomraader/gyldensteen-strand/ b) HHNK (https://www.hhnk.nl/prinshendrikzanddijk); c) Ecoshape (https://www.ecoshape.org/en/pilots/saltmarsh-development-marconi-delfzijl-9/); d) : Zeegrasherstel (https://zeegrasherstelwaddenzee.com/zeegrasherstel/); e) Programma Naar Een Rijke Waddenzee (https://rijkewaddenzee.nl/project/verkenning-naar-het-terugbrengen-van-de-platte-oester/); f) ReMeMaRe programme (https://ecsa.international/reach/restoring-meadow-marsh-and-reef-rememare) and seagrass restoration as a compensatory fish habitat (https://hornseaprojects.co.uk/hornsea-project-four/compensation-measures-consultation); g) Dublin Bay Biosphere Reserve (https://en.unesco.org/biosphere/eu-na/dublin-bay); h) Sigmaplan (https://www.sigmaplan.be/en/); i) Natuurpakket Westerschelde (https://www.zeeland.nl/natuur-en-landschap/natuurpakket-westerschelde); j) Programme LIFE-ADAPTO (https://www.lifeadapto.eu/home.html) k) BioPradaRia Project (https://biopradaria.weebly.com); l) Consejería de Agricultura, Ganadería, Pesca y Desarrollo Sostenible, Junta de Andalucía (https://www.juntadeandalucia.es/medioambiente/portal/documents/328613/31543413/20211108_Cat%C3%A1logo+andaluz+proyectos+absorcion+carbono+azul.ods/9c9a828b-ea85-adf2-af50-b628d8abaeb4?t=1639488133646); m) TransCoastal Adaptation (https://www.transcoastaladaptations.com/); n) South Bay Salt Pond Restoration Project, Phase2 (https://wildlife.ca.gov/Lands/Places-to-Visit/Eden-Landing-ER#10541121-restoration). **: Gyldensteen Coastal Lagoon is complete restored; ***: the surface to be restored will be an outcome from REWRITE.

3 Presentation and objectives of this deliverable

This deliverable takes part of the WP2 – "Establishing the state-of-knowledge and current trajectories of rewilding intertidal soft sediment seascapes in Europe and beyond", and more specifically the task 2.1 on "Establishing state-of-existing knowledge on intertidal coastal soft sediment seascapes" where data mining all existing data relating to stocks (biomass, concentrations, distributions) and flows (annual turnovers, yields, increases or declines over time) of the following six functions delivered by the ISS, and related measures, for the 10 DM:

Task 2.1.1 Carbon sequestration (including links to biodiversity), values for carbon stocks, biomass and rates of primary production by the 3 key habitats (mudflats dominated by microphytobenthos, seagrass meadows and saltmarsh), rates of gain and loss, transfer between carbon pools.
Task 2.1.2 Biodiversity and conservation, species occurrence and population densities, using existing biodiversity assessments, published work and assessment of conservation and ecological status of designated sites, for all those trophic levels where data exists, provide measures for species richness abundance, trophic position, food webs and productivity.
Task 2.1.3 Protection from coastal flooding as a mitigation and adaptation to climate change impacts, quantifying the minimum relative wave reduction provided by intertidal foreshores with varying ecological and geomorphological characteristics, using existing data from national meteorological, hydrographic, hydrological and geological agencies, project partners, and conservation agencies.
Task 2.1.4 Cultural biotic and abiotic services provided by current social and cultural uses assessing and mapping the plural tangible and intangible values of cultural ecosystem services, using existing data from scientific literature, grey literature and interviews.
Task 2.1.5 Identify current ecosystem structure in terms of landscape connectivity and fragmentation. Using landscape ecology metrics (e.g., splitting index, patch richness density, Simpson's diversity index), assessing seascape connectivity at the patch, habitat and seascape level; and then determine relationships between connectivity, ecological condition and the supply of associated ecosystem services.
Task 2.1.6 Identify the current governance and political mechanisms and frameworks. Create a governance 'map' for each DM based on policy and legal documents, grey literature, published reports, and interviews with established expert's at the national and regional scales, including nature protection agencies and NGOs, land planning policy-makers, and regulators/managers of intertidal resource use.

This deliverable focuses on the *tasks 2.1.1 and 2.1.2*: Carbon and Biodiversity, and addresses the following key objectives:

- Identifying the gaps in knowledge and data necessary to support effective rewilding and restoration strategies.
- Providing recommendations for data collection efforts for WP3 and future rewilding and restoration actions.
- Providing information to project the current and futures trajectories of ISS (WP2 and WP4)

4 Methodology and Approach

This section outlines the methodological and approach framework for gathering, synthesizing, and assessing existing knowledge on C sequestration and storage, and biodiversity within ISS seascapes in order to identify the knowledge gaps related to these aspects. The methodology includes the following steps:

4.1 Categorization of data types

The pyramidal approach involves categorizing the parameters related to our 6 tasks (from 2.1.1 to 2.1.6) into a series of increasing levels of complexity. These levels range from basic, with fundamental data, to more detailed measurements or understanding of the parameters and processes (Figure 4). This pyramid structure allows for comparison across our DMs and studies by identifying the minimal essential data needed for each parameter. Regarding Carbon and Biodiversity, the basic knowledge globally corresponds to the Carbon stock assessment and Biodiversity inventories across different habitat types. These data are the minimum information required to estimate fluxes and processes, corresponding the intermediate knowledge. Whereas higher level knowledge consists of datasets providing a full and deep understanding of the ecosystem functioning, including interactions between C and Biodiversity. The agreement on the categorization and hierarchy of data types for our 6 tasks was done during a specific workshop, organised by each task leader and concluded on a Excel grid to be filled by the 10 DM leaders (Figure 5).

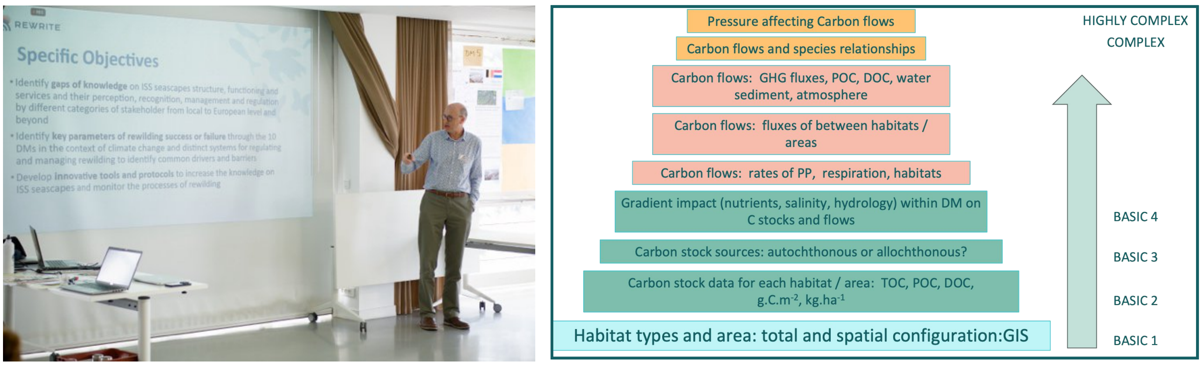
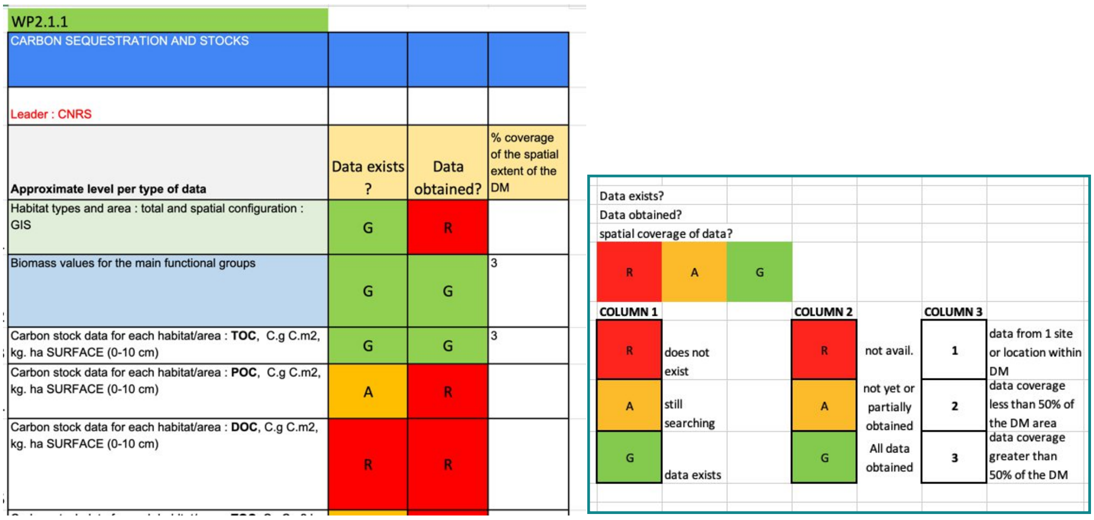


FIGURE 4. DURING THE KICK-OFF MEETING, GRAHAM UNDERWOOD (UESSEX), LEADER OF THE TASK 2.1, EXPLAINING THE PYRAMIDAL APPROACH. IN THE RIGHT, AN EXAMPLE IS GIVEN FOR TASK 2.1.1 C SEQUESTRATION.

4.2 Presentation of the grids and their completion

All Excel grids are stored on the Rewrite Cloud, protected by security access, and an example is shown in Figure 4. From M1 (October 2023) to M12 (October 2024), the DM leaders completed the grids using a standardized codification (Figure 4b), indicating the availability and coverage of data for the different parameters per DM. This task was the responsibility of the DM leaders and was completed by M12 to achieve milestone M4, '*Ecosystem services data availability stock take*', which corresponds to a completed matrix for all DMs, identifying the presence, robustness, and gaps in existing data.



WP2.1.1 CARBON SEQUESTRATION AND STOCKS			
Leader : CNRS			
Approximate level per type of data	Data exists ?	Data obtained?	% coverage of the spatial extent of the DM
Habitat types and area : total and spatial configuration : GIS	G	R	
Biomass values for the main functional groups	G	G	3
Carbon stock data for each habitat/area : **TOC**, C.g C.m2, kg. ha SURFACE (0-10 cm)	G	G	3
Carbon stock data for each habitat/area : **POC**, C.g C.m2, kg. ha SURFACE (0-10 cm)	A	R	
Carbon stock data for each habitat/area : **DOC**, C.g C.m2, kg. ha SURFACE (0-10 cm)	R	R	

Data exists?					
Data obtained?					
spatial coverage of data?					
R	A	G			
COLUMN 1		**COLUMN 2**		**COLUMN 3**	
R	does not exist	R	not avail.	1	data from 1 site or location within DM
A	still searching	A	not yet or partially obtained	2	data coverage less than 50% of the DM area
G	data exists	G	All data obtained	3	data coverage greater than 50% of the DM

FIGURE 5. DATA AVAILABILITY COMPILATION IN AN EXCEL GRID FOR EACH 2.1 SUB -TASK. EXAMPLE FOR DM1, GYLDENSTEEN, DK, FOR THE TASK 2.1.1.

To complete the Excel grids, 2 mains approaches have been used:

- *Literature review* involved both qualitative and quantitative analysis of existing datasets, reports, and scientific papers, identifying methods and results that are directly relevant to carbon and biodiversity in coastal soft sediments for each DM. Their reference (article, website, ...) are reported at the end of each Excel grid.
- *Expert consultations* was conducted to obtain qualitative feedback on the current state of knowledge, ongoing research, and pressing gaps, access to data...

4.3 Data management plan (in brief)

When available, data are stored on the Rewrite Cloud along with their corresponding metadata. In the case where it does not exist, metadata are generated with the assistance of the REWRITE data steward. For further details, refer to the REWRITE Data Management Plan, but a brief summary is given here:

In REWRITE, a structured data lifecycle approach is implemented to make the data findable, accessible, interoperable, and reusable (FAIR). The lifecycle of the data and metadata is explained in Figure 6, detailing the processes of data collection, processing, storage, sharing, and long-term preservation. Throughout its lifetime, the REWRITE project manages diverse datasets, including ecological, socio-economic, and governance-related data, to support interdisciplinary research. Additionally, compliance with ethical, legal, and regulatory frameworks is implemented, particularly regarding data privacy, security, and governance. By following best practices and standard in data management, it aims to maximize the scientific impact and long-term usability of its research outputs.

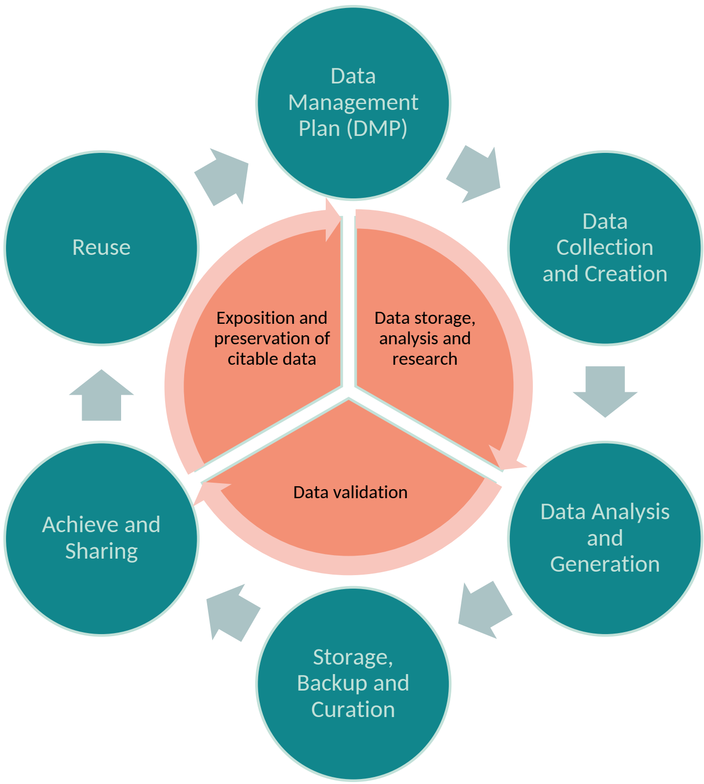


FIGURE 6. LIFECYCLE OF THE DATA AND METADATA IN THE FAIR FRAMEWORK

Metadata records in the Rewrite Cloud are structured according to established standards for the purpose of consistency, interoperability, and compliance with Open Science and FAIR principles. For general datasets, Dublin Core Metadata Initiative (DCMI) is used as the primary metadata schema to facilitate broad compatibility with institutional repositories, digital libraries, and international data-sharing platforms. For biodiversity-related datasets, Darwin Core (DwC) is implemented as an extension to Dublin Core. Darwin Core is specifically designed for biological and ecological data, to specify metadata fields such as scientific name, taxon rank, geo-reference, occurrence status, collection event, habitat description, and organism interactions. The integration of Darwin Core (DwC) is to enrich metadata by incorporating additional biodiversity-specific information, improving dataset accessibility and interoperability with global biodiversity data networks.

The Rewrite Cloud employs role-based access control (RBAC) mechanisms to guarantee data security and compliance with regulatory requirements. Authorized users are assigned specific access permissions based on their roles within the REWRITE consortium. Access logs and audit trails are maintained to monitor data usage and ensure adherence to data governance policies. Encryption data at rest and in transit is enforced utilizing Transport Layer Security (TLS) 1.3 to safeguard data against unauthorized access or breaches.

Data versioning is systematically implemented to track changes over time. Additionally, automated daily backup systems create redundant copies of stored data to prevent data loss due to hardware failures or cyber threats. A dedicated disaster recovery plan is located locally at Nantes University to restore all of lost or missing datasets in the event of unexpected disruptions.

4.4 Gaps Identification

For the first annual meeting, in Ghent, Oct 2024, all task leaders had to build common background, and identify the gaps of knowledge, based on the comparison of the pyramids of each DM (Figure 7). This deliverable (D2.1) focuses on Carbon and biodiversity.

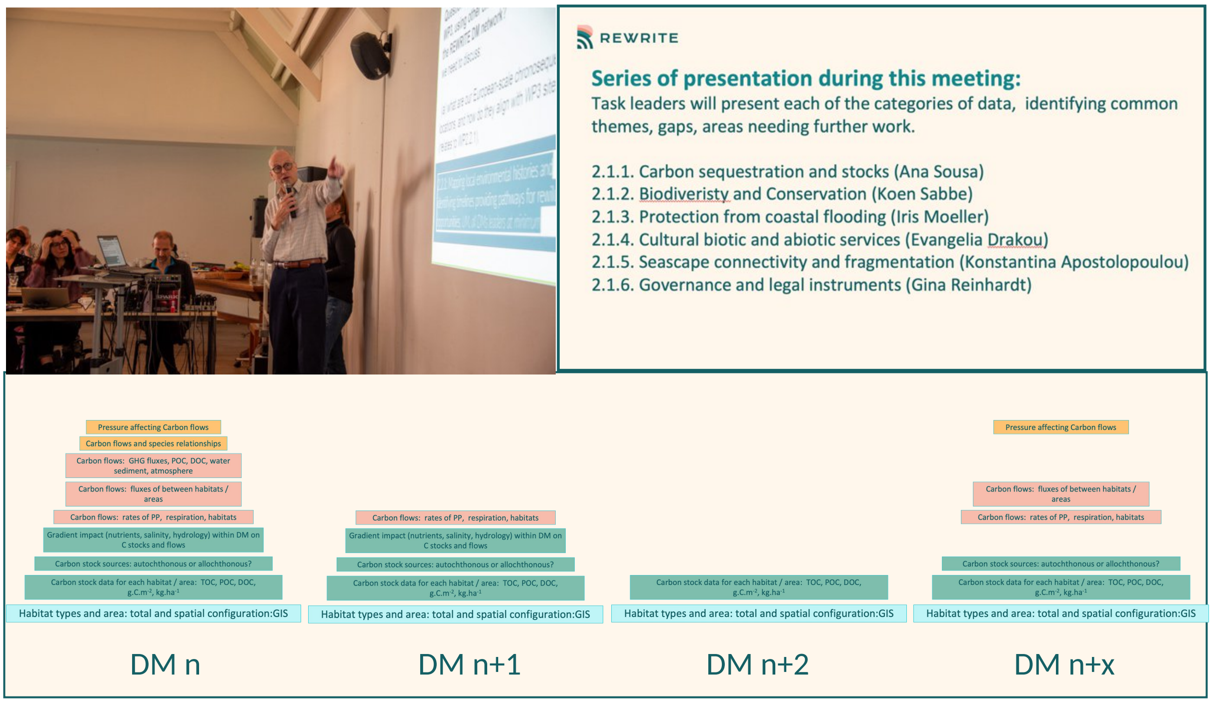


FIGURE 7. DURING THE FIRST ANNUAL MEETING, IN GHENT, GRAHAM UNDERWOOD (UESSEX), LEADER OF THE TASK 2.1, INTRODUCING THE SERIES OF PRESENTATION TO IDENTIFY COMMON THEMES, GAPS AND AREA NEEDING FURTHER WORK. ON THE BOTTOM, THE EXAMPLE OF COMPARING PYRAMID FOR THE TASK 2.1.1 CARBON SEQUESTRATION IS REPORTED.

5 Results and Discussion

The results and discussion section will summarize the key findings from the analysis of the pyramidal approach, per DM. It will provide a comprehensive list of the identified knowledge gaps related to carbon sequestration and biodiversity in ISS seascapes.

The grids are availed here: https://cloud.rewrite-project.eu/index.php/s/gBBmX69AJENjYJr

5.1 Carbon Sequestration

This task involves the sequestration, but also the storage of C. The assessment of C sequestration and storage is crucial to estimate the ISS seascapes' role in climate mitigation and adaptation. Vegetated mudflats (seagrasses and saltmarshes) and mudflats dominated by MPB can sequester C from the atmosphere, contributing to reduce the available CO_2 in the atmosphere, but also store C from internal and external riverine and oceanic sources (laterally-imported C). Therefore, ISS can be a C sink at a regional or global level, and contribute to the C sequestration (i.e. the Blue Carbon). Depending on the integrity, fragmentation and maturity of the ecosystem, these ISS can also be sources of C, instead of sinks.

The grids, completed for each DM by the DM leader, give an overview of C data existence, availability and spatial coverage of each target habitat. *At a basic level*, data availability for C stocks in the different compartments (sediment, primary producer (i.e. MPB, seagrass, saltmarsh), atmosphere)), and the type of C (biospheric or geologic), its origin (autochthonous or allochthonous), availability (refractory or labile) at the surface and in deeper sediments, depending of habitat and site, were assessed. **For C sequestration and stocks there is generally good data coverage for mapped habitats and biomass data**, but still questions around which habitat and the nature of some of the C stocks (sediments, flora, fauna etc). Total organic carbon stocks are well covered in a number of DMs, but limited for others.

In detail, habitats mapping is available for all DMs except for DM10. Biomass data are available for some DMs, but not for all functional groups (either flora or fauna). Therefore, some new data is needed for an overall estimation of C stock in living biomass in some DMs, either through new data acquisition or literature review data inclusion.

Data on the sediment POC / DOC (particulate organic carbon / dissolved organic carbon) is sparse and DOC data acquisition is needed to understand lateral C fluxes within or across habitats. DMs 1 (Gyldensteen lagoon), 3A&B (Essex and Humber), 4 (Dublin Bay) and 7 (Ria de Aveiro) to 10 (San Francisco Bay) have C stock data for the sediment surface (up to 10 cm depth) and for the target habitats, but other DMs have sparse data, i.e. available not for all habitats or not available. Data for deeper sediment layers (from 10 cm to 1 m depth) are available for DMs 1 (Gyldensteen lagoon), 3A&B (Essex and Humber), 4 (Dublin Bay) and 7 (Ria de Aveiro) to 10 (San Francisco Bay). Regarding sediment ^{210}Pb dating, data are scarce and patchy across DMs. There is still the need for harmonized understanding and agreement on the approaches and methods for establish C flow measures across the REWRITE DMs.

Concerning C flows data, *the intermediate level of knowledge*, sedimentation rates are available for DM3A&B (Essex and Humber), DM5 (Scheldt Estuary), DM6A (Loire Estuary), DM8 (Cadiz Bay) to 10 (San Francisco Bay), gross primary production and respiration data are available for DM1 (Gyldensteen lagoon), DM3A&B (Essex and Humber), DM6A&B (Loire Estuary and Bourgneuf Bay), 7 (Ria de Aveiro) to 10 (San Francisco Bay), but not for all target habitats, using different methods and data collection was not harmonized over space and time within and across DMs.

Finally, the most *complex level of knowledge*, which is the understanding of the whole C budget, including the Blue Carbon assessment is missing in most of the DMs, but could be achieved for some of them using existing data, incremented by specific new measurements during the project, as DM1 (Gyldensteen lagoon), DM5 (Scheldt Estuary) or DM6A (Loire Estuary).

5.2 Biodiversity

Biodiversity (and its conservation) represents important provisioning (e.g. food) and cultural (e.g. recreation, education) ES, and underlies (through Biodiversity–Ecosystem Functioning (BEF) relationships) many regulating (e.g. coastal protection, C sequestration) and supporting (e.g. nutrient cycling) ES. The grids, which were completed for each DM by the DM leaders, give an overview of data existence (yes, still searching, no), availability (obtained, partially obtained, not obtained) and spatial coverage (1 or a few locations within the DM, > 50% of DM area, > 50% of DM area) of biomass, biodiversity, areal coverage and (for selected parameters) structural and functional features of the main organismal groups for each DM, and the conservation status of habitats. For this task, there is no answer for the DM10 (San Francisco bay). Based on these grids, we identified the main gaps in knowledge, which is then used for focusing further data mining and/or guiding new data collection in WP3.

Conservation designation (GIS), current ecological/conservation and biotype maps are available for all DMs with some minor uncertainties for DMs 6 (Loire Estuary and Bourgneuf Bay) and 9 (Fundy Bay), for which data need to be mapped and most data still need to be obtained. NDVI maps (vegetations, microphytobenthos - MPB) are available for most DMs except DM1 (Gyldensteen lagoon), and with potential gaps/uncertainties for DMs 6-8. Macrophyte (saltmarsh, seagrass and seaweed) areal maps are available for most DMs, with some minor uncertainties for DMs 6 and 9 (data need to be mapped), most data still need to be obtained. For seaweeds, more gaps may exist. Vegetation types (structure or community types) are available for all DMs; vegetation height available for most DMs except uncertain for DMs 1 (Gyldensteen lagoon), 2 (Wadden Sea), 5 (Scheldt Estuary) and (partly) 6 (Loire and Bourgneuf bay). Vegetation biomass (field based) is missing for DMs1 (Gyldensteen lagoon), 2 (Wadden Sea) and 6 (Loire and Bourgneuf bay), and uncertain for DMs 4 (Dublin Bay) and 9 (Fundy Bay). Bacterial biomass is missing for DMs (Gyldensteen lagoon), 2 (Wadden Sea), 6 (Loire and Bourgneuf bay) and 7 (Ria de Aveiro), with gaps/uncertain for 3 (Essex and Humber), 4 (Dublin Bay), 5 (Scheldt Estuary) and 9 (Fundy Bay). MPB biomass (field based) is available for all DMs, except potential gaps/uncertain for DMs 1 (Gyldensteen lagoon) and 9 (Fundy Bay). MPB biodiversity (metabarcoding or microscopy) is available for DMs 3 (Essex and Humber), 5 (Scheldt Estuary), 6 (Loire Estuary and Bourgenuf Bay), 7 (Ria de Aveiro) and 8 (Bay of Cadiz), uncertain for 4 (Dublin Bay) and 9 (Bay of Fundy), missing for 1 (Gyldensteen lagoon) and 2 (Wadden Sea). Protist (non-MPB) biodiversity (metabarcoding or microscopy) is available for DMs 1 (Gyldensteen lagoon), 4 (Dublin Bay) and 8 (Bay of Cadiz), uncertain/gaps for 3 (Essex and Humber), 5 (Scheldt Estuary), 6 (Loire and Bourgneuf Bay) and 9 (Bay of Fundy), missing for 2 (Wadden Sea) and 7 (Ria de Aveiro).

Meiobenthos (all data types) is missing for DMs 1 (Gyldensteen lagoon), 2 (Wadden Sea), 4 (Dublin Bay) and 7 (Ria de Aveiro), and uncertain/gaps for DM 9 (Bay of Fundy). Meiobenthos biomass and community composition (microscopy) are available for DMs 3 (Essex and Humber), 5 (Scheldt Estuary), 6 (Loire and Bourgneuf Bay) and 8 (Bay of Cadiz). There is limited availability of meiobenthos metabarcoding data for DMs 5 (Scheldt Estuary) and 6 (Loire and Bourgneuf Bay). Macrobenthos all categories (biomass, biodiversity and metabarcoding) is not documented for DMs 1 (Gyldensteen lagoon), 2 (Wadden sea, except biomass), 4 (Dublin Bay), 8 (Cadiz Bay) and 9 (Bay of Fundy, although data most likely is available). Macrobenthos biomass is available for DMs 2 (Wadden Sea), 3 (Essex and Humber), 5 (Scheldt Estuary), 6 (Loire and Bourgneuf Bay) and 7 (Ria de Aveiro), community composition is also present for the latter four DMs. Macrobenthos metabarcoding data are most likely not available for any DM. Fish monitoring data are available for all DMs except DM1 (Gyldensteen lagoon), and with uncertainties for 2 (Wadden Sea), 5 (Scheldt Estuary) and 8 (Cadiz Bay). Bird monitoring data are available for all DMs, except DM9 (Fundy Bay) uncertain.

5.3 Knowledge Gaps

5.3.1 Carbon sequestration

As a whole, DMs 1 (Gyldensteen lagoon), and 3 (Essex and Humber) to 8 (Cadiz Bay), and 9 (Bay of Fundy) have more C data available, but data is not harmonized and the approaches and methods used need to be taken into account. Missing data include C origin (either allocthonous or autochthonous), sediment depth for C analysed is also very variable, and harmonized data is needed for comparison across demonstrators. Still, sediment data up to 1 m depth is crucial for Blue Carbon estimates for each habitat and across DMs. C fluxes are also relevant for GHG balance estimates (CO_2, CH_4, etc), and data are scarce.

5.3.2 Biodiversity and conservation

In general, DMs 3-8 have the most complete data sets, but gaps exist. DM1 (Gyldensteen lagoon) and also 2 (Wadden Sea) have most gaps. Gaps are mainly related to microbial groups (bacteria, MPB, meiobenthos), especially with respect to biodiversity, but also to biomass for bacteria and meiobenthos. Metabarcoding data are very sparse for most DMs. For many DMs, data on geographic coverage of the parameters is available, but many gaps exist (for specific DMs and/or parameters). Information on microbial group is essential however and should be a priority for WP3 as it is important for Task WP2.1.1 (C flows). Macrobenthos data are missing for many DMs but this is most likely related to the fact that these categories were not listed in the original spreadsheet, and these gaps need to be verified.

6 Recommendations for WP3 and data collection efforts

This section will provide actionable recommendations for WP3 and data collection efforts, based on the identified knowledge gaps and the needs of the REWRITE project. The final objective is to set up recommendations for efficient rewilding actions to enhance Carbon sequestration and biodiversity conservation.

6.1 Recommendations for Carbon Sequestration

In the scope of REWRITE, an accurate assessment of C stocks and fluxes in rewilded versus non-rewilded target habitats (mudflats, seagrasses, saltmarshes) is crucial, in order to accomplish the objectives of assessing the ISS seascape role in carbon sequestration and storage, and therefore, in climate regulation and mitigation. This assessment needs to be more detailed in certain DMs, to be defined or chosen according to overall REWRITE objectives. These data will need to be linked to some specific biodiversity data across habitats and DMs (WP2.1.2. Biodiversity and conservation). Overall, in order to evaluate the current C stock (all DM) and fluxes (some DM) across REWRITE DMs, we should compare rewilded (or at least restored or abandoned) sites vs. non-rewilded, expecting an impact on surface and deeper (up to 1 m) sediment layers, affecting each habitat C sink or source capacity. In addition, for a robust trajectory assessment, both spatial and temporal (backcasting and forecasting) analyses need to be done, including potential future trajectories in case of habitat gain or loss or fragmentation, as a result of the current global pressures. This trajectory assessment will allow us to build scenarios and estimate the impact of gain or loss of ISS ecosystems in terms of climate regulation mitigation potential.

The main recommendations are:

- As anticipated in the proposal, investigate C stocks and fluxes in rewilded *versus* non-rewilded target habitats in three target DM across Europe (Cadiz Bay, Ria de Aveiro and Scheldt), to address the objectives of the WP3 (task 3.1)
- Standardization of measurement techniques and methods, experimental design, data collection protocols and sample analyses protocols across sites, including ‘low-cost’ approaches (task 2.4)
- Improved modelling approaches for C fluxes and long-term projections of C storage in coastal ISS seascapes (task 3.3)

6.2 Recommendations for Biodiversity

As anticipated in the proposal, especially data on microbial biomass and taxonomic and functional microbial biodiversity are sparse or lacking, while these are essential for linking to important ecosystem services (especially C flows, Task 2.1.1) in these habitats (and especially tidal flats where MPB are the main primary producers). In addition, many available data on biodiversity have been obtained with different methods and by different researchers, while it is known that analyst-related errors can be significant. The advent of DNA-based biodiversity inventory methods now allows for a standardized approach of biodiversity patterns in ISS landscapes. DNA metabarcoding, as planned in WP3.1, will deliver detailed, integrated (prokaryote, MPB and non-MPB protist) data for selected DMs. During the spring and summer of 2025, coordinated sampling campaigns will be carried out to simultaneously gather information on carbon sequestration and biodiversity plus essential metadata in three core sites (DMs 5, 7 and – i.e. Scheldt, Aveiro and Cadiz). Microbial biodiversity data will also be collected in additional DMs (DM 1-3, 6). At each DM, rewilded sites (polders and salt pans that have been re-exposed to tidal influence) of different ages and reference sites will be sampled to obtain an inventory of microbial diversity along spatial (latitudinal) and environmental (elevation, sediment grain size, salinity, etc.) gradients. This intercalibrated data set will allow assessing how rapidly rewilded sites revert to the biodiversity status of the reference sites. At the three core sites, metatranscriptomic and metagenomic approaches will be used to compare the functional status of the microbial community between rewilded and reference sites. Metatranscriptome samples will be collected simultaneously with the carbon flux measurements, enabling an integrated view on the relationship between microbial biodiversity and ecosystem functioning between rewilded and reference sites. During the same sampling campaigns at the core DMs, stable isotope analysis of selected sources and consumers (2 sites/DM, 2 surveys/site, 400 samples/survey) (NIOZ; UAVR) will be carried out to comparatively analyse trophic transfer in the rewilded and reference ISS sites, complementing traditional surveys (e.g. UCA) or existing monitoring data (e.g. NIOZ, SDU). Trophic transfer will be related to the carbon flux and sequestration measurements, including the role of macrofaunal bioturbation (NIOZ; SDU).

7 Toward rewilding actions and stakeholder engagement

7.1 Link C and Biodiversity data to seascape structure (task 2.1.5)

To assess seascape structure and its relationship to ecosystem services (ES) and biodiversity, structural and functional connectivity are currently analyzed at different levels, calculating metrics to quantify aspects like fragmentation. The objective is to estimate how changes in seascape structure affect the supply of ES such as C sequestration, coastal protection, and cultural ecosystem services. In terms of biodiversity the links of structure with function are better known, but not within the rewilding trajectory. Overall the objective of task 2.1.5 is to generate evidence that allow to better explore the nature of these relations across the rewilding trajectory.

In particular, it is still not well explored or documented whether more connected coastal habitats are able to sequester or store more carbon. Is this relationship linear or is there an optimum of connectivity within the seascape habitats? How does this relationship change in connected but more variable seascapes? Within task 2.1.5, data on past and current carbon measurements on storage and sequestration, allows us to assess the correlation between these measurements and seascape structure (Figure 8). These relationships are explored across all DMs, allowing us to understand whether the observed patterns are stochastic or deterministic.

To be able to achieve this, the core challenges identified, include the need for spatially explicit data for carbon storage and sequestration rates in the past and present. Another big challenge is the variable data analysis and resolution given across time within the same DM, or among different DMs. To overcome these challenges, we work towards collecting the data and filling in the “gaps” through spatial processing techniques, such as regression or interpolation analysis, where applicable.

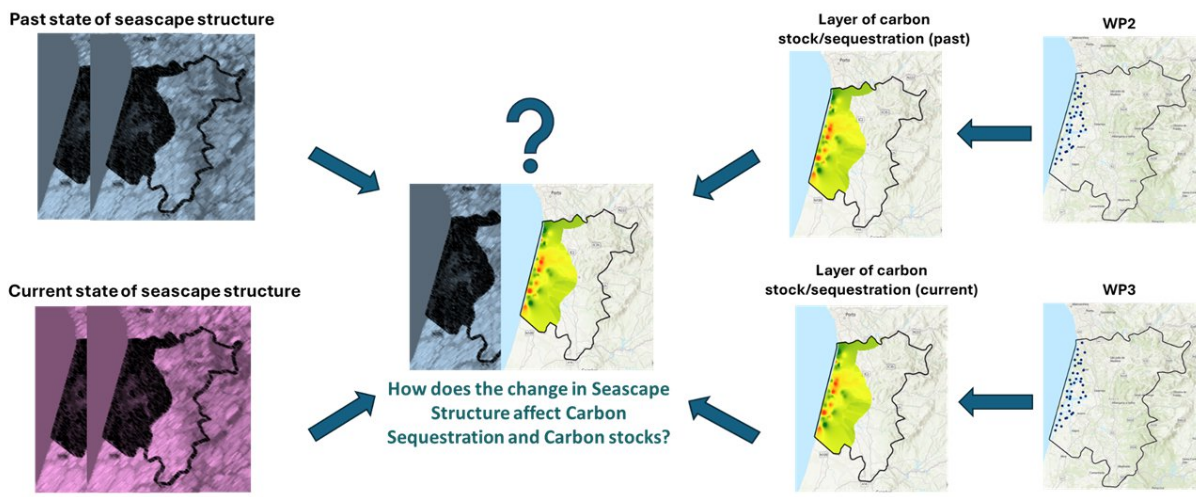


FIGURE 8. WORKFLOW OF RELATIONS AMONG SEASCAPE STRUCTURE AND CARBON MEASUREMENTS.

Similar to C sequestration, the role of seascape structure is critical for biodiversity and the distribution of biodiversity determines the functional connectivity within a seascape. For that reason, the reciprocity of this relationship is explored within Task 2.1.5. For this to be achieved data on a breadth of species present in the DMs is required, from microbiota, to coastal vegetation and birds and reptiles. Given that the goal is to assess the change in this relationship through the rewilding trajectory, a core challenge lies in the fact that there are no real time series of such data. Another shared challenge is that these data are not harmonized across DMs, making generalization a challenge. Harmonization can be overcome through data manipulation techniques by compromising with a lower resolution. The lack of time series however, might lead to more static assessment of these relationships for the DMs in which such data is missing.

7.2 Link C and Biodiversity data to Multi Actor Labs (task 4.1 and 4.2)

The findings from this deliverable (D2.1), along with task 2.2 (D2.2 on DM histories and trajectories) and task 2.2 (D2.3 Best practice guidelines for social innovation ISS rewilding) are expected to provide key input to the global MAL (G-MAL) both in terms of data and in terms of drivers of changes necessary to co-develop future ISS rewilding scenarios with stakeholders at global level. The G-MAL will then on one side, provide feedback to the tools for determining changes in ecosystems functions (D2.4) and one the other side, set up the ES baseline scenarios and ES functions that stakeholders will consider for co-creating scenarios at local level with the Local MALs (L-MAL) in the various DM. In addition the findings from the Narrative of Changes (D3.2) are expected to contribute in defining the driver of changes used in the MALs at both global and local level (Figure 9).

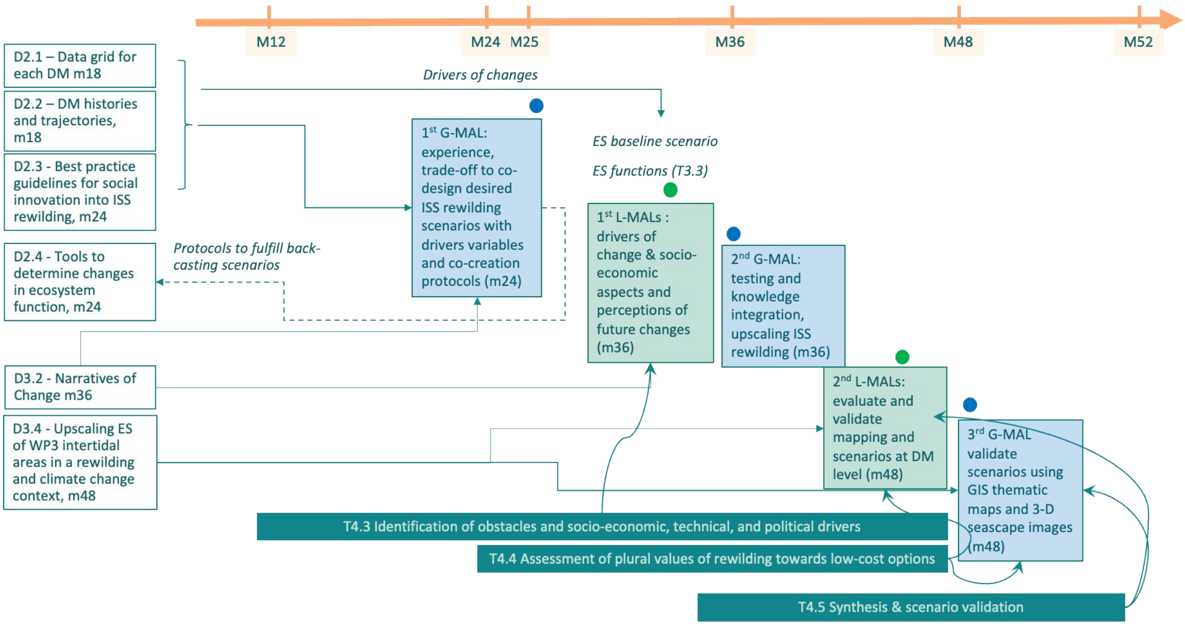


FIGURE 9 - INTERDEPENDENCIES BETWEEN THE MALS AND THE PROJECT TASKS

8 Conclusion

This cross-demonstrator analysis has supported the central role of carbon sequestration and biodiversity as foundational functions supporting a wide range of ES provided by intertidal soft-sediment (ISS) seascapes. Despite the diversity of geographical, ecological, and social contexts across the Demonstrators, a common understanding and knowledged emerged, and will play a critical outcomes in futures climate and biodiversity strategies.

Our pyramidal approach revealed significant variability in data availability, temporal continuity, and spatial resolution. Some DMs benefit from long-term, *in situ* observations and remote sensing data, while others rely more heavily on local knowledge or fragmented datasets. This diversity underscores the urgent need for shared protocols and long-term monitoring strategies.

Moreover, the exercise showed that the contribution of ISS to both carbon storage and biodiversity cannot be fully captured without integrating natural and social sciences. It is only through the inclusion of human perceptions, uses, and narratives that we can understand the societal value and governance potential of these ecosystems.

In conclusion, this preliminary synthesis calls for a stronger and standaridzed knowledge of ISS seascapes functionning to be integrated as key actors in the climate–biodiversity–society nexus. It needs the path toward a transdisciplinary, network-based approach to improve our capacity to assess, restore, and manage these fragile and essential systems.

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