Future Science Brief
Nº 11 June 2024

Marine habitat mapping

European
MARINE BOARD
Advancing Seas & Ocean Science

www.marineboard.eu

European Marine Board IVZW

The European Marine Board provides a pan-European platform for its Member organisations to develop common priorities, advance marine research, and to bridge the gap between science and policy in order to meet future marine science challenges and opportunities.

The European Marine Board (EMB) is an independent and self-sustaining science policy interface organisation that currently represents 38 Member organisations from 19 European countries. It was established in 1995 to facilitate enhanced cooperation between European marine science organisations towards the development of a common vision on the strategic research priorities for marine science in Europe. The EMB promotes and supports knowledge transfer for improved leadership in European marine research. Its membership includes major national marine or oceanographic institutes, research funding agencies and national consortia of universities with a strong marine research focus. Adopting a strategic role, the European Marine Board serves its Member organisations by providing a forum within which marine research policy advice is developed and conveyed to national agencies and to the European Commission, with the objective of promoting the need for, and quality of, European marine research.

www.marineboard.eu

European Marine Board Member Organisations

European Marine Board IVZW Future Science Brief N° 11

This Future Science Brief is a result of the work of the European Marine Board Expert Working Group on Marine Habitat Mapping. See Annex 1 for the list and affiliations of the Working Group Members.

Working Group Chairs
Simonetta Fraschetti, James Strong

Contributing Authors
Lene Buhl-Mortensen, Federica Foglini, Jorge M. S. Gonçalves, José Manuel González-Irusta, Helen Lillis, Mats Lindegarth, Georg Martin, Lenaick Menot, Eimear O'Keeffe, António Pascoal, Maria Salomidi, Timm Schoening

Series Editor
Sheila J. J. Heymans

Publication Editors
Britt Alexander, Ángel Muñiz Piniella, Paula Kellett, Ana Rodriguez Perez, Konstantina Bairaktari, Fernanda Bayo Ruiz, Sheila J. J. Heymans

External Reviewers
Carlo Cerrano, David Connor, Ellen Kenchington, Juan Ronco Zapatero

Internal review process
The content of this document has been subject to internal review, editorial support and approval by the European Marine Board Member Organisations

Suggested reference
Fraschetti, S., Strong, J., Buhl-Mortensen, L., Foglini, F., Gonçalves, J. M. S., González-Irusta, J. M., Lillis, H., Lindegarth, M., Martin, G., Menot, L., O'Keeffe, E., Pascoal, A., Salomidi, M., Schoening, T. (2024) Marine habitat mapping. Alexander, B., Rodriguez Perez, A., Kellett, P., Muñiz Piniella, A., Bayo Ruiz, F., Bairaktari, K., Heymans, J. J. [Eds.] Future Science Brief N°. 11 of the European Marine Board, Ostend, Belgium. ISSN: 25593-5232. ISBN: 9789464206234. DOI: 10.5281/zenodo.11203128

www.marineboard.eu
info@marineboard.eu

Design
Zoeck

Front cover image credit:
Roberto Rinaldi

First edition, June 2024

Foreword

Beneath the surface of our Ocean lies a complex tapestry of marine habitats, intricately connected and fundamental to the health of our Ocean and the life it sustains. The need for comprehensive marine habitat maps to help make decisions on activities at sea has never been more pressing. High-quality marine habitat maps are required to realise the ambitions of the European Union's Mission to Restore Our Ocean and Waters by 2030 and to navigate the challenges of the European Green Deal to simultaneously protect and restore marine ecosystems, and to scale-up offshore renewable energy and other Blue Economy sectors.

The European Marine Board's Future Science Brief on marine habitat mapping emphasises the crucial role of accurate and extensive marine habitat maps for achieving European and international goals for biodiversity, conservation, restoration and climate action. It outlines the science and policy needs to advance our understanding and documentation of marine habitats, from increasing the resolution of biological information to strengthening coordination mechanisms for interdisciplinary mapping efforts to fill critical gaps. International initiatives such as the Nippon Foundation-GEBCO Seabed 2030 project have placed a heavy and important emphasis on traditional hydrographic mapping. However, by going this important step further towards the advancement of novel cost-effective mapping technologies, mapping of ecosystems in three dimensions, supporting repeat mapping surveys to document changes over time, promoting standardisation and dissemination of mapping methods and products, and advancing habitat classification schemes, we can unlock the full potential of marine habitat mapping as a tool for informed decision-making. This Future Science Brief aims to inform policymakers, programme managers, research funders and the wider science-policy and scientific communities in the advancement of next-generation marine habitat mapping efforts.

The European Marine Board selected the topic of marine habitat mapping for a new activity in spring 2021. The Working Group kicked-off with a hybrid meeting at the Stazione Zoologica Anton Dohrn (Naples, Italy) hosted by the Working Group Chair, Prof. Simonetta Fraschetti. On behalf of the European Marine Board, I extend my gratitude to the Working Group Members for their collaborative effort in writing this document, bringing together diverse perspectives and approaches to marine habitat mapping. I would also like to thank the external reviewers for their constructive comments and Leonardo Tunesi (ISPRA) for valuable comments and insights on habitat classification schemes. Finally, as always, I would like to thank the EMB Secretariat, in particular Britt Alexander, for the coordination of the Working Group and for shepherding the writing, editing and reviewing of this document through to publication.

Fiona Grant
Chair, European Marine Board
June 2024

Table of Contents

Executive summary

Accurate and extensive marine habitat maps are fundamental to support a wide variety of marine policies and ambitions. These include the European Union's Marine Strategy Framework Directive and policies to deliver the ambitious plans of the European Green Deal. The simultaneous scaling-up of sustainable Blue Economy activities, while protecting and restoring marine ecosystems as part of the EU 2030 Biodiversity Strategy and the proposed Nature Restoration Law will require increased knowledge of marine habitats. Marine habitat mapping aims to create a holistic representation of the distribution of marine habitats in space and time, and provide insight into associated biological communities, ecological status and condition, and physical properties. Habitat maps are valuable spatial decision-support tools that inform the sustainable use of marine space when using an ecosystem-based approach. They can be used to assess the impact of anthropogenic pressures on marine resources and ecosystem services, to identify and plan new networks of marine protected areas and areas for restoration, and to inform maritime spatial planning. However, large areas remain unmapped and current maps predominantly focus on physical aspects of marine habitats and lack sufficient biological resolution, such as species and communities. Higher resolution maps are needed to better represent the linkages between the seabed and water column in three dimensions and to enable an ecosystem approach to mapping that considers the marine environment in the fourth dimension, capturing the timing of important ecological processes.

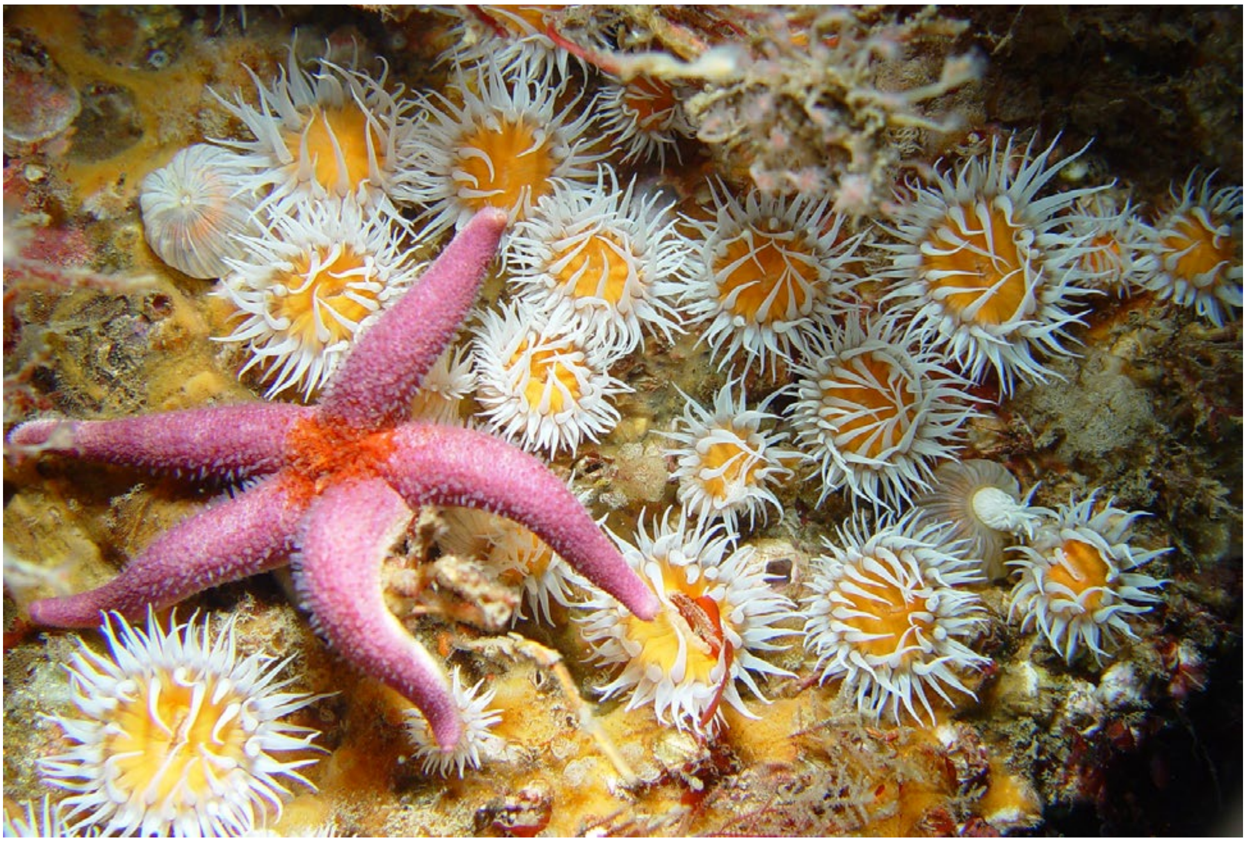
This Future Science Brief highlights science and policy needs and recommendations to advance marine habitat mapping in order to fulfil European and international ambitions for biodiversity, conservation, restoration and climate. It primarily targets policymakers, programme managers, research funders and the wider science-policy and scientific communities. It highlights current methods and future trends in the acquisition of data from the seabed and water column via remote sensing and direct, *in situ* techniques, combining data to produce maps using modelling approaches, and recommendations for adopting fit-for-purpose classification schemes. It provides an overview of what has been mapped and where within the European sea-basins, highlights the need to increase the quality and resolution of marine habitat maps, and identifies critical gaps in habitat types and geographic extent, including the deep sea, Natura 2000 sites and other Marine Protected Areas across all regional seas. Finally, it describes the need to improve the assessment and communication of uncertainty and confidence in maps, and for maps to be more easily accessible to a variety of stakeholders to increase their value for end-users and to the public for Ocean literacy.

To address policy needs and increase the capacity for the production and dissemination of accurate marine habitat maps, we recommend scientists/map producers and research funders to:

- Support multidisciplinary national and EU research projects to advance novel methods to increase the resolution of biological information within marine habitat mapping;
- Support national and EU research programmes that focus on repeat mapping to understand temporal change, particularly of ecologically significant spatial units, i.e. hot spots of ecosystem functioning where high rates of change are expected;
- Promote the standardisation of mapping methods and outputs in research and mapping programmes;
- Promote and incentivise research and mapping programmes to publish marine habitat mapping data according to the Findable, Accessible, Interoperable and Reusable principles and to submit data to centralised data services;
- Support public-private research collaboration for the development of cost-effective mapping tools; and
- Support dedicated mapping projects focusing on citizen science and reformatting mapping products that promote Ocean Literacy.

In addition, we recommend policymakers to:

- Strengthen national, regional, European and international coordination mechanisms for interdisciplinary mapping efforts to ensure effective use of mapping resources and identification of gaps;
- Establish an international effort to identify priority areas in need of mapping, with a focus on areas of the largely unmapped deep sea and coastal areas, which are under the greatest pressure from human activities;
- Require map producers (e.g. ICES Working Group on Marine Habitat Mapping, EMODnet, large mapping projects) or map users (e.g. the European Environment Agency, Joint Nature Conservation Committee) to produce best practice and reporting templates for the standardised assessment and reporting of map accuracy and confidence; and
- Advance habitat classification schemes, which lie at the heart of all marine habitat maps, to include quantitative characterisation of habitats to support the assessment of their condition. Habitat maps will be enriched further if these classification schemes link to other sources of information such as sensitivity to pressures and ecosystem services provision.



The advancement of novel methods to increase the resolution of biological information within marine habitat mapping is needed.

The European Marine Board acknowledges that while the Working Group members who wrote this document and its recommendations represent diversity in terms of European geographical location (see Annex 1), professional background, gender and career level, their views may not represent ideas from all forms of diversity. This document has a European focus, but its messages and recommendations are relevant to stakeholders globally. The diversity in scientific expertise in the Working Group has been crucial in highlighting different views and perspectives in marine habitat mapping from different communities (e.g. geologists vs biologists, coastal vs deep-sea researchers, modellers vs data collectors) and to address the complexity of the topic, adopting a common voice in this document.

2021 United Nations Decade
2030 of Ocean Science
for Sustainable Development

Contribution to the UN Ocean Decade Challenges and Outcomes

This Future Science Brief and its recommendations support the UN Decade of Ocean Science for Sustainable Development's (Ocean Decade) societal outcomes (O1 – O7) and challenges (C1 – C10) in the following ways:

- **A healthy and resilient Ocean'** (O2) where marine ecosystems are understood, protected, restored and managed and **'Protect and restore ecosystems and biodiversity'** (C2) by highlighting advances needed in marine habitat mapping to best plan and monitor ecosystem conservation and restoration activities.
- **'A productive Ocean'** (O3) supporting sustainable food supply and a sustainable Ocean economy, **'Sustainably feed the global population'** (C3) and **'Develop a sustainable and equitable Ocean economy'** (C4) by providing information on the distribution of vulnerable habitats within fishing fleet's activity areas in order to minimise fishing impacts and to select suitable sites for aquaculture.
- **'A predicted Ocean'** (O4) where society understands and can respond to changing Ocean conditions by providing recommendations on filling gaps in mapping habitat types and geographic areas to gain baseline information on which to base management decisions and recommendations to implement repeat mapping to detect change over time.
- **'An accessible Ocean'** (O6) with open and accessible access to data, information, technology, and innovation by highlighting the need for scientists and wider stakeholders to share maps and mapping data to increase uptake, dissemination and value.
- **'An inspiring and engaging Ocean'** (O7) where society understands and values the Ocean in relation to human wellbeing and sustainable development and **'Change humanity's relationship with the Ocean'** (C10) by providing recommendations on the use of marine habitat maps to increase public understanding of the Ocean.

Contribution to the EU Mission: Restore our Ocean and Waters

This Future Science Brief and its recommendations support the objectives of the EU Mission: Restore our Ocean and Waters in the following ways:

- **'Protect and restore marine and freshwater ecosystems and biodiversity'** by highlighting advances needed in marine habitat mapping to best plan and monitor ecosystem conservation and restoration activities.

And the cross-cutting enabling actions:

- **'Broad public mobilisation and engagement'** by providing recommendations on the use of marine habitat maps to increase public understanding of the Ocean.
- **'A digital Ocean and water knowledge system'** by highlighting the need for scientists and wider stakeholders to share maps and mapping data to increase uptake, dissemination and value. Marine habitat maps form the basis of spatial ecosystem models that are needed for digital twins of the Ocean.

1 Introduction

1.1 What is marine habitat mapping?

The term "habitat" has various meanings in different contexts and scales (Fraschetti *et al.*, 2018; Montefalcone *et al.*, 2021). Within the context of habitat mapping, a habitat refers to "a recognisable space which can be distinguished by its abiotic (i.e. physical) characteristics and associated biological assemblages[1], assessed at particular spatial and temporal scales" (ICES, 2005) (see Figure 1.1 for examples of different components of a habitat).

Marine Habitat Mapping (MHM) aims to gain a holistic representation of the distribution of marine habitats in space and time. Marine Habitat Maps (MHMs), in combination with other data (e.g. sensitivity matrices, spatial data on anthropogenic pressures, repeat mapping over time) may also provide insight into changes in ecological vulnerability and potential human impacts. The characteristics to be mapped in MHM initiatives depend on the aims, management needs, scale and context. MHM mainly refers to activities to produce maps that completely cover a specified geographical area using a combination of remotely-sensed techniques that collect data at a distance from the mapped area, direct[2] *in situ* (in water) observations (also referred to as ground truthing) and/or modelled data.

1.2 Why is marine habitat mapping important?

The marine environment hosts a wide variety of habitats. Benthic habitats (i.e. those associated with or occurring at the seafloor) are underpinned by various bottom types e.g. sandy and muddy seabeds, or hard bottoms, and include seagrass meadows, coralligenous formations, cold-water coral reefs, mussel beds, kelp and macroalgal forests and sponge aggregations. There are also habitats associated with the water column (i.e. pelagic habitats in the open Ocean). Pelagic habitats support commercially important fish species as well as vital processes maintaining ecosystem functions (e.g. photosynthesis from phytoplankton) and are tightly connected to benthic seascapes. Habitats can be geophysical, i.e. primarily shaped by geology and physical processes, and/or biogenic i.e. formed by living organisms and provide a habitat for other organisms[3].

Europe's citizens and economy depend on these habitats and their associated species to deliver critical provisioning (e.g. food), regulating (e.g. heat and carbon storage) and cultural (e.g. recreation and tourism) ecosystem services. MHMs showing the distribution of species and habitat types, and their functional diversity provide an initial inventory of these important resources (i.e. what, where and how much). Such maps also contribute to the assessment of the economic value of ecosystem services, and promote the integration of these values into accounting and reporting systems at European and national levels (Galparsoro *et al.*, 2014).

MHMs are important for gaining basic knowledge of marine habitats and to provide comprehensive advice on marine habitat conservation and restoration agendas to achieve the objectives set by European Union (EU) and international policies. There are, however, substantial gaps in MHMs in terms of biological detail, geographic coverage and coverage of different habitat types (Gerovasileiou *et al.*, 2019), and the majority of maps do not accurately reflect the ecological role and importance of marine habitats. Worldwide, widespread habitat loss and degradation in coastal and marine systems have been observed as a result of multiple human pressures and a lack of efficient conservation measures at large scales. There is, however, very limited, mostly qualitative information on degraded habitats and their recovery and restoration potential. As a result, current EU regulations underestimate ecosystem change due to human pressures, and the consequent reduction in habitat diversity and complexity.

[1] A biological assemblage is a group of species that coexist in a specific habitat

[2] Direct observations are those collected close to the object of interest

[3] Examples of biogenic habitats include some species of seagrass (e.g. *Posidonia oceanica*), coralligenous formations, cold-water coral reefs and mussel beds.

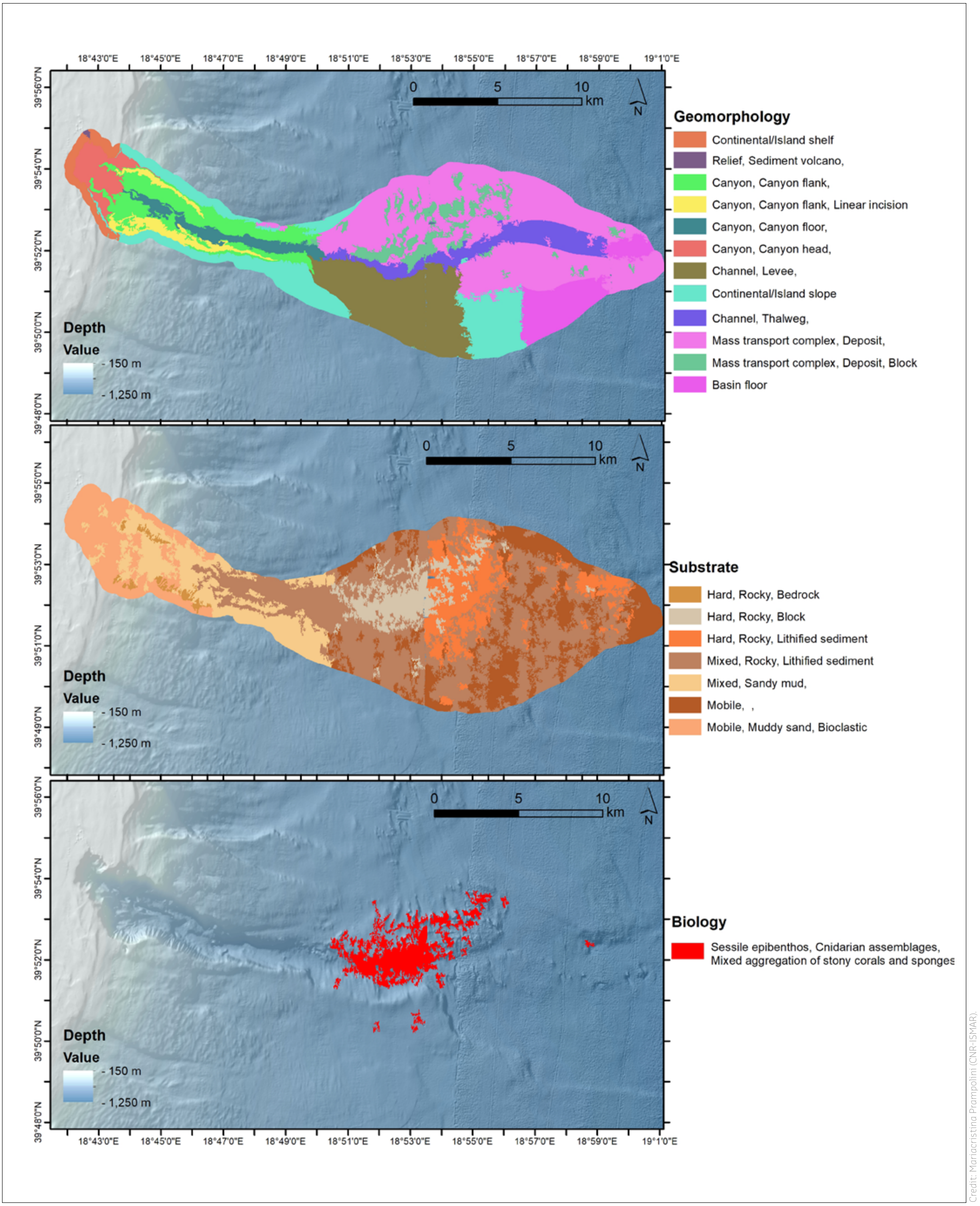


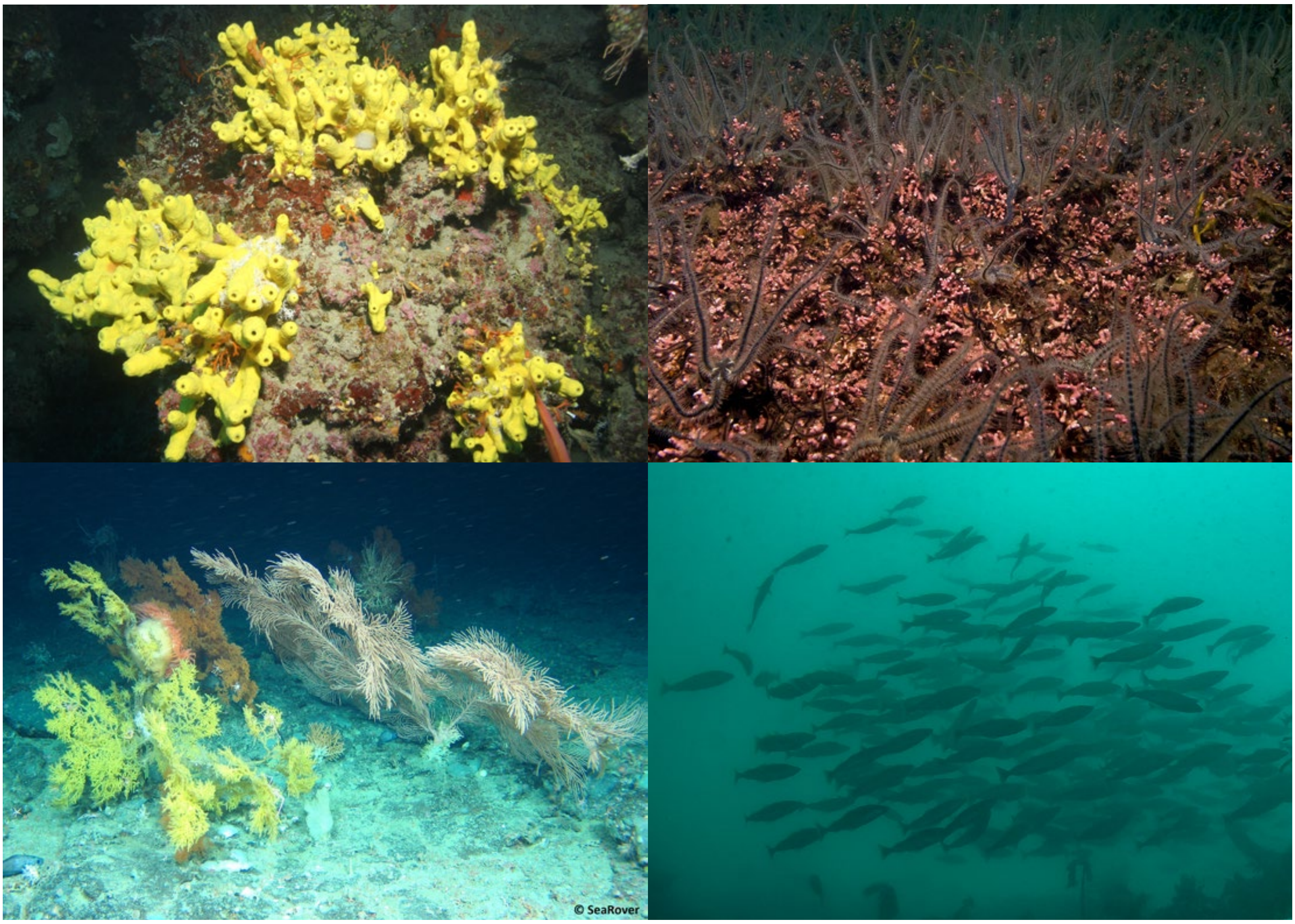
Figure 1.1. Maps showing different components of habitats in a submarine canyon: **(A)** physical shape of the seabed (i.e. geomorphology); **(B)** substrate (i.e. bottom type); and **(C)** biological assemblage (classified according to the CoCoNet[4] Habitat Mapping Scheme).

[4] https://cordis.europa.eu/project/id/287844/fr

1.2.1 Marine habitat maps are needed to fulfil policy objectives

MHMs enable spatial management of human activities and are critical for providing reliable information to support various policies and management tools (Table 1.1). The main EU policy driver for MHMs is the Marine Strategy Framework Directive (MSFD), which requires Good Environmental Status (GES) to be achieved across the entire seabed (i.e. the 22 Benthic Broad Habitat Types, BBHT), with agreed policy goals to have 75% of each BBHT in GES. MHMs are required to facilitate the reporting of these status assessments via the indicators that are used to evaluate the spatial coverage or extent of certain features or habitats. In addition, the coverage of Marine Protected Areas (MPAs) needs to increase to achieve the target of protecting at least 30% of European seas by 2030 and building a network of MPAs with improved connectivity[5] as part of the EU Biodiversity Strategy, and for the representative implementation of the Natura 2000 network. To plan, design and monitor networks of coherent and effective MPAs we need to know where habitats are, their connectivity, how they will change under climate change and ultimately, their ecological status (i.e. whether they are degraded or not). This knowledge will enable MPA networks to be designed to accurately represent ecological processes. Currently, most conservation actions, management decisions and policies are based on a two-dimensional approach and do not explicitly incorporate the three-dimensional nature of the Ocean (i.e. linking benthic and pelagic systems) or the fourth dimension (i.e. including time). In addition, mapping and assessment of ecosystems and their services within Member State's national territories is one of the key approaches of the EU Biodiversity Strategy, which aims to support their maintenance and restoration.

To plan and spatially prioritise active restoration interventions, we need to be able to document and monitor the location and extent of degraded habitats (Gerovasileiou *et al.,* 2019). The proposed EU Nature Restoration Law has set ambitious targets that demand a profound knowledge of the distribution and extent of European marine habitats to assess the percentage of each habitat that is in poor condition and therefore suitable for restoration measures (Hering *et al.,* 2023). To manage and sustainably exploit fish and other commercial stocks that may see changes in their distribution with climate change, MHM over spatial and temporal scales can also help to plan for the future.



Credit: Mišo Pavičić, IZOR (top left), Graham Saunders © Crown copyright (top right), George Stoyle © NatureScot (bottom right).

The marine environment hosts a wide variety of habitats including sponge aggregations **(top left)**, maërl beds, **(top right)**, deep-sea coral gardens **(bottom left)** and pelagic habitats associated with the water column **(bottom right)**.

[5] Connectivity is the extent to which populations in different parts of the species' range are linked by the movement of eggs, larvae or other propagules, juveniles or adults.

Table 1.1 Examples of international and EU policies, directives and conventions benefiting from MHMs, and objectives and activities were MHMs of the physical environment, habitats and species composition are of critical importance for their implementation.

POLICY/DIRECTIVE/CONVENTION	OBJECTIVES AND ACTIVITIES FOR WHICH MHMS ARE OF CRITICAL IMPORTANCE
International Level	
UN Convention on Biodiversity (CBD, 1992)	· Developing ecosystem-based management of fisheries and marine biodiversity, which requires spatial information on ecological values from local, regional and global scales.
UN Sustainable Development Goals (SDG's; United Nations, 2015)	· Mapping and monitoring biodiversity and ecosystem services for SDG14 ("Life below water"). · Planning for sustainable aquaculture and conservation of fish habitats for SDG2 ("Zero hunger"). · Monitoring and planning carbon sequestration and energy production for SDG13 ("Climate action").
UN CBD Kunming-Montreal Global Biodiversity Framework (CBD/COP/DEC/15/4, 2022)	· Providing guidance for the following targets: - Target 1: Plan and manage all areas to reduce biodiversity loss. - Target 2: Restore 30% of all degraded ecosystems. - Target 3: Conserve 30% of land, waters and seas. - Target 8: Minimise the impacts of climate change on biodiversity and build resilience. - Target 11: Restore, maintain and enhance nature's contributions to people. - Target 14: Integrate biodiversity in decision-making at every level.
EU Level	
Habitats Directive (Council Directive 92/43/EEC, 1992) and Birds Directive (Directive 2009/147/EC, 2009)	· Representative and sufficient implementation of the Natura 2000 network of protected areas, which are regionally designated. · Assessment of favourable conservation status to account for changes in areal extent and condition of habitats and species.
Water Framework Directive (Directive 2000/60/EC, 2000)	· Guiding the assessment of the extent of good ecological status within water bodies as an integral part of indicators and communicating to wider stakeholders. · Supporting working materials before, during and after assessment phases. MHMs help policy-makers to navigate and interpret the data, draw conclusions, and find knowledge gaps.
Marine Strategy Framework Directive (MSFD; Directive 2008/56/EC, 2008)	· Status assessments and programmes of measures for GES for MSFD descriptors, e.g. "Biodiversity" (Descriptor 1) requires estimates of the extent and quality of selected habitats and species in EU marine waters and "Seafloor Integrity" (Descriptor 6) involves assessing the extent and condition of 22 'Benthic Broad Habitat Types' (BBHT) which together cover the entire seabed of EU marine waters.
European environmental economic accounts (Regulation 691/2011, 2011)	· Member States must map habitat extent, classify habitats and assign monetary value to mapped classes in order to produce ecosystem accounts for terrestrial and marine ecosystems. The upcoming 2024 report by EUROSTAT will include data on the marine environment.
Common Fisheries Policy (Regulation EU 1380/2013)	· Understanding the spatial structure and connectivity among fish stocks, the location of Essential Fish Habitats, and the sensitivity of benthic habitats in order to manage stocks and support the environmental, economic and social dimensions of fisheries. · Site selection and expansion of sustainable aquaculture, which requires spatially explicit knowledge about benthic biodiversity, physical properties and competing human activities.
Maritime Spatial Planning Directive (Directive 2014/89/EU, 2014), included within the Integrated Maritime Policy (COM/2007/574 final, 2007)	· Planning, resolution of spatial conflicts and identification of synergies among sites for activities such as renewable energy, tourism, aquaculture, and fisheries, and in relation to achieving GES under MSFD and Favourable Conservation Status under the Habitats Directive. These decisions must be based on sound knowledge of the spatial distribution of habitats and their ecological and physical characteristics.
European Green Deal (COM/2019/640 final, 2019)	· Achieving the aims within the targeted policy areas for the marine environment, e.g. "Clean energy" (marine spatial planning of renewable energy), "Farm to fork" (site selection for aquaculture facilities and minimising fishing impacts) and "Biodiversity" (assessing status, identifying suitable areas for restoration and for designation of MPAs).
EU Biodiversity Strategy for 2030 (COM/2020/380 final, 2020)	· Identifying where habitats are, how big they are, their connectivity, and ultimately, their ecological status to enable MPAs and Natura 2000 site networks to be designed to accurately represent ecological processes in order to achieve the target of protecting at least 30% of European seas by 2030 (30x30 target).
Sustainable Blue Economy Strategy (COM/2021/240 final, 2021)	· Planning the sustainable growth of the marine and maritime sectors.
EU Nature Restoration Law (proposed; COM(2022) 304 final, 2022)	· Knowledge on the distribution and extent of the European habitats, including marine habitats, is required to assess the percentage of each habitat in poor condition and therefore in need of restoration measures. In its current form it will require an unprecedented effort to map the current (and in some cases past) distribution and extent of marine habitats, which are already severely affected by decades or even centuries of human impacts.

The scaling-up of offshore renewable energy and other Blue Economy activities are planned as part of the European Green Deal and the EU Sustainable Blue Economy Strategy, for which MHMs will aid spatial planning (Danovaro *et al.,* 2024). On a global level, the successful implementation of Sustainable Development Goal 14: Life Below Water (SDG14), also requires detailed knowledge of the distribution of marine biodiversity and ecosystem services.

1.2.2 Marine habitat maps are essential tools for informed management decisions

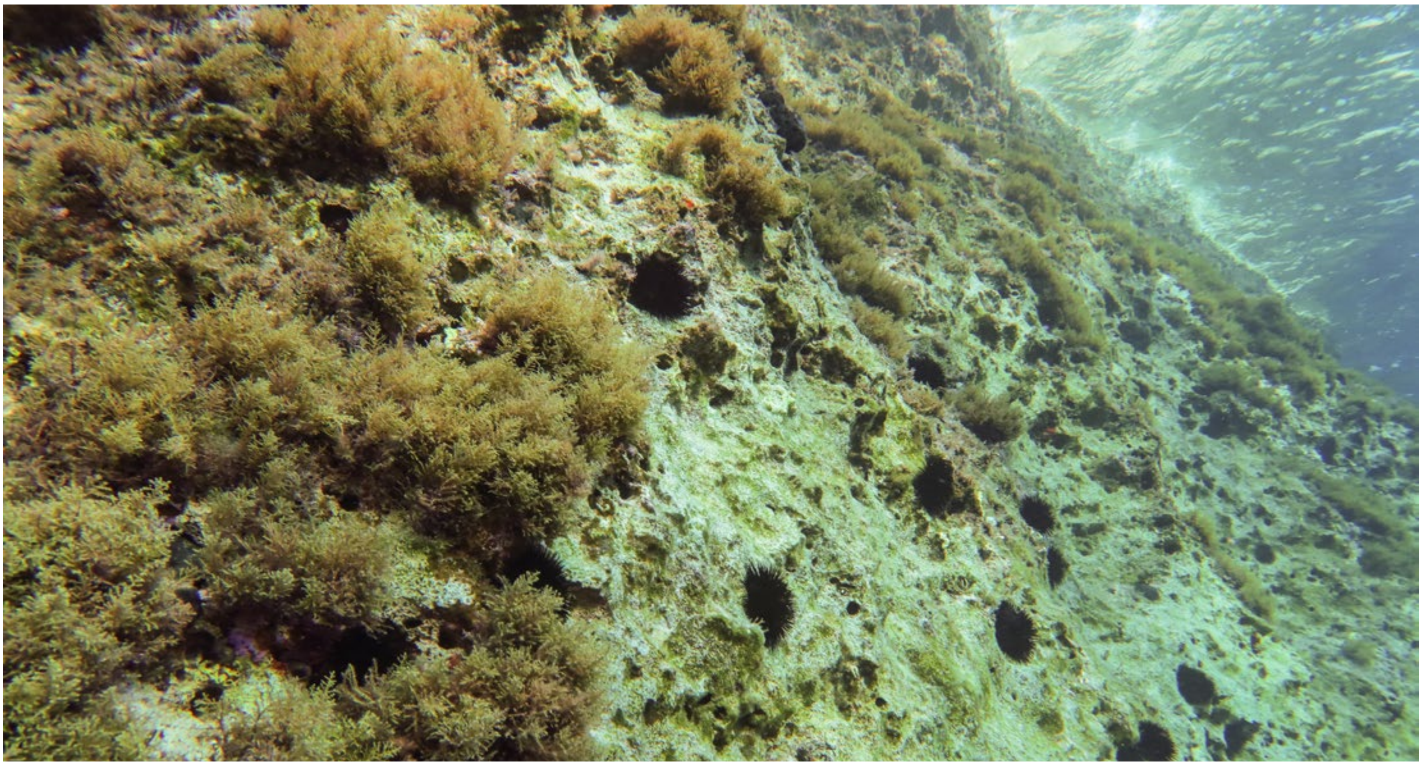
Ecosystem-based management is urgently needed but rarely implemented effectively due to a substantial lack of knowledge about biodiversity distribution and status, and ecological processes occurring in space and time. MHMs can enable the successful application of ecosystem-based management through simultaneously visualising various types of information (e.g. of human activities, species, ecosystem services), which can help to prioritise areas to be restored and protected. Other management tools, such as the development and application of "digital twins", which aim to allow decision-makers and stakeholders to test the outcomes of different management decisions using a virtual representation of the Ocean, also rely heavily on the availability of high-resolution MHMs.

1.2.3 Marine habitat maps support industry

MHMs are useful for some industry-led applications and are valuable for many different economic developments (see Box 1 for further information on the economic return on investment of MHM). MHMs should be prioritised in environmental impact assessment studies for new Blue Economy activities such as the siting of offshore wind farms, aquaculture facilities and underwater pipelines that are expected to occupy large areas. A further example of the importance of MHMs, is the Marine Stewardship Council's (MSC) ecolabeling for seafood, where fisheries must demonstrate that they are carefully managed and do not affect the structure, productivity, function, and diversity of the marine ecosystems. Local MHMs that include information about the distribution and status of important ecosystems are used for this purpose (e.g. Morris *et al.,* 2023).

Box 1 The financial return of marine habitat mapping

In 2008, PricewaterhouseCoopers (PwC) were commissioned to undertake a detailed appraisal of Ireland's national marine mapping programme, INFOMAR[6], which delivers comprehensive marine datasets for Irish waters to multi-sectoral end-users (see Table 4.1 for more information). PwC evaluated the costs and benefits, with benefits being identified and categorised as: commercial/resource; knowledge economy; legislative requirements and obligations; and environmental. The analysis estimated a four to six times return on investment based on economic maritime activity of interest for policymakers and private operators involved in offshore renewable energy, fishing and aquaculture (PricewaterhouseCoopers, 2008).



Credit: Alberto Colletti

To plan and spatially prioritise active restoration interventions, we need to be able to document and monitor the location and extent of degraded habitats.

[6] www.infomar.ie

1.3 Challenges facing marine habitat mapping

Effective management and conservation of marine habitats is more difficult than terrestrial habitats, due to limited knowledge of their conservation status. Approximately 27% of marine habitats in Europe are classified as 'unknown' (Maes *et al.,* 2020) and only a very small fraction of the seabed has been mapped at comparable resolution to that on land (Wright & Heyman, 2008). This is in part because MHM is more complex and technically demanding than terrestrial habitat mapping due to difficulty in accessing the vast Ocean. There are various technical difficulties of mapping through water of varying depths, including the lack of light penetration, which greatly limits optical remote sensing techniques such as satellite imaging.

This means that the extent and resolution of seabed mapping is highly variable, with 24.9%[7] of the seabed currently mapped using bathymetric data. Typically for chartering purposes, the same area hasn't been converted into MHMs due to the lack of ground truthing data necessary for modelling habitats. MHM is therefore more challenging than mapping of other remote locations in our solar system which do not have liquid surface water and the resolution of seabed data is significantly poorer than similar surface mapping of other planets. For example, NASA's MErcury Surface Space ENvironment, GEochemistry, and Ranging (MESSENGER) has mapped the entire surface of Mercury at 166m resolution (Ernst *et al.,* 2022); NASA's Magellan spacecraft mapped 98% of the surface of Venus at a resolution of around 100m (Sauders *et al.,* 1992; and NASA's Mars Reconnaissance Orbiter[8] has imaged the entire surface of Mars at 100m resolution, and over 60% of Mars has now been mapped at approximately 20m resolution (Sidiropoulos *et al.,* 2015). In comparison, satellite altimetry[9] has mapped the entire seabed but only at a resolution of 5900m on average (Tozer *et al.,* 2019).

Key challenges to mapping the Ocean floor include: (i) the need to rely on acoustic rather than optical techniques in aquatic environments; (ii) the demanding engineering required for working in deep, high-pressure environments; and (iii) the high cost of mapping expeditions including the need for ships and specialised equipment (see Table 2.1 in Chapter 2). The reliance on acoustic techniques (i.e. remote sensing techniques using sound rather than light) for seafloor mapping in all but the shallowest water restricts the detection of the seabed to predominantly physical features and properties (Brown *et al.,* 2011) rather than biological information. This process is slow and it is estimated that it would take almost 125 years to fully map the seafloor using acoustics[10].

Due to the difficulty in accessibility to collect direct, *in situ* observations, MHM to date has heavily relied on models to predict the presence of species in unsampled areas based on known physical features from depth data (i.e. bathymetry) and environmental conditions (see Chapter 3). Reliable predictive models require good data on environmental conditions that are correlated to *in situ* observations to ground truth the distribution of species and biological habitats (Stevens & Connolly, 2004). However, environmental data are not available in many areas or are not detailed enough to be useful for predicting species distribution. The use of proxies can therefore limit the accuracy of MHMs, and their value for use in management, conservation and restoration.

Despite the critical need to refine distribution maps of many species and biological communities, direct, *in situ* observations of marine life on the seafloor and in the water column (e.g. taken by SCUBA diving and Remotely Operated Vehicles, ROVs) are less abundant across space and time than physical mapping data, limiting the ability to accurately map their distribution. In addition, the identification of species is difficult and typically requires the collection of physical samples, as many species cannot be identified from images alone. Taxonomists capable of identifying species are becoming increasingly rare, while new technologies such as environmental DNA (eDNA[11]; Thomsen & Willerslev, 2015) have limitations, including incomplete reference databases. For these reasons over 90% of marine species are estimated to be unknown to science (Mora *et al.,* 2011). The importance of marine habitats for biodiversity lies in the small-scale complexities of patterns and processes, which require high spatial, temporal and taxonomic resolution. New technologies that increase the spatial coverage of high-resolution direct observations are emerging, and show promise for improving the quality and resolution of MHMs (see Chapter 2).

A further challenge is the tendency for MHM efforts to focus mostly on benthic habitats. Currently, the water column is mostly mapped according to single physical variables (e.g. salinity, temperature or physical currents). However, three-dimensional mapping of large ecosystem patterns and processes, such as ecological connections including life cycles, food webs and biogeochemical cycles (Boero *et al.,* 2019), still largely do not exist due to significant data gaps. These gaps can greatly limit MHM ambitions and are important to overcome for the production of predictive models of species distributions. Combining data from different scales and collected using different techniques also poses problems and often results in uncertainties with the use of proxies, and ultimately, end products.

7 https://seabed2030.org/our-mission/
8 https://mars.nasa.gov/resources/8333/a-decade-of-compiling-the-sharpest-mars-map/
9 Satellite altimetry is a technique used to measure the height of the Ocean's surface from space, which varies depending on bathymetry therefore indirectly providing information about the seabed.
10 https://www.nist.gov/how-do-you-measure-it/how-do-you-measure-depth-ocean#:~:text=Despite%20the%20advantages%20of%20using,world%27s%20oceans%20have%20been%20mapped
11 eDNA is genetic material collected directly from environmental samples such as sediments or seawater.

2 Collecting data for marine habitat mapping

Data collection to create MHMs can be carried out via remote sensing and/or through direct observations (i.e. *in situ* data) (Figure 2.1; see Glossary for definitions of technical methods referred to in this Chapter). Remote sensing techniques typically collect data at a distance from the mapped area (e.g. satellite imaging from space or sonar data for the seabed collected from a surface ship or mid-water autonomous platform) and generate continuous spatial data. In shallow areas satellites, Light Detection and Ranging (LiDAR) and drones (i.e. Unmanned Aerial Vehicles, UAVs) are emerging as viable remote sensing techniques for data collection. *In situ* data are collected via direct observations from the seabed and water column using various types of samplers, cameras and/or SCUBA divers and provide information on physical and biological properties, which is required to ground truth remotely-sensed observations. SCUBA diving is used to collect ground truthing data particularly in environments that are challenging to reach using other techniques, such as submarine caves. In general, public-private partnerships can help to advance novel methods to collect MHM data.

Both remotely-sensed and *in situ* data can be used in isolation to produce maps. Remotely-sensed data have extensive coverage, but low biological resolution, while *in situ* data are highly localised observations containing a high level of biological detail of habitat types. If habitats cannot be directly detected in remotely-sensed data, models can be used (see Chapter 3) to link and extrapolate *in situ* observations with remotely-sensed data to produce maps at resolutions and spatial extents appropriate for the aims of the specific MHM initiative and including relevant physical and/or biological variables (e.g. Angeletti *et al.,* 2019).

2.1 Collecting remotely-sensed data

2.1.1 Current methods

Remote sensing techniques vary in resolution, spatial coverage and scope of application. For the sea-surface and shallow-water benthic and pelagic habitats (in clear waters), satellite and airborne methods are cost-effective ways of collecting data over large areas. Depending on water properties, these methods can look into the top 0-100m of the Ocean, and have been particularly effective at mapping seagrass and kelp habitats at shallower depths (e.g. Casal *et al.,* 2011). For the seabed, remote sensing can be used to directly detect features and can generate satellite-derived bathymetry data. An example of an airborne method is bathymetric LiDAR, which relies on infrared and blue-green laser pulses to measure down to 40-70m below sea level, although resolution and accuracy are impacted by visibility, with reduced efficiency in turbid waters. They can measure the depth of the seabed to an accuracy within one metre, collecting precise and detailed measurements, enabling more accurate mapping of coastal waters. In addition, UAVs can be systematically adopted to facilitate mapping of coastal habitats across areas that are tidally restricted to other mapping equipment, and can also collect ground truthing data.

Multibeam Echosounders (MBES) are widely used both in the deep sea and shallow water, to collect contiguous (i.e. continuous across a geographic area) data over large areas about bathymetry (depth and shape), softness (an indicator of substrate type), and roughness/rugosity of the seabed (an indicator of substrate type and habitat complexity) (Lurton, 2010). The resolution and coverage of MBES bathymetry and backscatter[12] data are governed by water depth and by the technical specificities of the MBES device such as frequency. In areas down to a depth of 200m, higher frequencies are ideal for achieving greater resolution. MBES coverage is directly proportional to water depth, therefore MBES is more cost-effective in terms of acquisition time in deeper waters. Higher-resolution data can be acquired by bringing the MBES closer to the target, e.g. using platforms that operate closer to the seabed such as Autonomous Underwater Vehicles (AUVs). These methods provide contiguous three-dimensional data (i.e. benthic and water column) that serve as the basis for the production of MHMs. These data, together with seabed ground truthing using direct samples obtained from grab sampling and/or photographs, allows for geological interpretation and detection of biogenic habitats due to the differences in their signals. Bathymetric LiDAR, where feasible (i.e. in clear or turbid water), has increased survey efficiency when compared to shallow-water MBES (Prampolini *et al.,* 2020).

[12] Backscatter data measures the intensity of sound waves released from Multibeam Echosounder devices reflected back from the seabed and are used to measure substrate softness and texture.

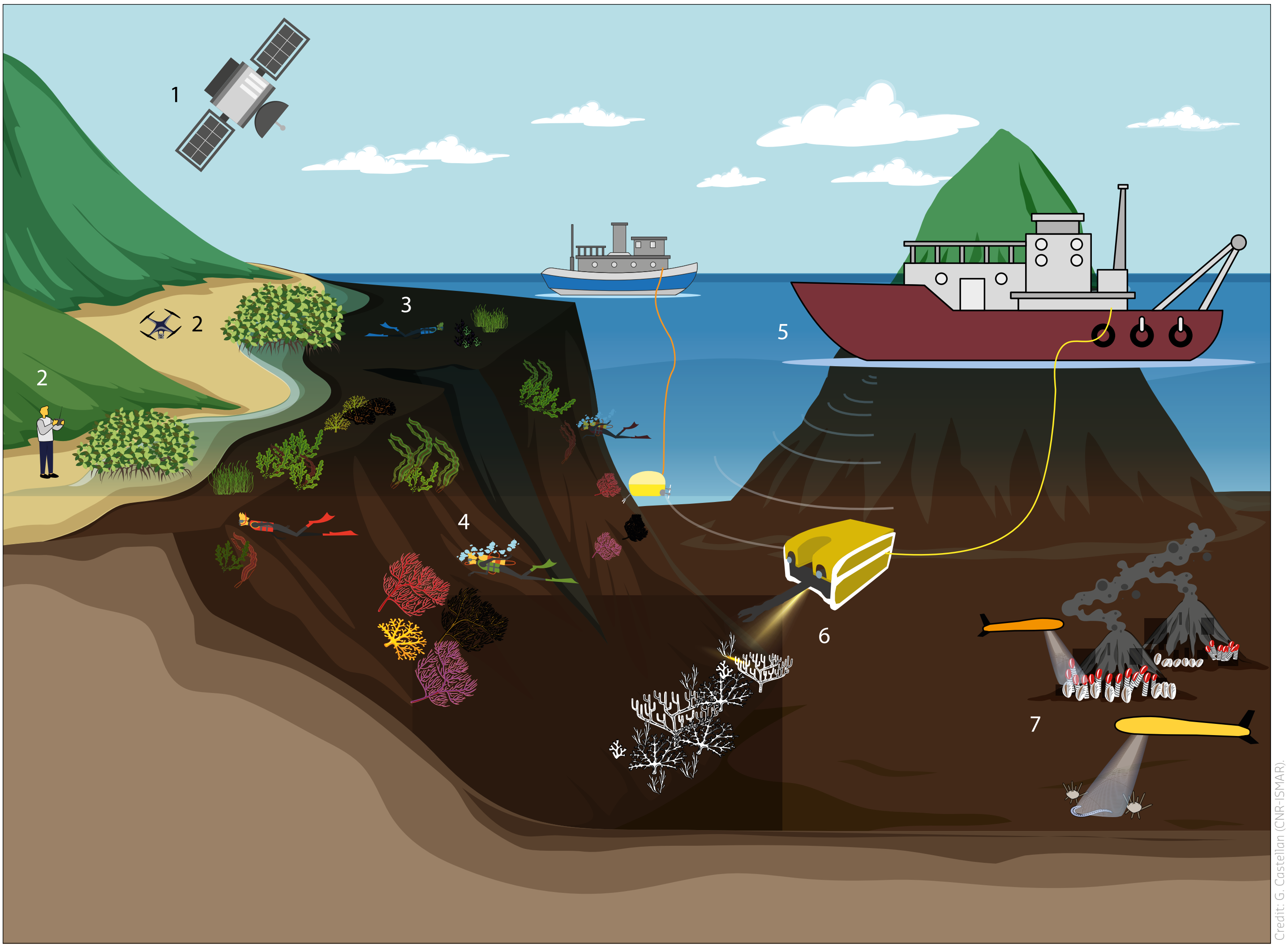


Figure 2.1 Overview of MHM approaches over a depth continuum, which can be used according to the aim of the mapping initiative. MHM from intertidal to shallow depths is performed by satellites **(1)**, Unmanned Aerial Vehicles (AUVs) or drones **(2)**, snorkelling **(3)** and scuba diving **(4)**. Multibeam Echosounder systems and side-scan sonar on board oceanographic vessels **(5)**, unmanned underwater technologies e.g. Remotely Operated Vehicles (ROVs) **(6)**, and Autonomous Underwater Vehicles (AUVs) **(7)** are used for MHM in deeper water. Note that multibeam echosounder and side-scan sonar can be used for MHM in both shallow and deep water.

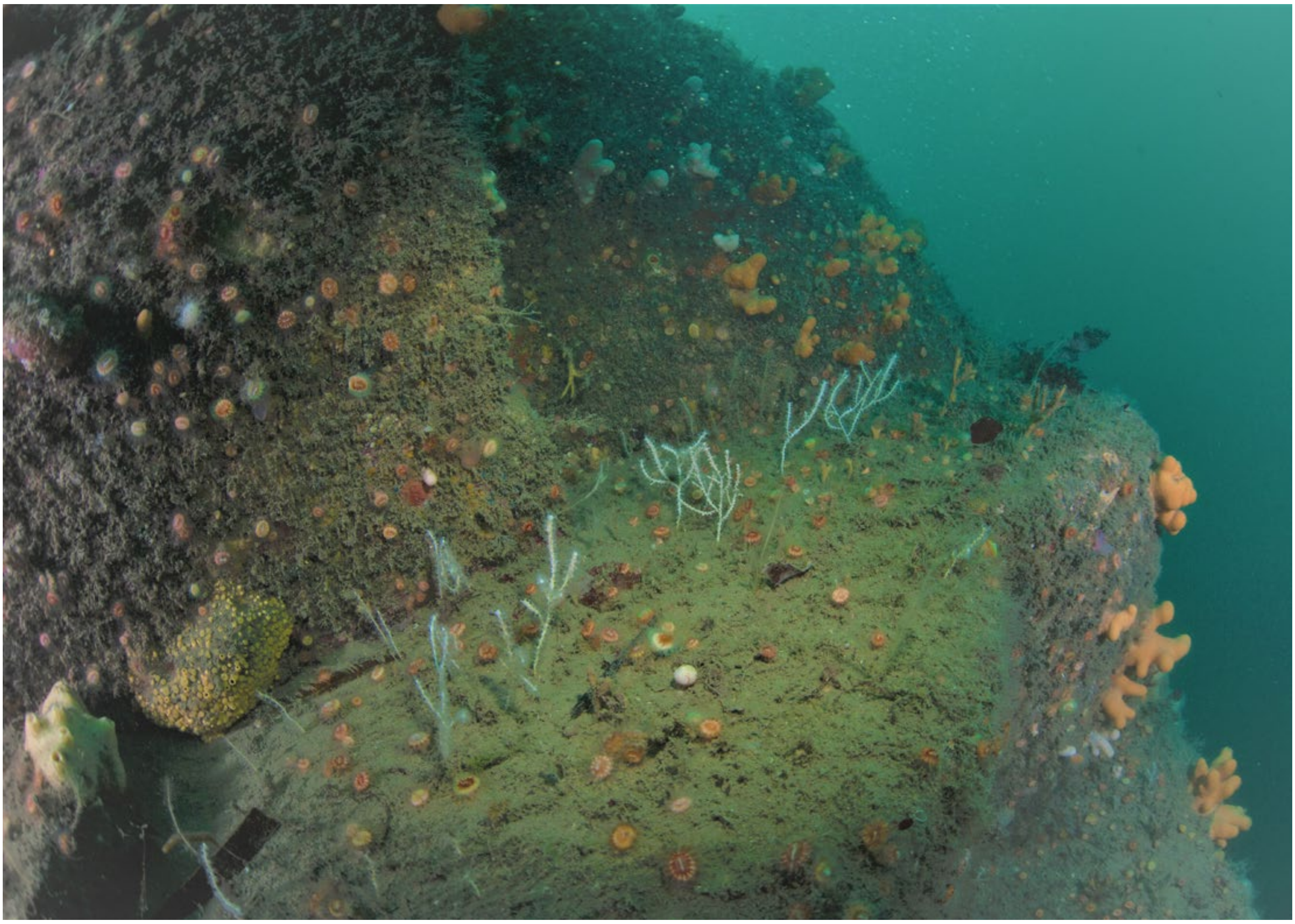
Side-Scan Sonar (SSS) is also widely used for MHM in shallow and deep water. It operates by emitting acoustic pulses to the sides of a survey vehicle or sonar tow-fish (i.e. an object carrying sonar equipment that is towed behind a vessel). The returning echoes provide detailed imagery of the seafloor and of objects. It provides higher resolution images compared to MBES backscatter, particularly in deeper water where the tow-fish is closer to the seabed. Both SSS and MBES backscatter technologies are valuable and serve different purposes, with SSS focusing on detailed imaging and being more suitable for object and feature detection, while MBES backscatter emphasises bathymetric data and seafloor characterisation.

Hydro-acoustic sensors are also widely used by industrial hydrographic surveyors and commercial fishermen to produce seabed maps that increase efficiency and reduce the environmental impact of their activities. This offers collaborative opportunities with scientists.

2.1.2 Future trends

Future aims for remotely-sensed data collection include efforts to increase resolution, spatial coverage, information content, operational efficiency and cost-effectiveness. Data should increasingly be processed within the sensor itself or at a local collection point to allow building of virtual Ocean environments for applications such as situational awareness (e.g. for pilots to be able to comprehend the environment around their robot), virtual research environments (e.g. immersive virtual reality displays of complex data streams) and digital twins (i.e. coupled observation and simulation data frameworks for human and Artificial Intelligence (AI)-based scenario interpretation). Mapping with MBES at angles other than straight-down (e.g. by mounting sonar heads at an angle) allows mapping of previously inaccessible habitats like vertical walls, which although rare, are often inhabited by diverse, sessile organisms (Zapata-Ramírez *et al.*, 2016). The cost-effective collection of MBES data can also be supported through the continued collection of 'underway' data (i.e. opportunistic data collected during transits or non-mapping voyages). Such opportunistic data collection is currently being undertaken by Ships of Opportunity[13] and Seabed2030[14] Finally, the increased use of autonomous underwater and surface platforms offers numerous advantages including: (i) reduced survey costs; (ii) access to remote and challenging locations; (iii) improved data resolution through greater proximity to the seabed; and (iv) a greater potential to dramatically de-carbonise data collection.

Irrespective of the depth and the instrument to be used, future trends in the collection of MHM data should recognise that the Ocean is an interconnected three-dimensional volume where physical, geological, biogeochemical and biological characteristics change and interact (see Figure 2.2). In parallel to collecting seabed data, MBES should be used for water-column imaging (see Section 2.1.3) to collect additional backscatter data on the pelagic habitat. In addition, time is also a highly relevant fourth dimension (European Marine Board, 2019) that complements dynamic three-dimensional MHM approaches and should be taken into account to assess the functioning of ecosystems, also reflecting the rapid turnover of life forms and seasonality. High resolution temporal data can be collected from Ocean observatories and can provide valuable data on the stability of habitats. However, this is still challenging considering that we are very far from having mapped the Ocean even once at sufficient resolution. Including the time dimension in mapping can further support an ecosystem-based management approach for marine ecosystems.



Credit: George Stoyle © NatureScot.

Mapping with MBES by mounting sonar heads at an angle allows mapping of habitats like vertical walls, which are inhabited by diverse, sessile organisms.

[13] https://community.wmo.int/en/ship-opportunity-programme
[14] https://seabed2030.org/

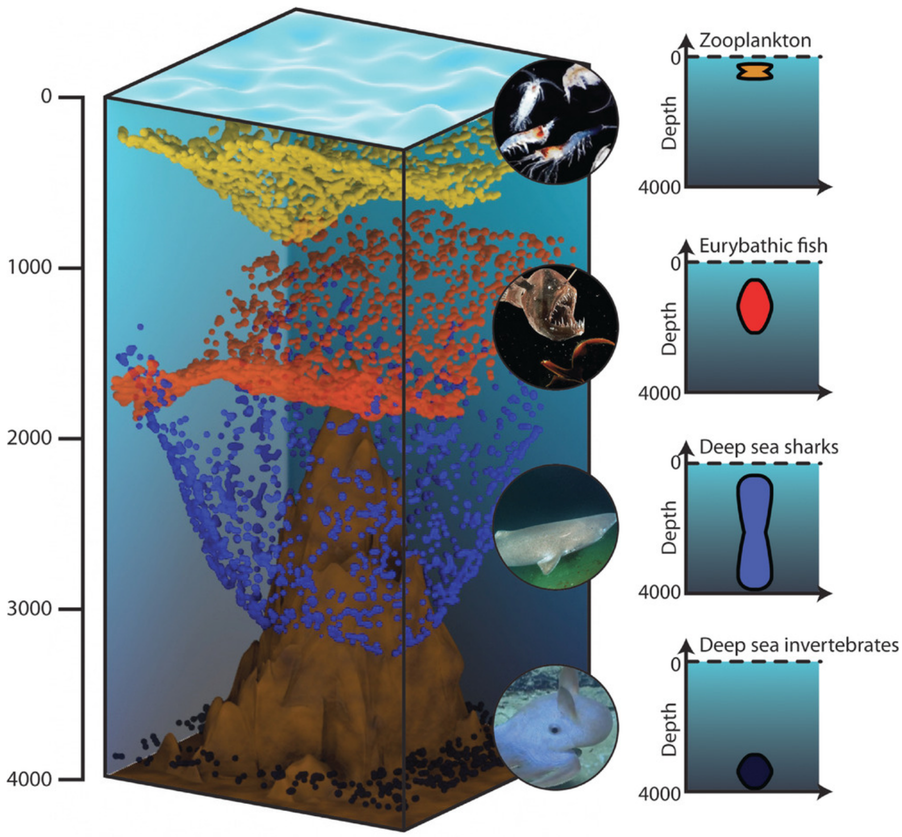


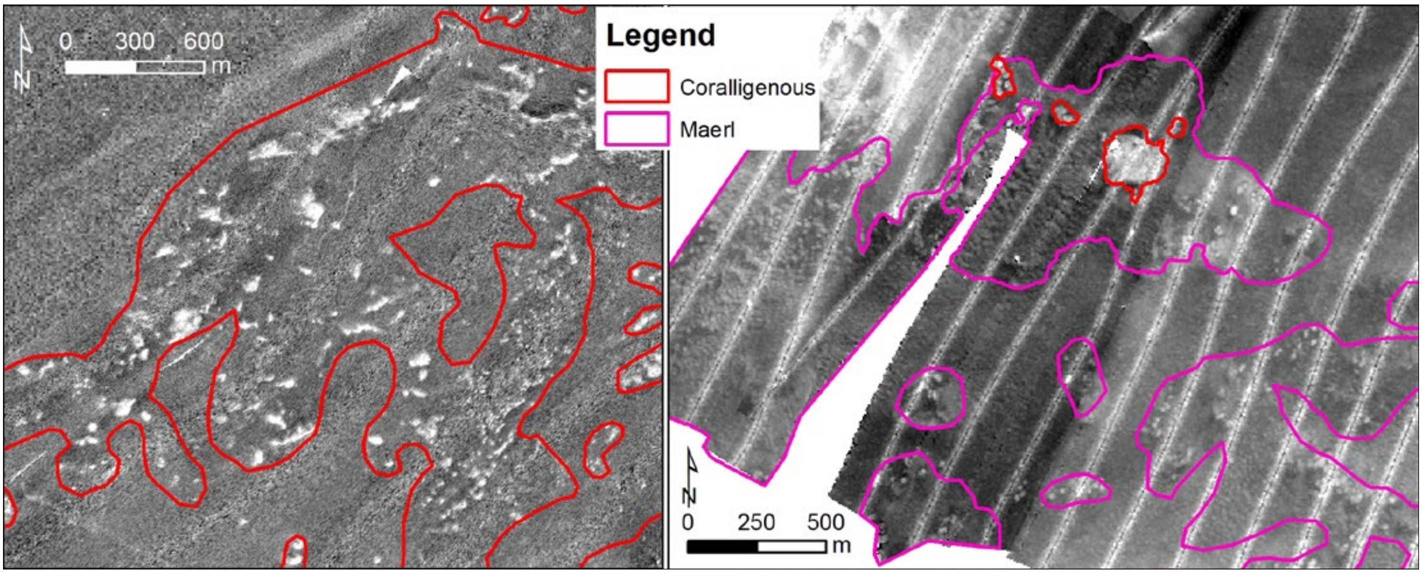
Figure 2.2 Graphical representation showing the integration of benthic habitat and water column data to show the three-dimensional structure of a deep-sea ecosystem. Three-dimensional marine habitat mapping includes multiple depth ranges of the distribution of biodiversity and includes species distributions by incorporating their life cycle, trophic interactions and exchanges between the water column and the seafloor (Levin *et al.*, 2018; CC BY 4.0 DEED).

To compare large-scale maps over time, the repeated collection of MBES backscatter data is particularly valuable. The global consortium "GeoHab Multibeam Backscatter Working Group"[15] is working towards improving technology and standards for this type of data collection. In theory, repeat mapping over time (using remote sensing and *in situ* data) would help to understand: the longevity of maps and mapping data (i.e. how long they remain relevant determined by rate of change of mapped features and human pressures); mobility of features and likely seasonal influences on marine communities. It would also help with monitoring condition and/or recovery in designated areas and early warning for tipping points[16], which has not been widely studied (see Rindi *et al.* 2024 for an example). However, mapping vast and unknown areas of the Ocean for the first time is still the priority.

Some seabed types, such as coralligenous formations and maërl beds, show a similar acoustic signal in backscatter data caused by subtle variations within the habitat itself, that are scale- and resolution-dependent (Lurton *et al.*, 2015; Figure 2.3). These ambiguities can be addressed by proper design of ground truthing and the acquisition of data with multispectral MBES, where the sensors acquire several MBES data using different acoustic frequencies simultaneously. This can result in increased contrast between seabed features and substrate types (e.g. mud, coarse sediment, rock), and thus increase the predictive power of the data for MHM applications. However, multispectral mapping is challenging due to extensive data being required from multiple frequencies, which demands robust ground truth support. Limited and inaccurate data constrain utility, hindering correlation between *in situ* substrate observations and high-resolution acoustic data. This restricts the achievable detail in multispectral mapping. Although more research is essential in this field, and additional testing and validation of the methods are necessary, the efficacy of distinguishing seabed features through the application of a multispectral mapping approach has been proven across a diverse range of seabed sediment types (Brown *et al.*, 2019).

[15] https://geohab.org/backscatter-working-group/

[16] A tipping point is a critical point at which a rapid and unexpected shift is triggered and an ecosystem transitions to a new state with altered composition and functioning



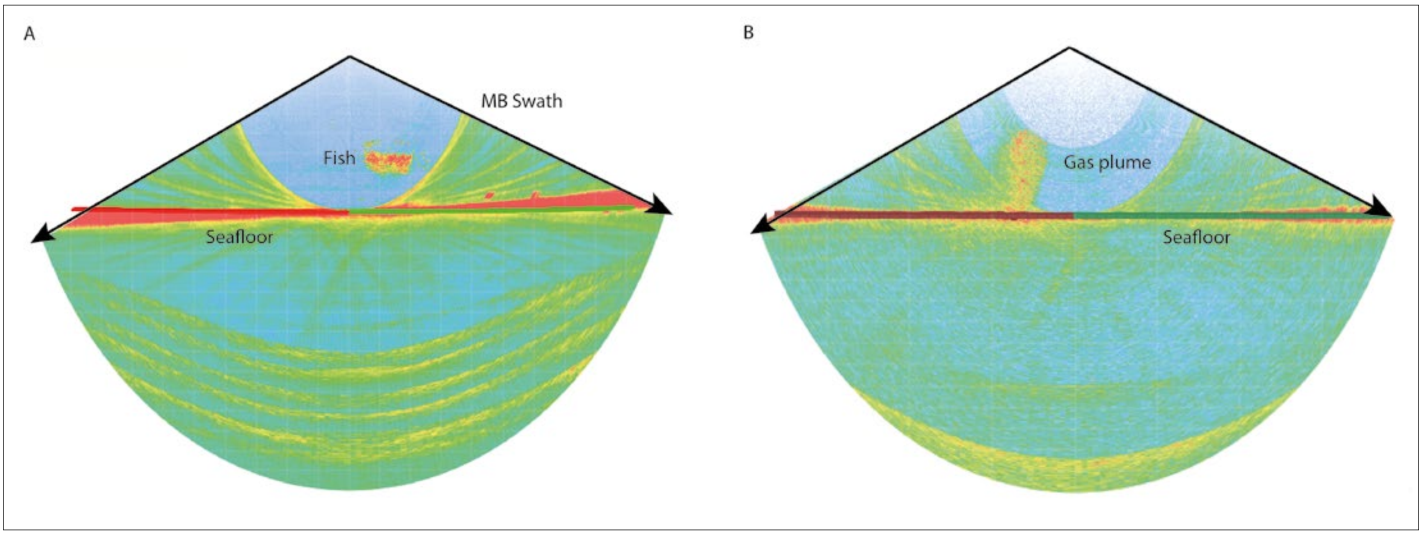
Credit: CNR-ISMAR.

Figure 2.3 Backscatter data showing coralligenous formations (red polygons) and maërl beds (violet polygons) in different areas. The acoustic backscatter signal is similar for the two habitats, and interpretation was only possible due to the ROV images collected in the areas.

2.1.3 Current methods and future trends for water column mapping

There has been less focus to date on mapping the water column compared to benthic habitats. Current methods for water column mapping include those used in modern oceanography: satellites for collecting surface oceanographic data (e.g. on seasonal climatology, chlorophyll-a concentration) that can be used in mapping; drifting "Argo"[17] floats that collect data on temperature, salinity and changes in climate and hydrological cycles down to a depth of 2,000m; underwater gliders equipped with a variety of sensors; and other forms of AUVs that are becoming increasingly important tools for cost-effective data collection on both environmental and biological variables from the water column (e.g. plankton). An example is the use of an AUV to autonomously detect an upwelling front and track its movement on a fixed latitude in four dimensions (i.e. vertical, across the front, along the front, and time), revealing high spatial and temporal variabilities (Zhang *et al.,* 2015).

Marine habitat mappers are interested in how pelagic processes influence benthic habitats, and equally, how seabed geomorphology modifies pelagic habitats (see Figure 2.4. for an example). Modern MBES is able to collect water column data, which provides information on the distribution of acoustically reflective features (e.g. fish, plankton, gas bubbles) within the water column above the benthic area surveyed. However, this information alone is insufficient to map pelagic habitats. As such, multidisciplinary groups (i.e. including marine benthic and plankton mappers, and oceanographers) need to work more closely at large spatial scales, to gather the required environmental information to characterise pelagic habitats and processes connected to the seabed.



Credit: Federica Foglini (CNR-ISMAR) and Fabio Di Giovanna (UNINA).

Figure 2.4 Image of the water column derived from multibeam data showing **(A)** fish and **(B)** a gas plume.

[17] https://argo.ucsd.edu/

Credit: Alberto Colletti (right).

In situ data collection is currently mostly conducted using cameras mounted on moving platforms such as remotely operated vehicles **(left)**. However, imaging techniques do not provide the same level of taxonomic identification as physical samples taken using grabs **(middle)** and SCUBA diving **(right)**.

2.2 Collecting *in situ* observations for marine habitat mapping

2.2.1 Current methods

Traditional *in situ* data collection techniques include the use of grabs, corers, dredges, trawls and SCUBA divers to collect samples and observations. Observations are currently mostly conducted with cameras, which is a non-destructive method providing high resolution data on the water column, seabed substrate and epibenthic communities (i.e. on or just above benthic habitats), often at depths that are inaccessible to divers (Prampolini *et al.,* 2020). Although imaging techniques do not provide the same level of taxonomic discrimination as physical samples taken using destructive methods, they do provide information on substrate, habitat structure, biological community composition, resource abundance, biomass, etc. Video footage provides more information about the extent and patchiness of habitats compared to still images, while still images tend to have higher resolution, allowing finer level of taxonomic identification. Cameras are typically mounted on moving platforms such as ROVs, AUVs, towed underwater platforms or drop cameras suspended from a cable directly below a ship. Extracting information from images has typically been a laborious task, mostly done by manual image annotation (Castellan *et al.,* 2020) resulting in a serious bottleneck in the production of MHMs. Current approaches in using AI for this task have shown promising results, yet need to be further developed and standardised to allow wide adoption and application in monitoring tasks (see Section 2.3).

2.2.2 Future trends

In the future, *in situ* data collection should aim to decrease costs (Table 2.1) through the greater use of autonomous platforms (i.e. AUVs) and AI for image processing. This will mean moving away from single, all-purpose, massive and complex vehicles that serve all science demands towards multiple, low-cost, low-operation profile vehicles with one, or just a few sensors that operate in parallel. This also increases mapping efficiency, as tasks can be done in parallel. Operating AUVs together with other robotic platforms such as benthic crawlers (i.e. robots that move independently carrying scientific instrumentation for scanning a continuous track of the seabed for periods longer than one month), or landers (i.e. robots able to provide high-resolution time-series data at fixed locations), can build a network, or swarm, of sensors to map an area efficiently. The cost-effectiveness of AUVs is also improving due to miniaturisation, allowing deployment from smaller vessels or even from the shore. The greater duration of time for which modern units are able to operate is also helping to lower costs. Furthermore, AUVs are able to operate much closer to the seabed when compared with surface platforms. This proximity facilitates the collection of higher resolution products such as micro-bathymetry (i.e. capturing fine-scale details such as ridges and valleys) from *in situ* lasers and full coverage photo mosaics from onboard cameras.

Making these vehicles intelligent enough to analyse raw data and implementing communication within an underwater network of robots can guide the selection of optimal observation and sampling locations, and steer vehicles efficiently and safely. This will help to implement efficient and cost-effective mapping, which maximises information obtained while minimising the resources and efforts required. The suggested approach involves the initial production of an overview map by intelligent sensor platforms that reduce and pre-classify data using AI, which speeds up later data analysis. Keeping these platforms in the Ocean, without the need for monitoring by a nearby surface vessel, substantially increases the area from which data can be collected. Such persistent autonomous systems are well suited to map and monitor seasonal changes in habitats (including both the seabed and the water column) and the identification of thresholds of changes and species invasions.

Despite still being very challenging, eDNA is a promising approach to support broad scale MHM as a ground truthing technique. eDNA methods offer a number of important advantages over traditional techniques, including non-invasive sampling, and lower cost and effort. Enabling the characterisation of biodiversity across broad taxonomic groups, eDNA can provide valuable insights into biodiversity patterns and processes, including shedding light on the consequences of anthropogenic pressures and informing management actions. However, there are still important limitations, including the lack of standard protocols for eDNA sampling in the field and analysis in the lab, and gaps in taxon coverage in reference libraries, which means that many sequences derived from eDNA analysis cannot be assigned to their source taxon. This currently limits the value of eDNA for high-resolution map production. For more information on eDNA, see the Ocean and Biodiversity Chapter of Navigating the Future VI[18].

[18] https://www.marineboard.eu/navigating-future-vi

Credit: PlanBlue.

Hyperspectral imaging technology offers the potential to collect more detailed and efficient *in situ* mapping data.

Hyperspectral imaging can be used to collect *in situ* imagery in the visible portion of the electromagnetic spectrum (390-700nm) at up to 1nm resolution (Montes-Herrera *et al.,* 2021). It captures images using many wavelengths, resulting in finer resolution and more detailed information. This additional optical resolution is useful for broader-scale automated classification of species and seabed features, each of which has a distinct pattern of electromagnetic light that is reflected across different wavelengths. To collect more detailed and efficient *in situ* mapping data, additional light sources can be used that induce fluorescence within a species (e.g. Teague *et al.,* 2019). However, due to their cost, these cameras are not currently widely used. Equally, the database of spectral signatures required to match (i.e. cross-reference) and identify species and features, must be greatly expanded to enable reliable and broader application of this technique.

Underwater photogrammetry has increasingly been used (e.g. Figure 2.5) to accurately measure the three dimensions of benthic habitats to represent their complexity. Photogrammetry uses multiple overlapping photographs to determine the size, shape and position of features. Recent developments in hardware and image processing have made the reconstruction of high-resolution three-dimensional models of relatively large areas (1ha / $0.01km^2$) possible (Pulido Mantas *et al.,* 2023). The value of photogrammetry derived from imagery is that expensive sonars are not required. The limitation is that it is dependent on optical imagery, which typically limits data collection to very close to the seabed (limiting the spatial extent of mapping) or only mapping in very shallow waters, using diving or aerial platforms.

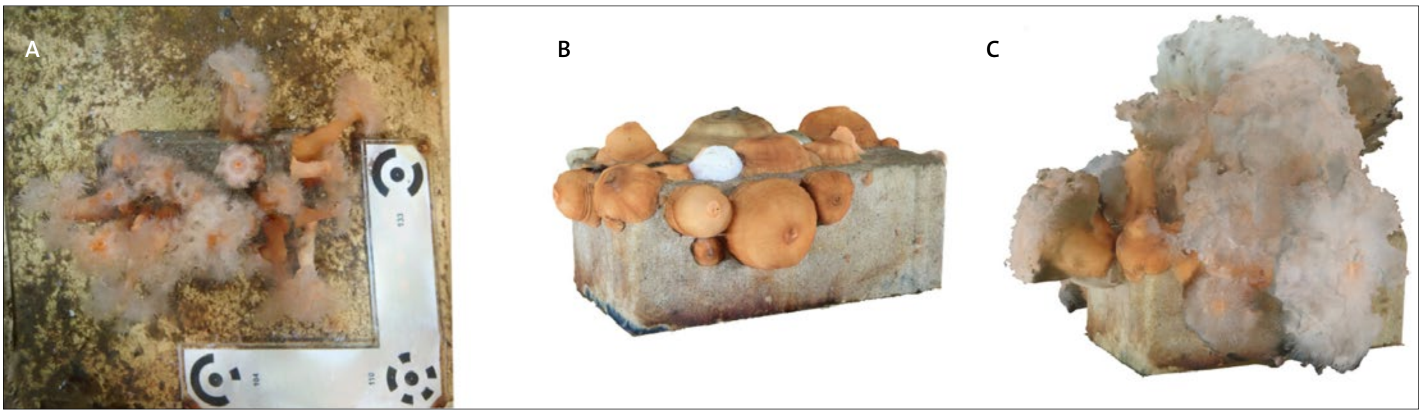


Figure 2.5 3D models of a sea anemone generated using photogrammetry: **(A)** *in situ* image, **(B)** retracted anemone, **(C)** fully extended anemone (Marlow *et al.* 2024; CC BY 4.0 DEED).

Table 2.1 Overview of MHM data collection platforms, data types, achievable European Union Nature Information System (EUNIS) level (see Section 3.3), associated use cases, spatial scale and resolution, and estimated acquisition costs. Costs are intended to provide a very broad indication of the order of magnitude of the economic effort according to the different aims, resolution, platforms and research frameworks of MHM initiatives.

	PLATFORM	DATA TYPE	EUNIS LEVEL ACHIEVABLE	FIT-FOR PURPOSE USES	POTENTIAL EXTENT [km^2]	RESOLUTION [m]	COST [€k/km^2]
Remote sensing	Satellite	Gravity data to measure bathymetry/ images	Up to 4	Large-scale/low-resolution inferences on physical/ biological habitats, predictive modelling	10 trillion	1000	0.5
	Ship >1000m water depth	MBES/SSS	Up to 3	Large-scale/low-resolution inferences on physical habitats, predictive modelling	1000	100	5.1
Remote sensing and *in situ* observations	AUV	MBES/SSS and images	Up to 3	Small-scale/high-resolution inferences on physical habitats, predictive modelling	10	1	3.2
	UAV/drone <10 m water depth	Images	Up to 6	Mapping of biological habitats, predictive modelling, *in situ* observations	0.1	1	0.5
In situ observations	ROV	Images	Up to 6	Mapping of biological habitats	0.1	<0.01	4.3
	Small boat <20 m water depth	Images from drop cameras	Up to 6	Mapping of biological habitats, predictive modelling	1	10	1.6
	SCUBA diving	Images and *in situ* observations (e.g. species lists)	Up to 6	Mapping of biological habitats, direct mapping of features	1	10	4
	Sampling (grabs, dredges cores, etc. using small/ big vessels	Sediment and faunal sample	Up to 6	Mapping of biological habitats, predictive modelling	0.1	1	8

2.3 Integrating artificial intelligence within marine habitat mapping

The application of AI techniques, such as machine learning and deep learning (i.e. learning patterns directly from data), have the potential to contribute to and revolutionise many aspects of MHM, from the acquisition of data through to the production and interpretation of end products, including automated image analysis (Figure 2.6). The recent migration to autonomous survey vehicles has generated opportunities for AI to plan missions and/or respond to the detection of features, for single devices and swarms of multiple devices using onboard autonomous decision-making. The future proliferation of autonomous vehicles and the advancement of digital cameras could drive an exponential increase in the quantity, quality and complexity of habitat imagery. Traditionally, the number of days at sea limited the number of images that could be collected. The availability of human expertise to examine and annotate these images is also a key limiting factor. AI techniques could increasingly drive the development of machine vision, where machines are able to autonomously perceive, interpret and understand visual data. This approach, in combination with expert opinion, is reducing the effort needed to manually annotate the presence and location of species in large datasets (e.g. Piechaud & Howell, 2022).

The taxonomic 'identification' of species is the greatest challenge for AI. The automation of biodiversity recognition through analysis of videos and photographs has a high potential for the development of biodiversity monitoring programmes. An increasing number of online platforms now automate species identification e.g. iNaturalist[19], Ocean Vision AI[20], Squidle+[21], Video and Image Analytics for Marine Environments (VIAME[22]), Ecotaxa[23], CoralNet[24] and Linne Lens[25]. Most of these identification systems still have limited capabilities to identify multiple species in the same image and the size of species that they can 'see'. This limits their ability to provide quantitative estimates of abundance, which hinders the possibility of deriving meaningful biodiversity indicators (e.g. GES for MSFD) compared to techniques that detect many more species per sample, such as grabs, cores and SCUBA. Furthermore, many species can only be identified through dissection and examination of internal structures (e.g. most sponges), impairing the ability to identify species from such data.

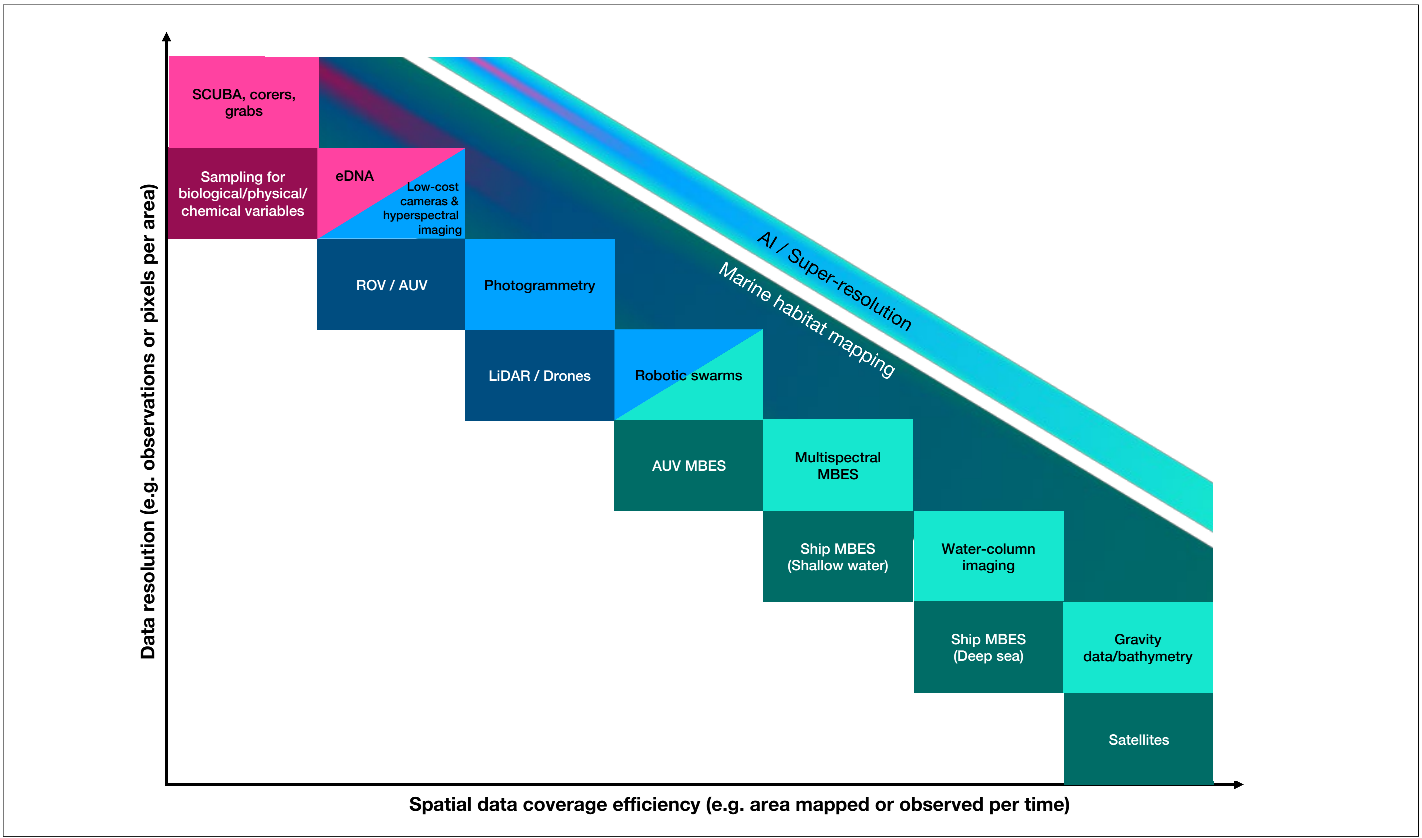
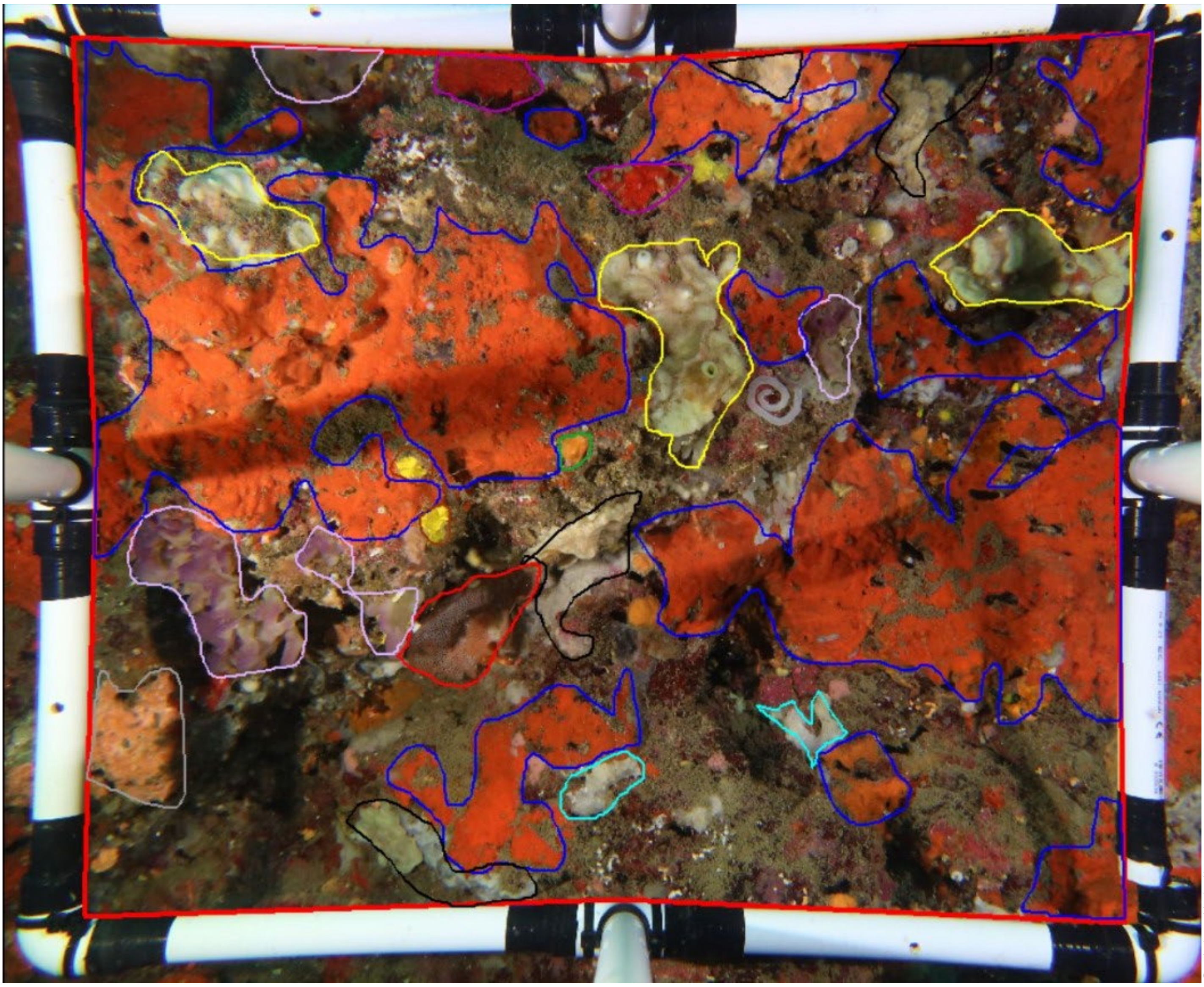


Figure 2.6 AI can be used across the various techniques for data collection, enabling super-resolution (i.e. enhanced resolution) at scale. Green boxes indicate examples of data obtained from remote sensing techniques; pink boxes indicate data from *in situ* techniques; and blue boxes indicate data obtained from both remote sensing and *in situ* techniques.

[19] https://www.inaturalist.org/
[20] https://www.mbari.org/news/ocean-vision-ai-uses-the-power-of-artificial-intelligence-to-process-ocean-imagery/
[21] https://squidle.org/
[22] https://www.viametoolkit.org/
[23] https://ecotaxa.obs-vlfr.fr/
[24] https://coralnet.ucsd.edu
[25] https://lens.linne.ai/en/



The taxonomic 'identification' of species is the greatest challenge for artificial intelligence.

These systems are also limited in their capacity to identify objects of interest and to classify them due to the variability in the underwater imagery (e.g. natural variability of individual samples, lighting, fields of view, changes in orientation, background habitats, visibility) and the shortage of annotated imagery that is manually classified by humans for training AI models. In addition, many of the existing annotated datasets are not produced or stored in a format that is immediately available for AI training. The application of deep-learning techniques, such as deep convolutional neural networks, can partially overcome some of the background variation common in seabed imagery (Salman *et al.,* 2016) and overcome issues associated with shortages in training data (Malde *et al.,* 2020). The wider implementation of standardised annotation systems for seabed imagery with data in the correct format, will greatly improve the size and compatibility of training data needed by the AI community. In the absence of high-quality data for training and validating AI models, there is a risk of inaccurate identification or quantification of species or features on the seabed, thereby inflating map error.

Demand for machine vision and AI methods for the assessment of marine ecosystems is growing rapidly, driven in part by greater access to autonomous Ocean observing systems (Durden *et al.,* 2021) and the number of applications using this technology (e.g. deep-sea mining exploration, monitoring of MPAs and restoration sites). Thus, the development of AI techniques for extraction and use of ecological data will require an ever-closer collaboration between computer scientists, marine ecologists and environmental policy specialists (Guidi *et al.,* 2020).

2.4 Recommendations

To advance data collection for MHM, we recommend scientists/maps producers and research funders to:

2a) Further integrate biological data

Scientific attention and funding should increasingly be directed towards improving knowledge of the distribution of marine species and habitats, which is still extremely limited. More maps that characterise and represent the distribution and extent of the biological components of marine habitats are critical for increased understanding of the ecosystem patterns and processes needed to promote scientifically-sound conservation, restoration and management decisions. The adoption of innovative technologies to collect more high-resolution biological data and to improve the spatial and temporal scale of cost-effective mapping is a priority.

2b) Further integrate water column data

Three-dimensional MHM that integrates benthic habitats and the water column should be supported. This will enable more high-resolution data on species distributions to be included in mapping, taking into account life cycle, trophic interactions and exchanges between the water column and seabed. Three-dimensional MHM that includes connectivity in ecological systems can be incorporated into 3D systematic conservation planning, fundamental for underpinning design and management of conservation areas.

2c) Support temporal/repeat surveys

The majority of seabed habitats are relatively stable (e.g. rock, mud). However, some geomorphological and hydrological features are highly mobile (e.g. megaripple bedforms, the water column). Equally, habitat condition and species composition can change significantly over time, meaning that repeat mapping surveys are often necessary for monitoring change over time (i.e. the fourth-dimension) e.g. every six years for the MSFD. Repeated mapping exercises are particularly helpful for the monitoring of naturally dynamic ecosystems with strong seasonality and sensitive biogenic habitats, such as cold-water corals, seagrass and reef building organisms, which are vulnerable to human pressures. This will require the development of cost-effective methods (recommendation 2d), specifically the greater use of autonomy and AI (recommendation 2e) to reduce costs and standardised methods (recommendation 2f) to enable the reliable detection of change.

2d) Implement cost-effective mapping

Remote sensing and direct, *in situ* data collection need to be cost-effective. To achieve this, the continued development, adoption and coordination of autonomous platforms, such as AUVs and UAVs should be financially supported by EU, national and international sources. Strategic coordination towards interoperability of robotic platforms should also be supported. Important areas for development include enhancing platform reliability, endurance, capability, reducing unit cost, and developing multiple networked vehicles equipped with complementary sensors capable of operating cooperatively while adapting their spatial and temporal sampling strategies in real time using onboard decision making. It is recommended that sufficient resources are allocated to train and maintain sustainably sized teams of multidisciplinary experts, including taxonomists. Repositories are needed that facilitate Findable, Accessible, Interoperable, and Reusable (FAIR) data publication (see recommendation 5a) to support the collection and distribution of information from autonomous sources, which will in turn improve cost-effectiveness. Cost-effective mapping can also be supported through the continued collection of 'underway' data (i.e. opportunistic data collected during transits or non-mapping voyages). Stronger national and regional coordination for shared resources and facilities is also required e.g. via European infrastructures such as the European Marine Biological Resource Centre (EMBRC[26]).

2e) Further integrate AI

Efforts to promote the complete integration of AI into MHM should be supported in order to handle the exponential increase in the volume of data collected from the combined use of autonomous platforms and modern sensors, and to enhance data acquisition. The methods and infrastructure to embed AI in routine data collection and processing should be made widely and freely available within the MHM community. AI-derived information needs to be aggregated centrally, using standardised formats and metadata, to increase its availability. Lastly, efforts to promote the development and retention of machine-learning expertise in the marine sciences is necessary in the face of industrial demand.

2f) Develop and apply standards for data collection and processing

Standardisation is essential to make MHM consistent across borders and over time. Existing best practices should be collated to produce standardised methodologies for the operation of survey platforms, and remote sensing and ground truthing techniques. Standardisation will, in part, provide provenance of all data collection and processing steps. This information should be provided in human and machine-readable formats and needs to be published in a standardised manner, alongside MHMs i.e. in FAIR data repositories and services (recommendation 5a).

[26] https://www.embrc.eu/

3 Combining data to produce marine habitat maps

Although remote sensing and *in situ* ground truthing survey methods and technologies have improved dramatically, it is challenging to provide full coverage MHMs of both the seabed and the water column through these methods alone. Remotely-sensed data and models (e.g. biological models and Ocean models of temperature and salinity) are therefore often used to extrapolate ground truthing observations across the mapped area (Figure 3.1).

A physical habitat map delineates the environmental characteristics and features of a given area, such as substrate type (e.g. mud, sand, rock, minerals), depth, seafloor morphology (including inclination/slope) and water flow. Physical habitat maps provide full coverage at broad spatial scales and are created by segmenting the seabed according to remotely-sensed abiotic variables, e.g. depth, seabed reflectivity (i.e. the acoustic energy reflected from the seabed), Ocean colour, and physical and chemical variables that can be modelled globally. In contrast, a biological map illustrates the spatial distribution of species, or communities of species, within that area, providing insights into biodiversity, species composition and potential for ecological interactions. When both pelagic and the benthic habitats are included in maps, these offer understanding of both the physical environment and the associated biological communities in an entire ecosystem. In the early days of MHM, interpolation between samples (i.e. the process of deducing the relationship between two points in a dataset) and boundaries between habitats were determined by hand. This was resource intensive and the availability of physical samples of the seabed limited their spatial coverage. Increasingly, physical MHM approaches and ground truthing, *in situ* observations are merged using distribution models, where mathematical relationships between physical attributes and biological units are used to predict the distribution of habitats. These approaches are described in more detail on the next page.

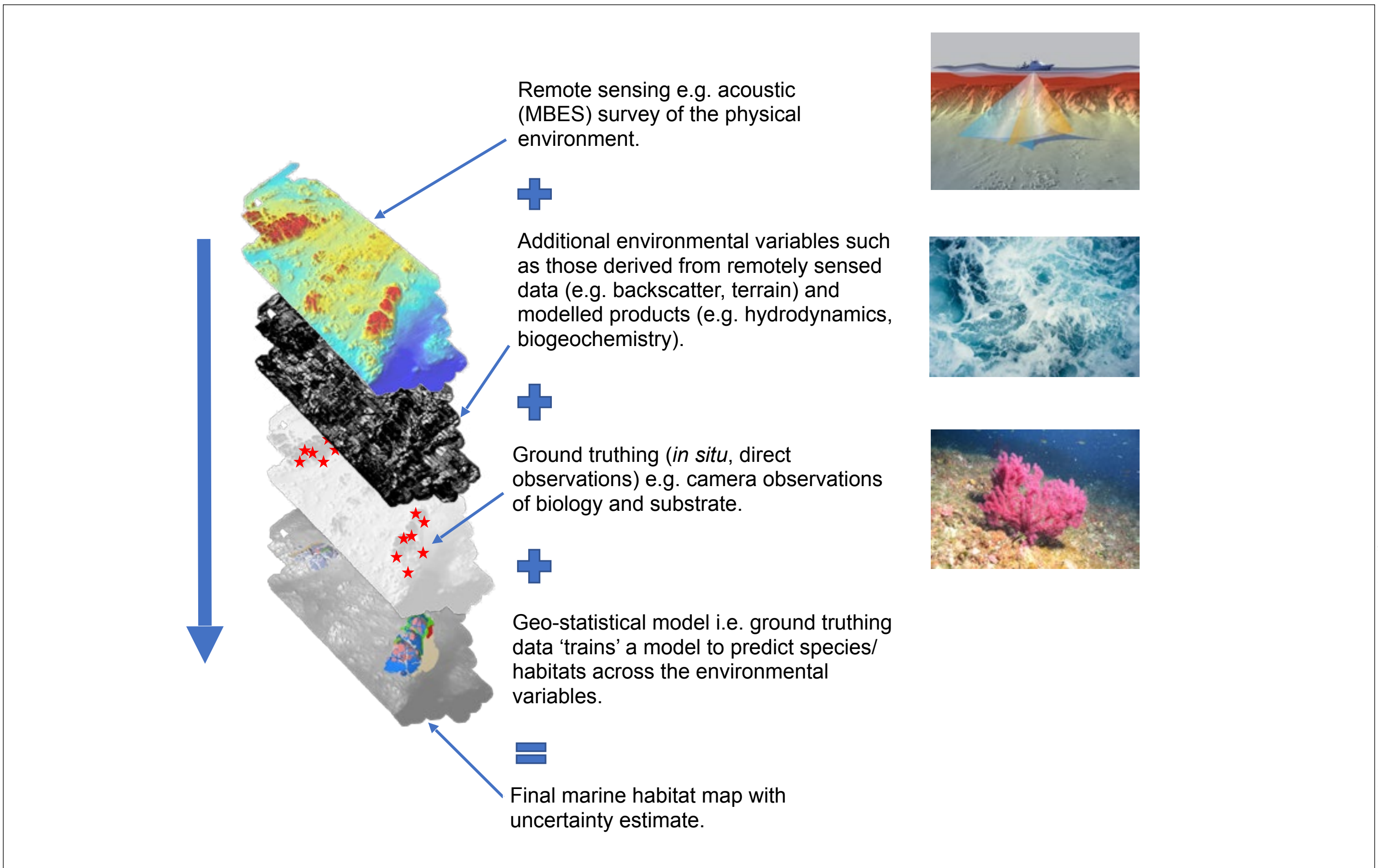


Photo credits: Elisabetta Campiani, CNR-ISMAR (top); Christoffer Engstrom, Unsplash (middle); Mišo Pavičić, IZOR (bottom)

Figure 3.1 Current workflow for the production of benthic habitat maps that combines remote sensing and derived variables from remotely-sensed data or modelled products, with *in situ* observations within a geo-spatial model.

3.1 Physical and biological habitat maps

A physical habitat map identifies areas with distinct physical conditions that are deemed to be suitable for certain groups of species. Among others, substrate type is an important physical driver of the distribution of species that live on or in the seabed, and therefore physical habitat maps are often in the form of a substrate map. These are often created using a combination of remote sensing data from Multibeam Backscatter (MBES) or Side-Scan Sonar (SSS), supplemented with photographs or physical samples of the seabed. Additional information may be layered on top of a substrate map based on other physical variables known to influence the distribution of biological assemblages, such as depth, geological features, currents and light attenuation in the water column. Together, this combination of physical information can result in a more informative map that classifies the seafloor according to narrower, biologically-relevant categories, which are sometimes created in the absence of any biological data. This is the approach taken in the production of the European Marine Observation and Data Network (EMODnet) broad-scale seabed habitat map for Europe, known as "EUSeaMap" (Vasquez *et al.*, 2023; see Figure 3.7). Whilst relying heavily on physical proxies, sometimes at a coarse resolution, its complete coverage of European seas makes it useful, although not sufficient, to inform regional-scale and national marine ecosystem assessments such as for the MSFD, Regional Sea Convention assessments and the integrated ecosystem assessments coordinated by the International Council for the Exploration of the Sea (ICES)[27].

Maps built using physico-chemical variables are often used as proxies for habitats and consequently biological assemblages. However, this association is only applicable if the following criteria are met: (i) there is a sufficient understanding and training data of the typical assemblages of species present; (ii) the environmental requirements of the assemblages are understood; and (iii) the environmental requirements do not overlap too much. Some have narrow, distinct distributions, whilst others can tolerate a wide range of conditions, which makes it difficult to use physical proxies. Therefore, depending on the types of species and/or assemblages of interest and the region of interest, the usefulness of physical habitat maps as proxies for biological habitats can vary.

Biological habitat maps rely on the same data as a physical habitat map, plus biological data obtained via direct observations (e.g. underwater photography, grab sampling, MBES). Biological samples take more effort and time to collect, store and process than physical samples and are more expensive. It can also be difficult to use the biological information to inform the classification of the acoustic data derived from MBES or SSS because not all biological assemblages have a distinct signature that can be observed acoustically. The main exception to this is biogenic habitats, which tend to have acoustic signatures that distinguish themselves from the surrounding substrate.

As a result of the difficulty in biological habitat mapping, there are far more substrate maps (i.e. focusing on physical characteristics of the seabed) than biological habitat maps in Europe (see Figure 4.3. showing coverage of substrate and biological habitat maps in European sea basins). However, the development of reliable biological habitat maps covering large spatial scales is a prerequisite to assist decision-making processes and for environmental assessments such as the MSFD. Mapping spatial patterns of marine biodiversity can be carried out at a range of scales and the choice of scale depends on the aim of the mapping activity. For example, fine spatial resolution data are required for the proper management of MPAs, including Natura 2000 sites, while broad-scale analyses are more suited for the broad identification of candidate areas for MPA designation and the allocation of other human uses at sea using marine spatial planning. There is a need to develop guidance on appropriate scales of mapping required for different applications.

3.2 Distribution models in marine habitat mapping

Although some biological features can be detected directly from remote sensing data (e.g. biogenic habitats such as seagrass beds from satellite imagery and cold-water coral structures from MBES), most current MHMs that contain biological information are the product of models. The most commonly used are distribution models, also known as habitat suitability models or species distribution models (Elith & Leathwick, 2009). These models typically predict the probability of the presence, or the habitat suitability, for a given species, or selection of species when applying joint species distribution modelling (see Figure 3.2 for an example). They can use traditional statistical methods or AI methods, such as machine learning, to determine the relationships between biological assemblages and environmental variables. Traditional methods include: correlative models (i.e. relating known probabilities of species presence to environmental variables); mechanistic models (i.e. relating physiological information about a species gained from literature or laboratory experiences to environmental variables for assessing their fitness at specific locations); and process-oriented models (i.e. estimating species distribution based on processes such as ability to disperse and biotic interactions) (Melo-Merino *et al.*, 2020). AI methods offer additional predictive power due to their ability to incorporate more complex interactions, and could lead to better representation of marine habitats' multifaceted nature (e.g. Effrosynidis *et al.*, 2018), however, increased model complexity could lead to challenges in interpretation of model outputs.

[27] https://www.ices.dk/community/groups/Pages/IEASG.aspx

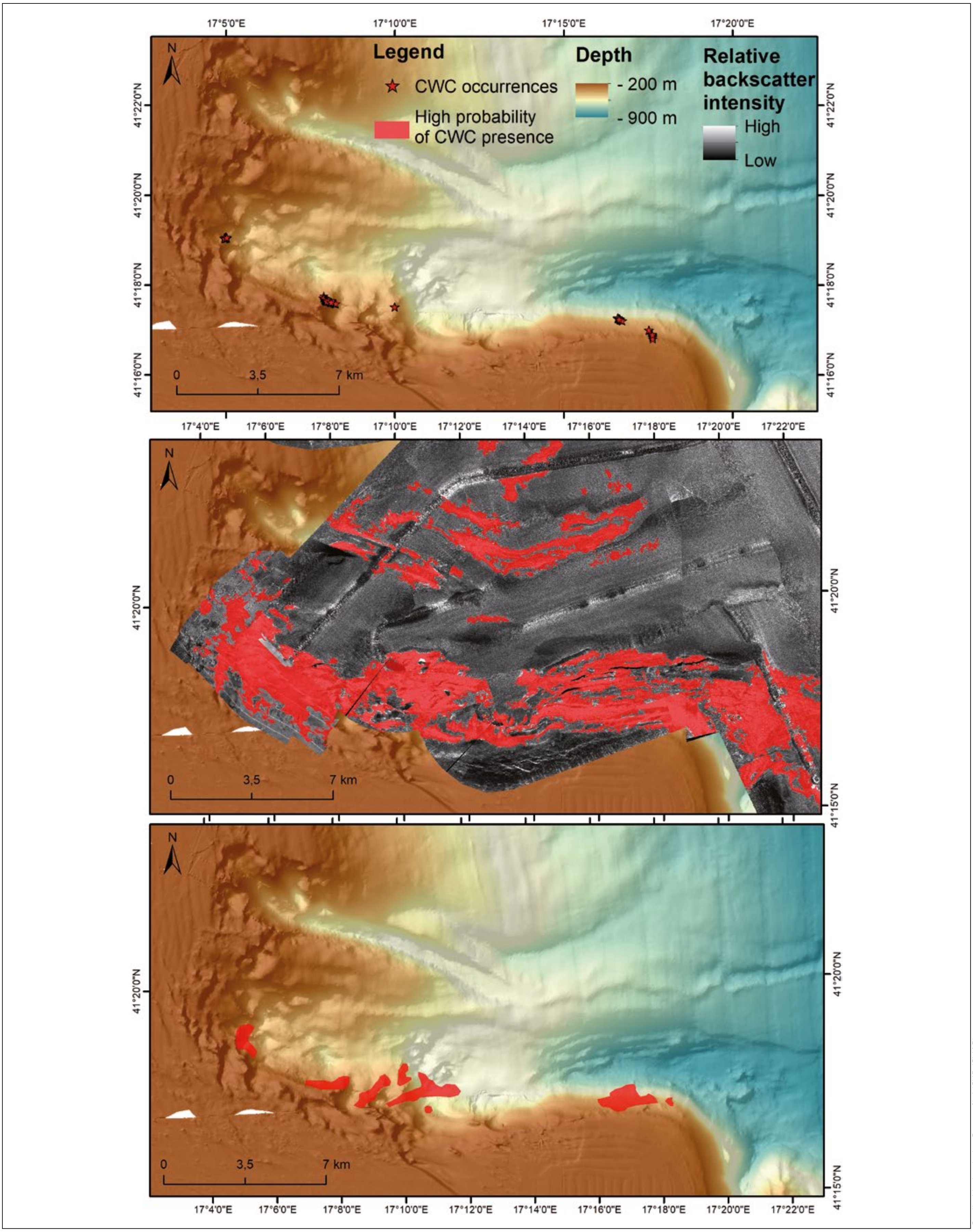


Figure 3.2 Examples of maps made using models. **(A)** Occurrences of cold-water corals (CWC) in the Bari Canyon. **(B)** Distribution of CWC habitat inferred from geophysical data (bathymetry and side-scan sonar) and CWC occurrences (data from Prampolini *et al.*, 2021). **(C)** Modelled habitat suitability for a CWC (data from Bargain *et al.*, 2018). Red areas indicate a high probability of CWC presence.

Different approaches are used to model the distribution of species and habitats, depending on the type of data available to fit the model e.g. single species models using presence-only or presence with absence/pseudo-absence data (i.e. observations of where the species of interest is not present or similar observations where proxies suggest the same species is highly unlikely to be present), multi-species data (i.e. for joint species distribution modelling) or quantitative predictions using abundance, density or biomass (see Annex 2). However, these models do not predict the distribution of the 'occupied' habitat itself, but only the existence of a suitable habitat or the probability of presence. They are, therefore, proxies for the real distribution of a species or habitat, which will usually occupy a smaller fraction of this space. Models can also be trained on data on present conditions together with climate change projections to provide predictions of distribution under differing climate scenarios (Figure 3.3).

In principle, habitats and species distribution models based on the best available biological information can guide management and restoration efforts: i.e. predictions of species or habitat presence/absence, combined with information about human pressures (Fabbrizzi *et al.,* 2020). The modelling process provides additional information on the environmental variables potentially driving the distribution of the modelled species or habitats (e.g. current speeds, depth, temperature and dissolved oxygen). Although modelled outputs currently provide the best available evidence for the ''potential'' distribution of most marine species and habitats (i.e. non-biogenic habitats and species that cannot be directly observed in remote sensing data), greater efforts need to be made to improve the accuracy, transferability and repeatability of these models. Species distribution models need to be improved by the collection of higher quality environmental data at finer resolution and better species occurrence datasets.

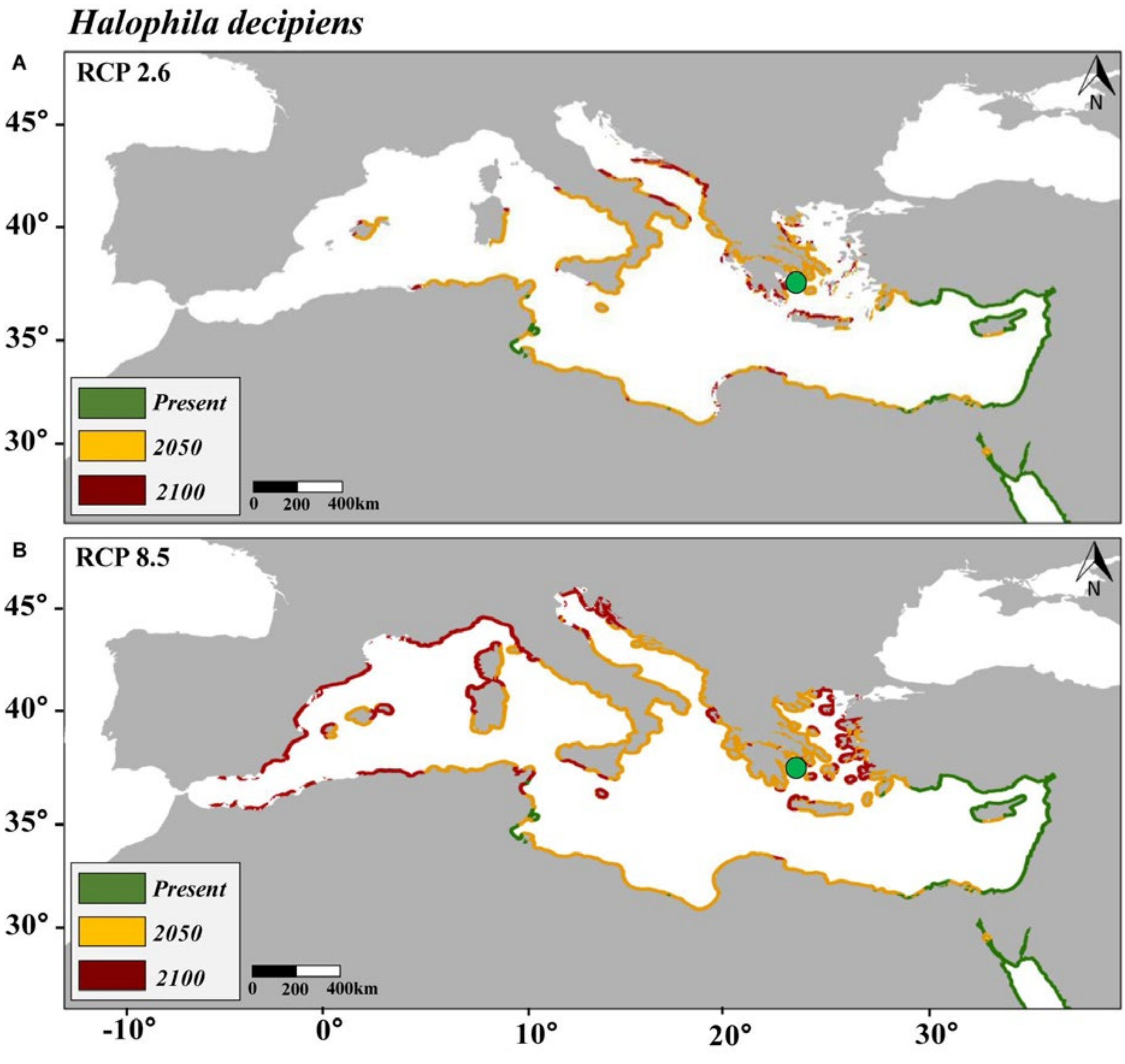


Figure 3.3 Maps of the distribution of predicted habitat suitability (using salinity and temperature) for the seagrass *Halophila decipiens* in the Mediterranean Sea under present conditions and future scenarios of climate change based on two contrasting carbon emission projections: Representative Concentration Pathway (RCP) 2.6 (**top**) and 8.5 (**bottom**) by 2050 and 2100. Yellow shows additional habitat by 2050 in relation to present distribution and red shows additional habitat in 2100 in relation to 2050 (Beca-Carretero *et al.,* 2020; CC BY 4.0 DEED).

EUNIS level 4 defines individual communities (or biocenosis) e.g. macroalgal communities dominated by kelp species.

3.3 Are European habitat classification schemes fit-for-purpose?

Habitat Classification Schemes (HCSs) are sets of instructions that identify, delimit, and describe the habitats of distinct species and communities by categorising them into "classes" (Robinson & Levings, 1995). Well-defined and comprehensive HCSs are central to the production of MHMs. Once MHM data have been collected, HCSs facilitate the classification of discrete data (i.e. categorical data such as substrate) and continuous data (e.g. salinity) into ecologically relevant spatial units (Strong *et al.*, 2019). These units are comparable between maps produced by different scientists, in different areas and at different times because they use the same system to label areas hosting similar benthic assemblages. The use of a standard HCS adds significant value to a map because it allows the map to be combined with other maps and/or translated into other HCSs and used for multiple purposes. For a comprehensive overview of how different aspects of HCSs can influence the information content and format of MHMs see Strong *et al.* (2019).

There are several HCSs used to define marine habitats worldwide (Montefalcone *et al.*, 2021). In Europe, the European Nature Information System (EUNIS[28]) HCS is the most comprehensive and the latest version was published in 2022. The EUNIS HCS is included in the larger EUNIS information system[29], which is a database that brings together European data from several databases and organisations and contributes to the knowledge base for implementing the Biodiversity Strategy 2030. It is managed by the European Environment Agency (EEA) and aims to cover all terrestrial, freshwater and marine habitats in Europe in a hierarchy that allows users to define habitats at different levels of detail (see Figure 3.4 for an example of a map classified using EUNIS).

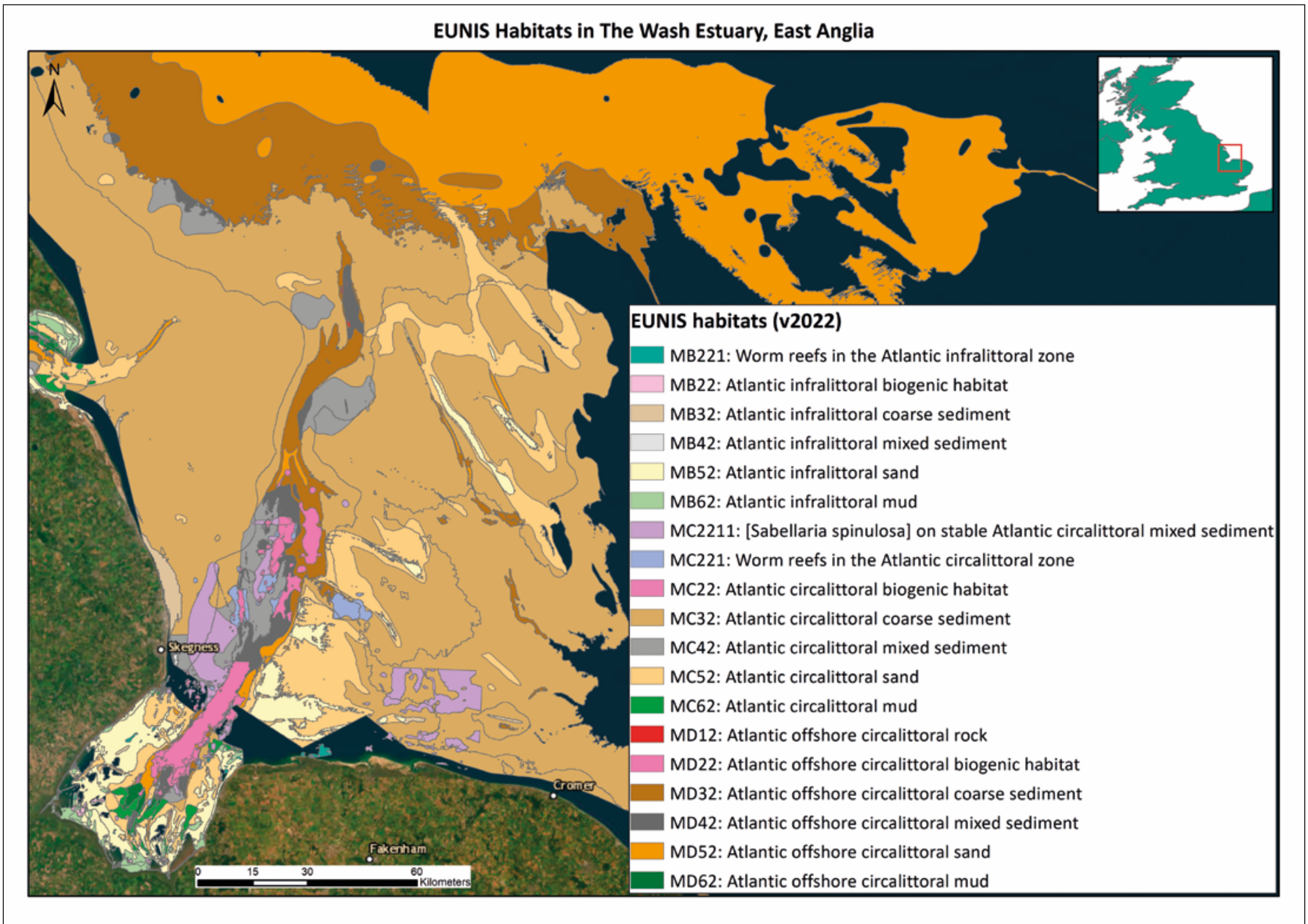
For marine benthic habitats, EUNIS facilitates the comparable reporting of habitats for environmental management under several pieces of legislation at the national level. EU-wide, it facilitates the six-yearly reporting of the MSFD, which includes reporting the extent of Benthic Broad Habitat Types (BBHTs) and Article 17 reporting of the Habitats Directive, which includes reporting the extent of Annex I habitats that Member States must designate, protect and manage. For some HCS, listed habitats are not quantitatively defined in terms of species abundance, or condition, which makes the use of these schemes less effective for the consistent production of maps and the subsequent use of those maps for management.

[28] https://www.eea.europa.eu/data-and-maps/data/eunis-habitat-classification-1

[29] https://eunis.eea.europa.eu/

The benthic marine section of the 2022 version of EUNIS divides the classes into the following levels (note that level 1 separates terrestrial and marine habitats):

- **Level 2** is based only on substrate type (e.g. rock, biogenic habitat) and broad biological zones related to depth (e.g. littoral, infralittoral, circalittoral). These broad terms are applicable across all biogeographic regions of Europe and translate directly to the BBHTs that EU Member States must refer to for the MSFD (European Commission, 2017).
- **Level 3** adds a qualifier that refers to the main biogeographic regions of European seas (Arctic, Atlantic, Baltic Sea, Black Sea and Mediterranean Sea). This is important because the biological character of habitats varies geographically, such that the same functional habitat (e.g. a surf beach, an exposed rocky shore) hosts different species and communities depending on its geographic location. This is caused by variation in abiotic variables, particularly temperature and salinity, and species origins via larvae transport from prevailing Ocean currents.
- **Levels 4-6** add information about the distinct species and communities that can be observed within each level 3 class i.e. habitat classes defined by their species (e.g. the octocoral *Virgularia mirabilis* and the sea star *Ophiura* spp. with the bivalve *Pecten maximus* on circalittoral sandy or shelly mud). They also include additional abiotic factors where relevant, such as substrate, depth and light. Level 4 defines individual biocenosis[30]/communities (e.g. the Mediterranean photophilic algae biocenosis or macroalgal communities dominated by kelp species). Level 5 defines assemblages characterised by specific species (e.g. the barnacle *Chthamalus* spp. on exposed upper eulittoral rock) and level 6 has the greatest level of biological and physical specificity (e.g. the barnacles *Chthamalus montagui* and *Chthamalus stellatus* on exposed upper eulittoral rock).



Credit: EMODnet Seabed Habitats.

Figure 3.4 EUNIS (v2022) habitat map of the Wash Estuary, East Anglia, United Kingdom classed to level 5.

[30] Biocenosis is a synonym for biological communities used in the Barcelona Convention.

The adequacy of the previous version of EUNIS system was evaluated by Galparsoro *et al.* (2012) and many of their recommendations were incorporated within the subsequent EUNIS updates, so that the 2022 version better reflects the main biogeographical regions of Europe's seas based on their distinct combinations of salinity and temperature regimes. It also includes habitat cross-reference tables to other regional HCSs such as HELCOM HUB[31] and UNEP MAP-RAC/SPA[32] to support harmonisation of ecosystem definitions and mapping. However, limitations with the system remain, which are discussed further below.

3.3.1 Standardisation of terms within classification schemes

For the consistent use of a HCS, the named habitat classes need to be clearly defined. This ideally requires the use of quantitative thresholds for defining habitats in terms of their spatial and compositional properties. Furthermore, the variables used to define the habitats, and ideally the condition of these habitats, should be closely aligned to the variables reported by standard mapping techniques such as sonar (depth and intensity values), cameras and particle size parameters delivered by cores and grabs. The development of quantitative definitions of HCS classes is of interest predominantly for the Atlantic in order to more precisely define its benthic communities and annual changes should also be considered. The development of quantitative definitions of HCS classes is not considered a priority for the Mediterranean Sea, where a more qualitative approach is preferred due to differences compared to the Atlantic in seafloor characteristics and biodiversity levels, which do not require in-depth definitions.

Both Galparsoro *et al.* (2012) and Strong *et al.* (2019) recommended the inclusion of quantitative definitions of classes within HCSs to improve consistency in their application, particularly for soft bottom sediment types. This would provide a more robust basis for: (i) initial classification of habitats; (ii) the estimation of how well an observation fits an assigned class; and (iii) greater certainty about the detection of change in habitat condition, extent and spatial configuration over time during repeat mapping.

The challenge for the 2022 version of EUNIS (and associated BBHTs under the MSFD), which uses common terms at level 2 in an endeavour for consistency for all regions, is to strike a balance between consistent definitions and biologically-relevant definitions across regions. These are sometimes in conflict due to both regional differences in the predominant conditions that drive the distribution of biological communities and historical approaches to defining habitats in each region. Consequently, benthic species assemblages do not always fit neatly into the BBHT defined combinations of substrate classes and depth (e.g. Cooper & Barry, 2020). In some cases, the use of substrate classes as proxies for habitats is sufficient. However, there is large variability within substrate classes. At small scales, different species assemblages can inhabit the same habitat type, representing natural variability that, should not play a role in the identification of habitat distribution at large scale. This is a fundamental issue, which has the potential to undermine comparisons across regions under the MSFD and wasn't fully addressed in the 2022 EUNIS update.

Habitat classification levels (i.e. resolution of biological information) required by map producers and users need to be aligned. This has been taken into account by EUNIS since its early versions and addressed by adopting an approach with different levels that are nested, and that can be chosen according to the cartographic detail required. Nevertheless, an assessment is needed of how to close the gap between efforts to describe habitats for: GES assessment for the MSFD; the Habitats and Birds Directives; the 30x30 target under the EU Biodiversity Strategy 2030; and prioritisation under the proposed EU Nature Restoration Law. The Habitats Directive Annex I habitat types include very broad and not very detailed typologies and particular effort is needed to align these with HCSs. In addition, relevant Essential Ocean Variables (EOVs[33]) should also be clearly correlated with EUNIS classes to avoid generating alternative typology and datasets for Europe.

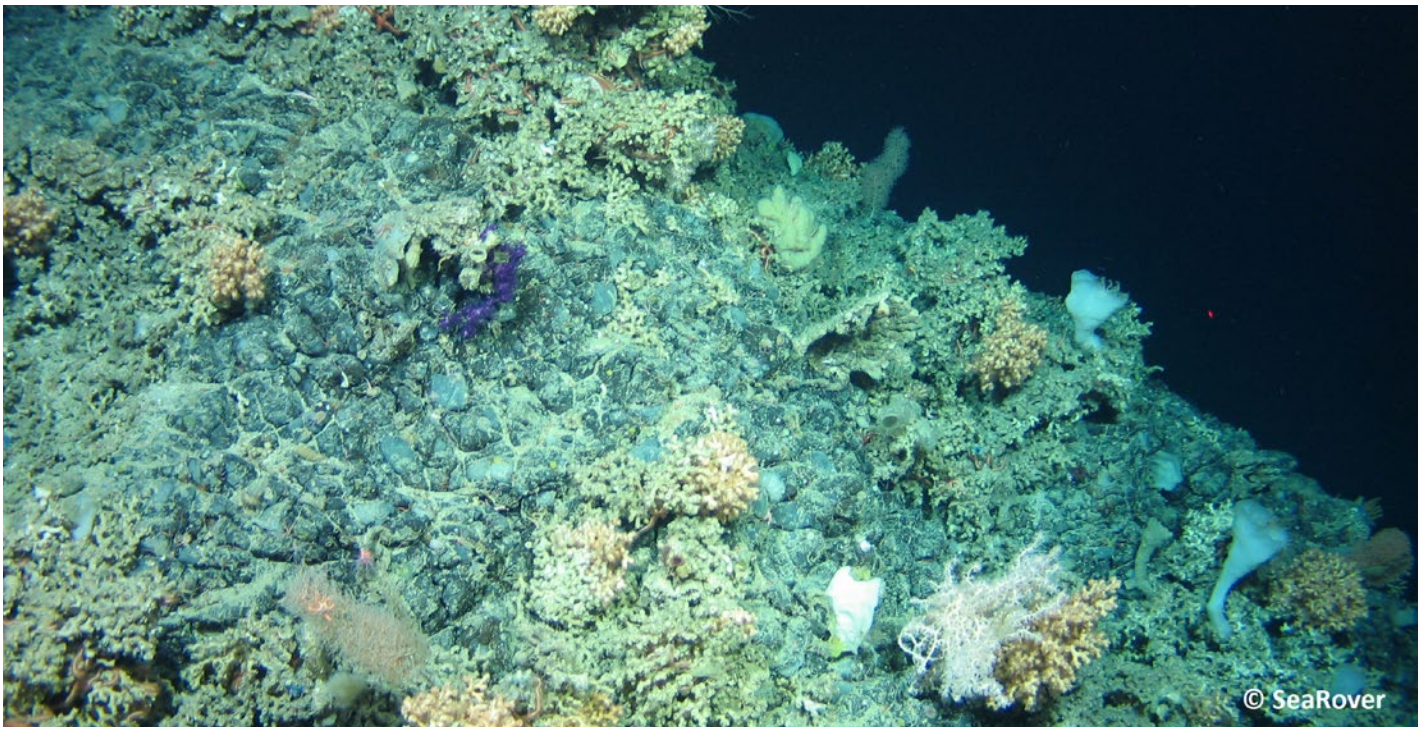
3.3.2 Completeness and update mechanisms for classification schemes

EUNIS is an important Europe-wide HCS, and the basis for EUSeaMap, which is the only Europe-wide habitat map. However, there are some limitations. The original version of the marine section of EUNIS was based on the marine HCS for Britain and Ireland (Connor *et al.*, 2004) where most information was available at that time. The EUNIS system is currently widely used on the Atlantic coasts of Europe. Since 2004, EUNIS has expanded gradually to include classifications for the Baltic and Mediterranean Seas, and newly-developed classifications for pelagic habitats and the deep sea, advancing the system's comprehensiveness in terms of its geographical coverage of European seas. Recently, in the Mediterranean Sea, the Barcelona Convention classification was revised to include new habitats discovered in the last 30 years (Montefalcone *et al.*, 2021). It was conducted in parallel to the update of EUNIS to ensure that the two systems are as aligned as possible. It would be desirable that other regional classifications follow a similar alignment process in the future.

In the 2022 revision of EUNIS, some improvements were made regarding the Atlantic region, however many other areas remain underrepresented, i.e. the Black Sea, Bay of Biscay and Azores (Galparsoro *et al.*, 2012), since only a small fraction of Europe's seas are well studied. The current update mechanism for EUNIS is *ad hoc* and relies on a small number of experts from the European Topic Centre on Biological Diversity[34]. The marine section of EUNIS requires an increase in resources in order to improve its update mechanism.

[31] https://helcom.fi/baltic-sea-trends/biodiversity/helcom-hub/
[32] https://www.rac-spa.org/
[33] https://goosocean.org/what-we-do/framework/essential-ocean-variables/
[34] https://www.eea.europa.eu/data-and-maps/data-providers-and-partners/european-topic-centre-on-nature-protection-and-biodiversity

It is widely accepted that HCSs require an element of generalisation so as to make the habitat classes more widely applicable. This can lead to the broader schemes having reduced applicability in areas beyond where they have been developed. The poor fit of some classes in generic schemes continues to lead to the development of alternative classifications. One example is the EU FP7 project CoCoNet, which developed the "CoCoNet Habitat Mapping Scheme", an integrated, multi-scale and hierarchical approach to classify habitats from coastal waters to the deep sea (Boero *et al.,* 2016). The challenge for a broad, unifying HCSs is to draw upon these bespoke schemes during update iterations without compromising their generality or consistency of classification. Improvements should also be made to the way new biological habitats are proposed, reviewed, accepted and published as part of EUNIS.



Credit: Guido Villani (top).

EUNIS has expanded gradually to include classifications for the Baltic and Mediterranean Seas, and newly developed classifications for pelagic habitats and the deep sea.

3.3.3 Additional attributes: human pressures and ecosystem services

Habitat cross-reference tables (e.g. JNCC, 2018[35]) enable the translation of a map into various HCSs, which can be useful for assessments and reporting for different legislation. It is recommended that custodians of HCSs update their habitat descriptions to include additional attributes such as sensitivity to human pressures, conservation value (e.g. IUCN Red List[36]) , habitat condition and ecosystem service provision (Strong *et al.,* 2019).

The increase of human activities is causing unprecedented changes to marine ecosystems. In some cases, the extent of these changes is so large that the structure and function of habitats and ecosystems have no historical analogues (i.e. they are novel ecosystems) (Bulleri *et al.,* 2020), generating further issues for classification. Thus, habitat condition should become a priority to include within MHM efforts and EUNIS levels 4 and 5 (and 6 for the Atlantic, which is the only area that this level is present). For most coastal marine ecosystems there is little understanding of the impacts of multiple stressors, which is considered one of the most challenging questions for ecosystem-based management. This information is relevant for all EU and international environmental legislation to achieve targets for the implementation of restoration measures and for monitoring of the marine environment.

Habitat sensitivity matrices assign categories of habitat sensitivity (in terms of resistance and resilience) to various human pressures e.g. using the Marine-Evidence-based Sensitivity Assessment (MarESA) tool (Tyler-Walters *et al.,* 2023). Linking a sensitivity matrix to a map allows the creation of a map showing the sensitivity of habitats to a pressure and overlaying this with a map of human pressures can indicate areas at the highest risk of impact. Maps of cumulative human impacts have been produced for various areas of Europe (Korpinen *et al.,* 2021; Figure 3.5) and at multiple scales in order to combine multiple pressures into a single comparable estimate of cumulative human impacts revealing relevant gaps (Bevilacqua *et al.,* 2018). However, a key limitation is the need for research on the most basic information, such as distribution of habitat types and whether and how different anthropogenic pressures interact (Halpern *et al.,* 2008).

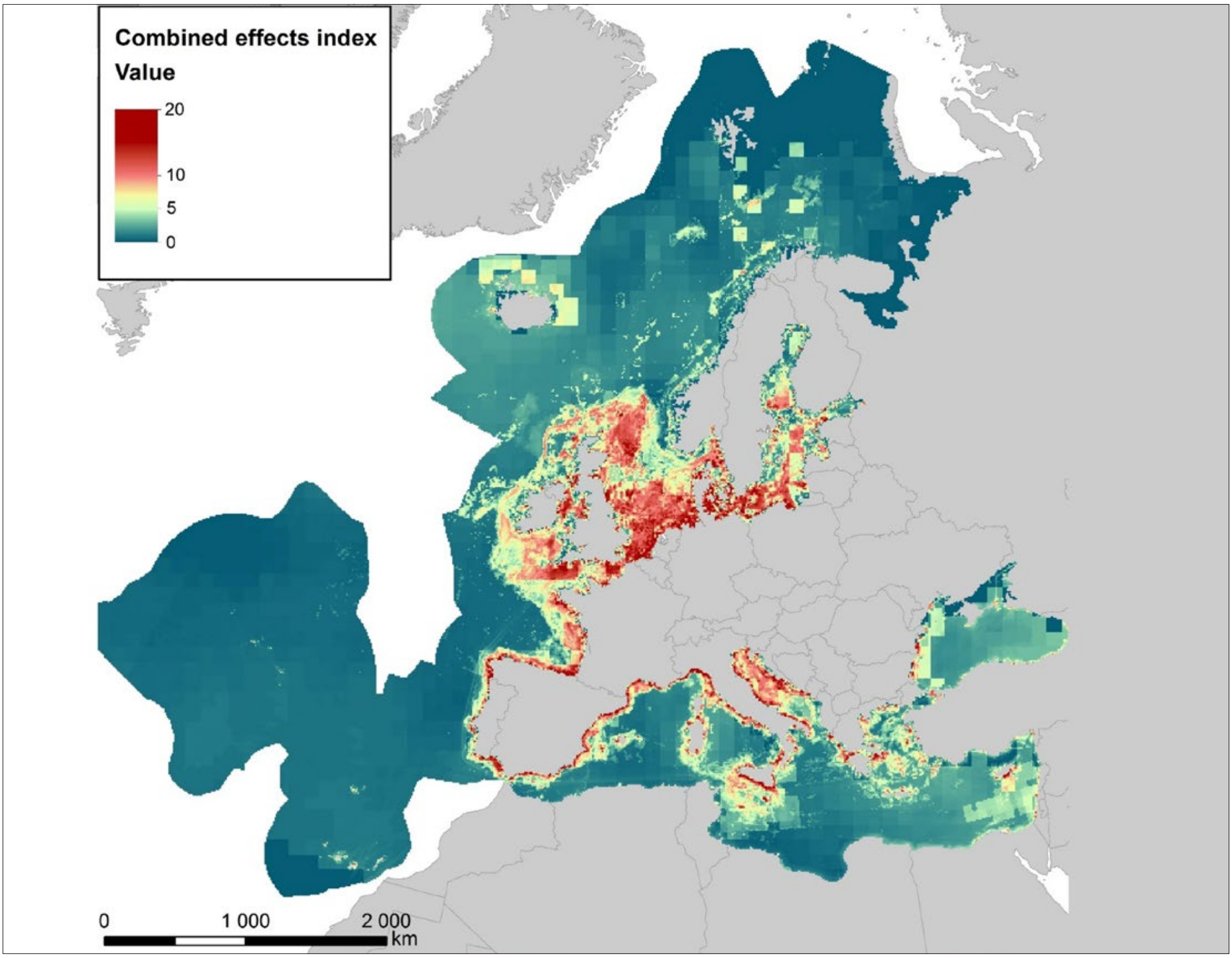


Figure 3.5 Combined effects of anthropogenic pressures in Europe's seas. See Korpin *et al.* 2021 for an explanation of the development of the index values (Korpinen *et al.,* 2021; CC BY 4.0 DEED).

[35] https://mhc.jncc.gov.uk/resources#correlationtables

[36] https://www.iucnredlist.org/

The mapping and assessment of the ecosystem services provided by marine habitats is also a highly valuable source of information for understanding their current and potential benefits to society. Galparsoro *et al.* (2014) showed that ecosystem services can be attributed to habitat classes, which allow a habitat map to be transformed into a map of ecosystem services, facilitating the valuation of the seabed and water column for natural capital accounting (Figure 3.6). Their results indicated that more than 90% of the mapped area in European waters provides biodiversity maintenance and food provision services, while nursery grounds providing reproductive and nursery services are limited to half of the mapped area. Benthic habitats generally provide more known services closer to shore and in shallower waters, compared with deeper offshore habitats. This gradient is likely to be explained by difficult access (i.e. distance and depth) and lack of scientific knowledge for most of the services provided by offshore habitats.

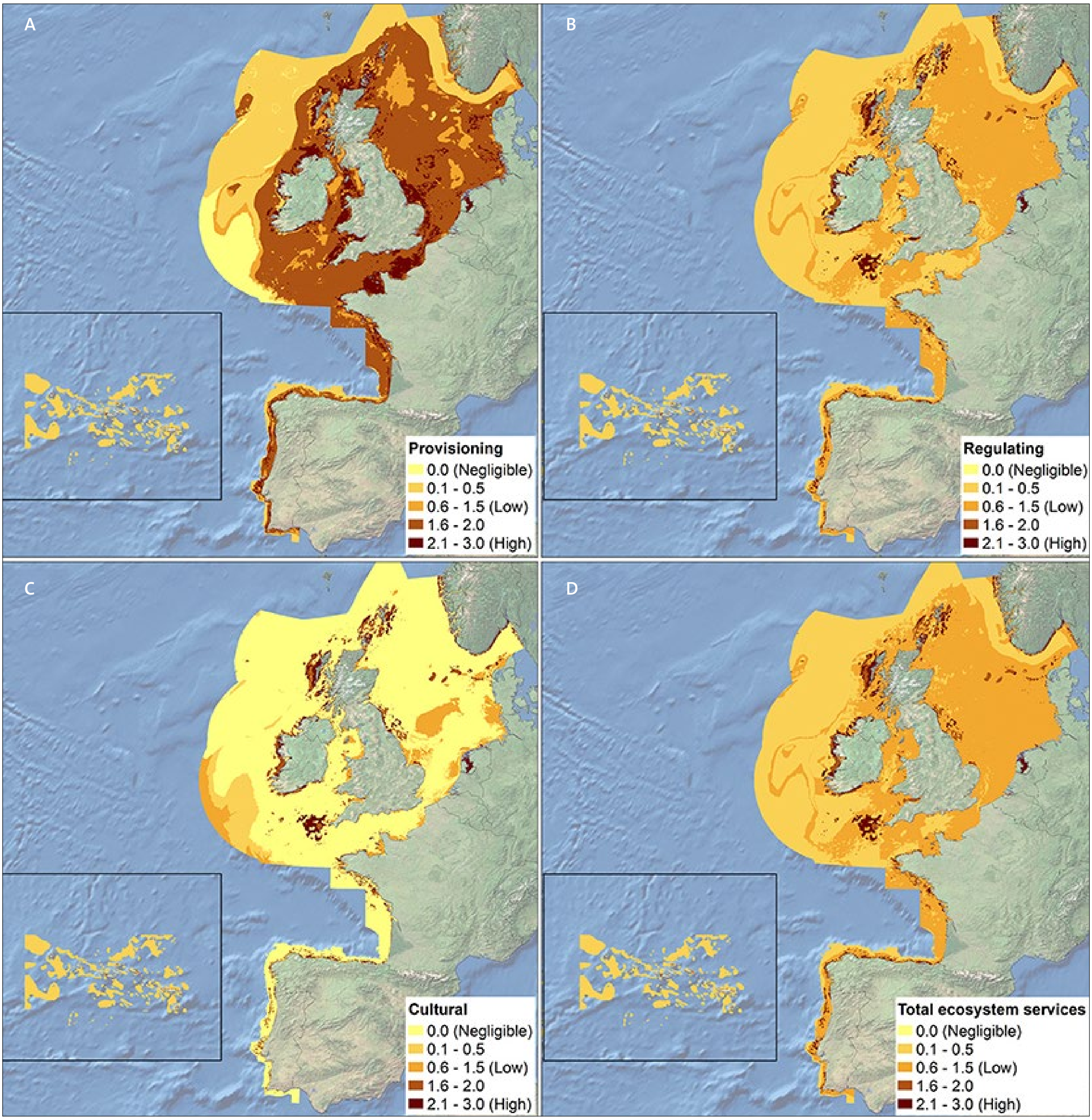


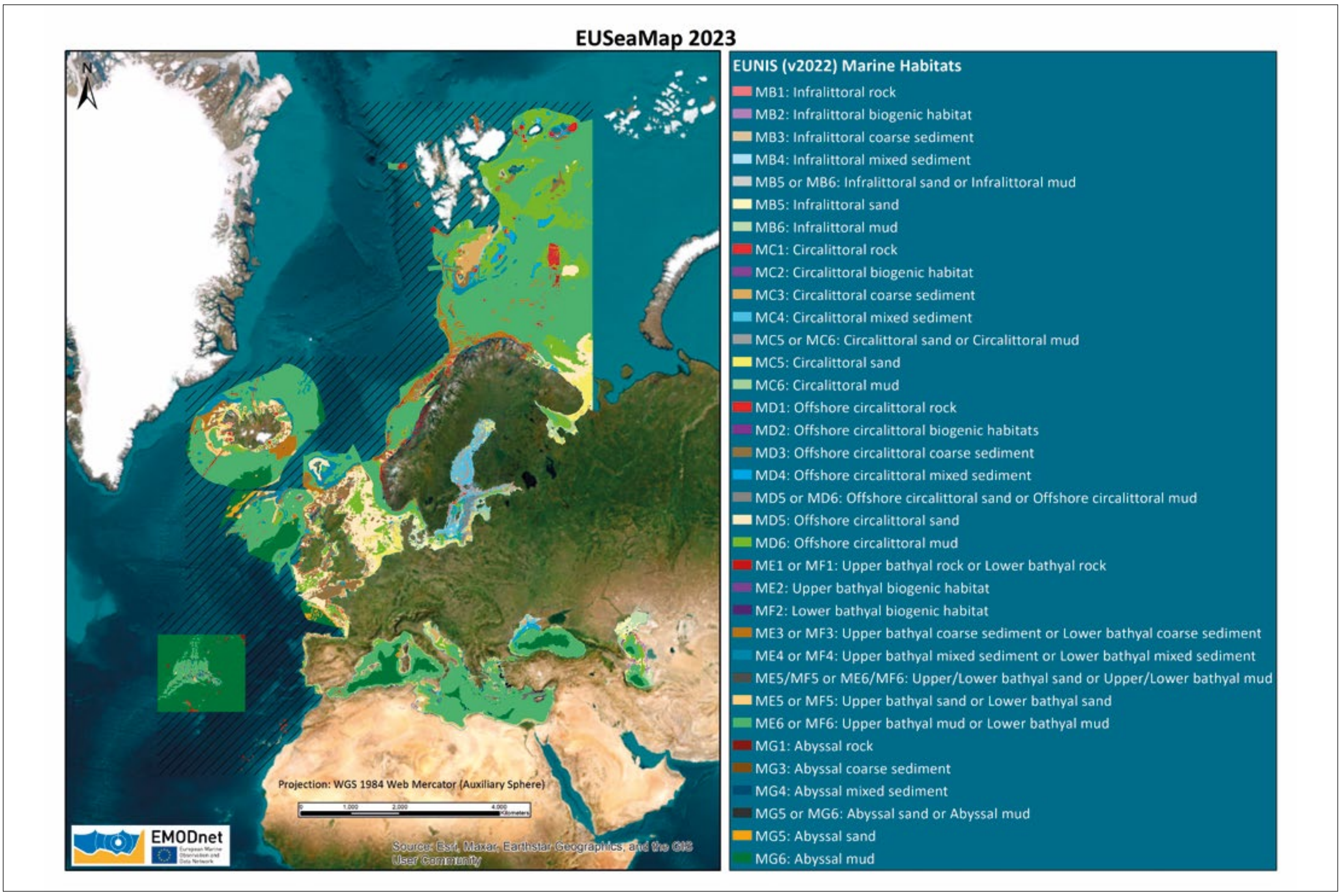
Figure 3.6 Maps of ecosystem services: **(A)** provisioning services; **(B)** regulating services; **(C)** cultural services; and **(D)** total ecosystem services (Galparsoro *et al.*, 2014; CC BY 3.0 DEED).

3.4 Assessing and communicating accuracy and confidence

The availability of online maps and open source data has promoted the use and adoption of maps for various purposes. However, it is impossible to produce maps that are completely accurate and satisfy all needs. Highly accurate terrestrial maps have led to the assumption that maps accurately show the location and name of objects, therefore maps are often used without considering their accuracy (i.e. certainty within a map in terms of location and the quality of labelling for mapped units). Compared to terrestrial habitat maps, MHMs rely more on proxies than direct observations. This is especially true for broad-scale maps where species and habitats are modelled rather than being directly detected by remote sensing (i.e. fine-scale maps), meaning that the accuracy of MHMs is more variable than that of terrestrial maps.

MHMs are produced by interpreting multiple and varying types of data (see Chapter 2), each with their own sources of error. There are also errors associated with analysis and interpretation techniques. In addition, many habitat classification definitions are imprecise and one person's understanding of a habitat may be different to another's. Map accuracy is reduced by the accumulation of these errors within the map (Strong, 2020). Map error rates are estimated by using an independent dataset to test the predicted map classes. Map confidence relates to its fitness for a specific use and is determined by its accuracy and its intended purpose by the end-user.

Due to the complex nature and multiple sources of error in MHMs, it is difficult to enforce a single, quantitative approach to describe confidence. However, it is necessary to consistently and accurately assess and communicate the confidence of MHMs so they can be used effectively by end-users who should be able to understand their limitations (see Figure 3.7 for EUSeaMap v2023 and Figure 3.8 for its associated confidence map). Failing to report accuracy may mean that too much trust and confidence are attached to maps, which may subsequently fail to support the desired purpose of the end-user. There is often a discrepancy between map accuracy and end-user expectation, which can undermine the mapping process and the products generated. It is, therefore, essential that map producers report informative, standardised, and ideally spatially explicit, measures of map accuracy and assumptions used to generate maps. Equally, map users need to specify their requirements, in terms of accuracy for specific purposes, so that map confidences can be estimated. There are several studies that have sought to standardise the methodology for assessing accuracy when determining the value of and understanding the source of error in MHMs (e.g. Mitchell *et al.,* 2018). A consistent and widely adopted accuracy assessment will benefit both the development of mapping methodologies as well as those needing to use the maps produced.



Credit: EMODnet Seabed Habitats.

Figure 3.7 EUSeaMap (v2023) broad-scale seabed habitat map for Europe.

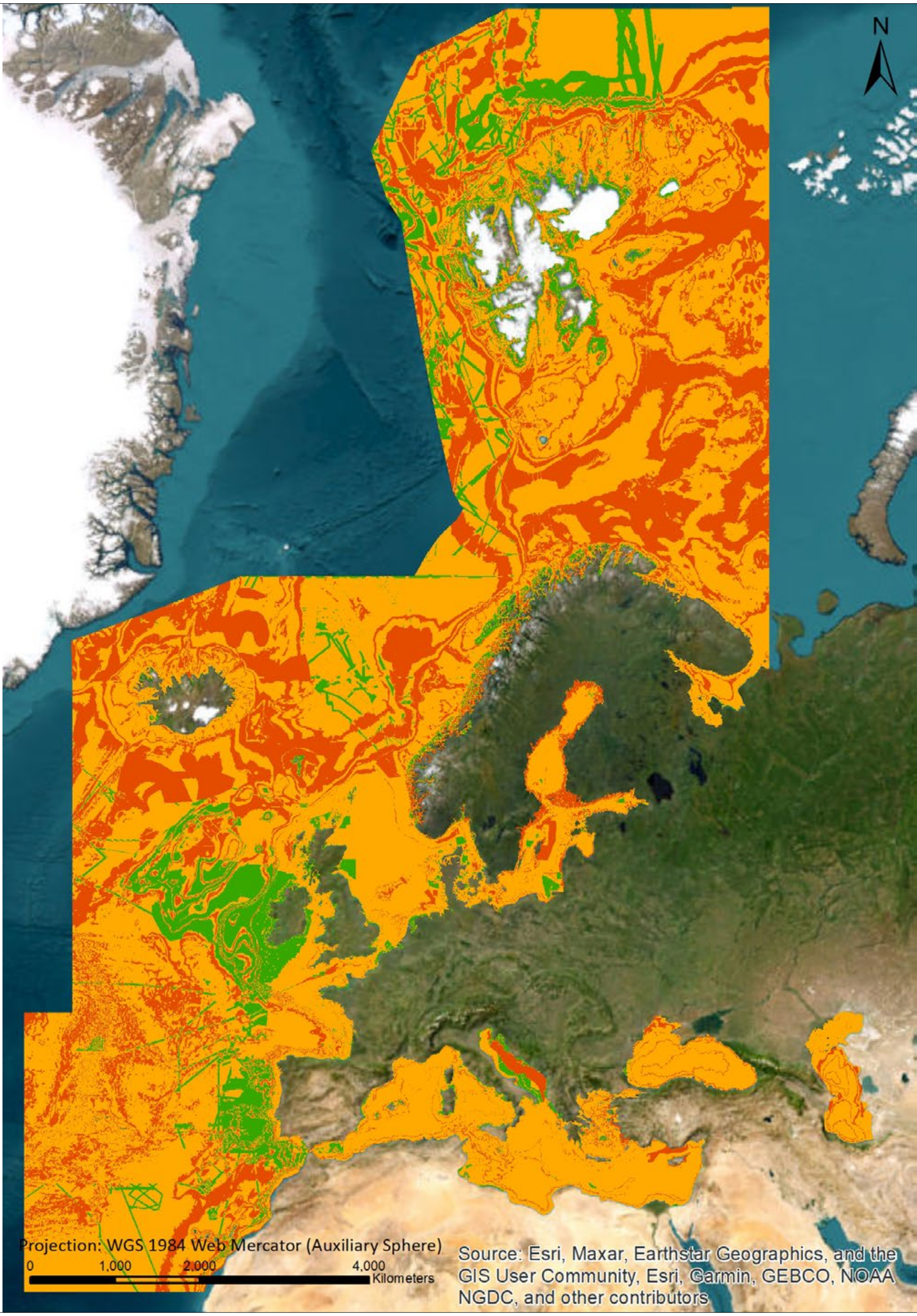


Figure 3.8 The 'confidence' map associated with EUSeaMap (v2023) giving an idication of the quality of the data sources and methods used to create the map. Red = low, orange = moderate and green = high confidence (Vasquez *et al.*, 2023).

3.5 Recommendations

To advance distribution modelling and HCSs for MHM, we recommend scientists/map producers and research funders to:

3a) Improve the datasets used in spatial models

Improving model outputs through high-quality data at finer resolution on environmental variables and better species occurrences datasets is a priority. This would allow for more reliable predictions, and help to identify suitable and unsuitable areas for species and communities. The use of more ecologically relevant variables at a higher resolution will make models more sensitive to differences in multiple ecological preferences among species.

3b) Standardise the production and validation of spatial models

Best practice documents to improve standardisation must be generated and applied to geospatial modelling techniques used to merge data and generate map data. This is particularly important as these models are complex statistical tools that need to meet a series of robustness requirements throughout their development. We therefore recommend that: (i) best practice guidance is developed on the selection of modelling approaches to improve consistency; and (ii) best practice documents are generated for implementing the recommended models e.g. providing advice on sourcing suitable observations where species and habitats are not present, i.e. absence data, which is informative for model training, environmental predictors, model resolution, model parameters and assessing their predictive performance. The ICES Working Group on MHM (WGMHM[37]) could be well placed to develop such documentation, also involving the institutes part of the EMODnet Benthic Habitats consortium. Better understanding and communication of results and limitations of distribution models to managers and policymakers is also a priority, and one of the most important challenges in the field of MHM.

3c) Better assess, communicate and standardise map accuracy and confidence

The consistent calculation and presentation of the accuracy estimates associated with MHMs will facilitate a better understanding of their value and use for specific tasks. It is recommended that standardised accuracy assessments are produced and widely communicated amongst the MHM community. Where possible, these standardised accuracy assessments should include: (i) an overall (global) value of map accuracy; (ii) accuracy information on specific classes or subsets depicted on the map; and (iii) a spatially explicit depiction of model performance, model agreement (i.e. when multiple models are available within the same area) or map accuracy. It is also recommended that this information be presented within a standardised reporting template using consistent, well-referenced and easy-to-understand terminology. Accessible guides are needed for map users to interpret these map accuracy reports and establish whether products are appropriate to use for the specific purpose they require, as different end-users need different assessment values and map products with different resolutions.

In addition, we recommend custodians of HCSs (e.g. the European Environment Agency for EUNIS) to:

3d) Develop quantitative definitions of HCS classes, and regional definitions of broad habitats and biogeographic regions

Habitats need to be defined quantitatively (i.e. using variables and scales appropriate for mapping methodologies). This is important to consistently classify and represent habitats in maps and for using maps to monitor change in habitat condition, extent and spatial configuration over time. This will require compromises between biological relevance per region and consistency across regions. Definitions should be published, followed by strategic outreach and communication to ensure they filter down to practitioners across their regions of application. Regional working groups may be required to establish how the levels and habitat classes are defined, potentially facilitated through the Regional Sea Conventions, as already done by the Barcelona Convention for the Mediterranean. Furthermore, these regional working groups should seek to establish quantitative definitions of habitats at the lower levels of the classification hierarchy to further improve consistency in recording.

3e) Improve the process of revision and further development of HCSs

A simple online tool should be developed to allow scientists to submit proposals for revisions to a HCS. A mechanism is then required to ensure that suggested revisions undergo an appropriate level of peer review, which could be coordinated in collaboration with user groups such as the Regional Sea Conventions. Custodians of HCSs, including EUNIS, are encouraged to add additional attributes to habitat descriptions such as sensitivity to human pressures, conservation value, habitat condition, ecosystem service provision and correspondence to habitats in other HCSs and lists, using existing information and facilitated by tools such as the Marine Evidence-based Sensitivity Assessment (MarESA).

[37] https://www.ices.dk/community/groups/pages/wgmhm.aspx

4 What and where to map

4.1 What has been mapped?

EU Directives and international legislation have generated a large number of EU programmes and funding frameworks that have contributed to national and regional MHM e.g. BALANCE (Al-Hamdani & Reker, 2007), MESH[38], MESHAtlantic[39], iAtlantic[40], ATLAS[41], CoCoNet and BENTHIS[42] (Andersen *et al.*, 2018). For most countries, inter-institutional cooperation at national level is very weak and they lack coordinated national MHM programmes. Notable exceptions with ongoing national programmes seeking to map their entire seabed are Norway (MAREANO[43]) and the Republic of Ireland (INFOMAR) (Table 4.1). These long-term and systematic programmes are unparalleled in their ambition, and eventual rewards, in terms of scientific achievement, economic return and efficiency of marine management. However, few countries are prepared to commit the resources required to sustain ongoing national mapping programmes, with punctuated, but valuable projects being favoured instead e.g. PNRR-MER[44] (Italy), INTEMARS[45] (Spain), SedAWZ (Germany), REBENT[46] (France), and Mapping of coastal and demersal marine habitats in the Adriatic Sea under national jurisdiction[47] (Croatia).

Table 4.1 Examples of national programmes with ongoing efforts to map their entire seabed.

NATIONAL MAPPING PROGRAMME	COUNTRY	OBJECTIVES
MAREANO	Norway	· To map bathymetry, sediment composition, contaminants, biological assemblages and habitats in Norwegian waters. · To provide data to assess the consequences of human activities. · To provide data to implement ecosystem-based management plans in different parts of the Norwegian Exclusive Economic Zone (EEZ). · To have full coverage of the Norwegian EEZ upon completion.
INFOMAR A joint venture between Geological Survey Ireland, the Marine Institute and its predecessor, the Irish National Seabed Survey (INSS)	Ireland	· To produce integrated mapping products covering the physical, chemical and biological features of the seabed. · To provide comprehensive and freely accessible marine datasets for Irish waters via a dedicated web mapping portal. · To provide data to sustainably manage Ireland's marine resources. · To have full coverage (bathymetry and backscatter data) of the Irish designated shelf area upon completion.

[38] https://maritime-spatial-planning.ec.europa.eu/practices/mesh-survey-scoping-tool
[39] https://keep.eu/projects/395/Mapping-Atlantic-Area-seabed--EN/
[40] https://www.iatlantic.eu/
[41] https://www.eu-atlas.org/
[42] https://www.benthis.eu/en/benthis.htm
[43] https://mareano.no/en
[44] https://www.isprambiente.gov.it/en/projects/sea/pnrr-mer-marine-ecosystem-restoration
[45] https://intemares.es/en/
[46] https://rebent.ifremer.fr/
[47] https://galijula.izor.hr/en/lansirana-je-jedinstvena-nacionalna-karta-morskih-stanista/

In addition, several Regional Sea Conventions (e.g. HELCOM[48], OSPAR[49], Barcelona[50] and Black Sea[51]) and the ICES Working Group on Marine Habitat Mapping were, and presently are, active in the coordination of MHM. At an international level, the Nippon Foundation[52] and the General Bathymetric Chart of the Oceans (GEBCO[53]) came together in 2017 to identify how Ocean mapping might support SDG14. They launched the ambitious Seabed 2030[54] project to build the necessary technical, scientific and management framework to compile all available seabed mapping information into a seamless digital map of the Global Ocean floor by 2030 (Mayer *et al.*, 2018). Seabed 2030 are also partnering with private companies to map marine habitats[55]. There is however still improvement to be made in national, regional, European and international coordination of mapping activities, including of public and private institutes carrying out geological, hydrographic, environmental and biological mapping.

In the past, MHMs were mostly published in the grey literature or as technical reports by public research institutes. Over the past two decades, the main outlet has shifted to scientific peer reviewed journals as the appreciation of, and level of sophistication in MHM has evolved. To make these data available to a wide range of end-users, EMODnet Seabed Habitats[56] collate and publish MHM of European waters on the EMODnet Portal[57]. Since 2009, almost 1,000 MHMs have been made publicly available as separate data layers and as part of composite products that combine the information from the entire collection of maps in order to display the best estimate of the distribution of key habitats (see Figures 4.1 and 4.2 for examples). Another key product of EMODnet Seabed Habitats is 'EUSeaMap', the predictive broad-scale seabed habitat map for Europe, which is available in three Europe-wide classification systems[58] and two regional classifications[59] (Figure 3.7). EMODnet has the most comprehensive collation of seabed habitats in Europe to-date and its products are used by many stakeholders, including national bodies and Regional Sea Conventions in quality status reports and assessments for EU Directives e.g. the MSFD (see Section 4.4).

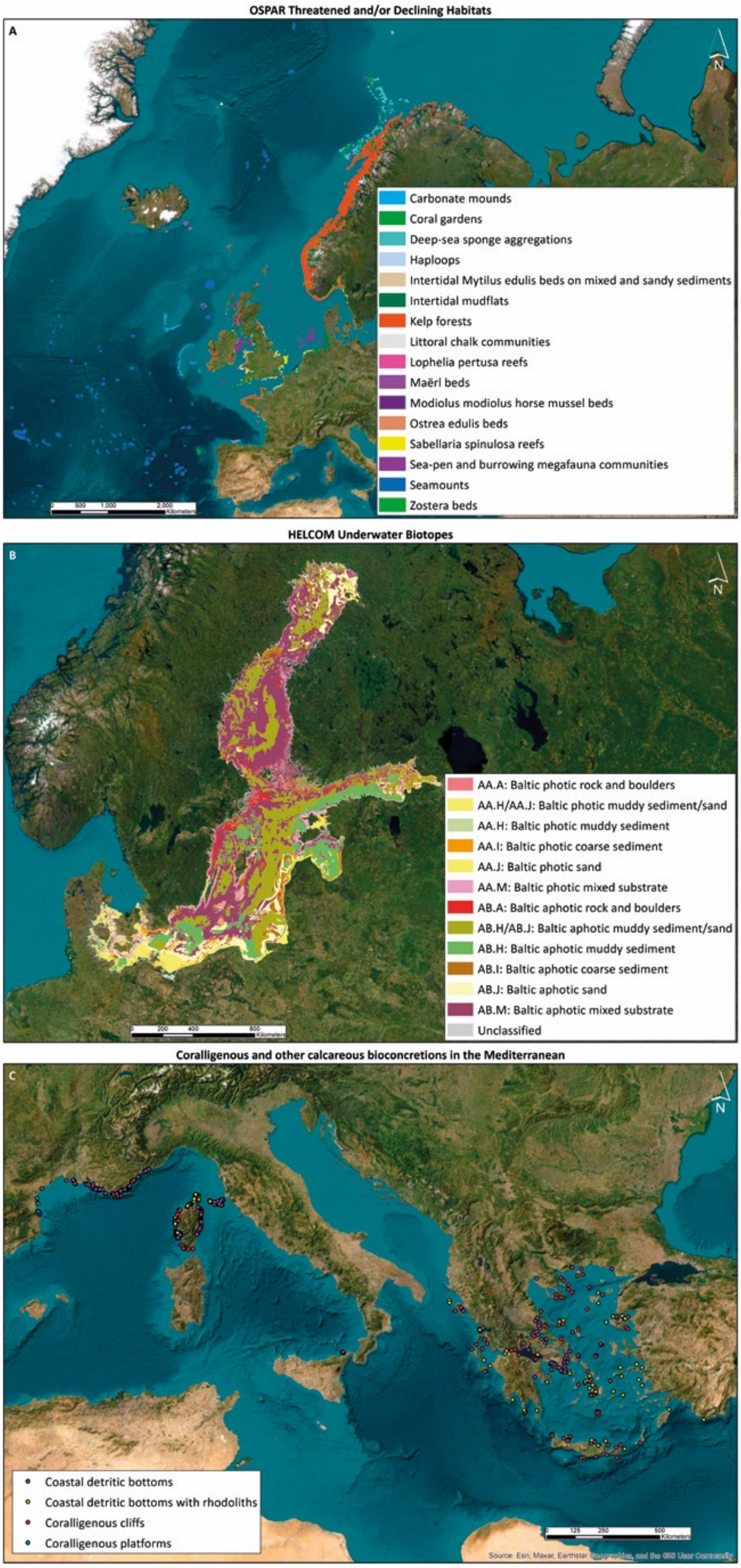
EMODnet Seabed Habitats have collated maps from individual surveys across six regional seas in Europe: North-East Atlantic, Arctic, Baltic, North Sea, Mediterranean, and Black Sea (Table 4.2). These maps vary in scale, biological detail, classification system and modelling method used. Most are translated to the EUNIS classification (58%); one third are of marine habitats listed in Annex I of the Habitats Directive whose conservation requires the designation of Special Areas of Conservation as part of the Natura 2000 network (32%); and a small proportion adopt other classification systems (10%). The North-East Atlantic (50%), Mediterranean (25%) and North Sea (18%) are the best mapped regional seas in terms of numbers of available maps.

A large number (68%) of EMODnet Seabed Habitat maps collated from surveys describe biology at a species or community level, however it is important to note that this does not equate to spatial coverage. This suggests that there are considerable data available on marine habitats. However, if we compare the extent of maps displaying substrate only with those showing a biological component (Figure 4.3), we can clearly see that biological habitat maps generally cover small areas, mostly confined to coastal regions. This is because it is more difficult and time-consuming to collect biological data in larger offshore areas.

Table 4.2 Overview of the number of maps from surveys by region and classification system that are available in the EMODnet Seabed Habitats portal[60].

CLASSIFICATION SYSTEM	NUMBER OF MAPS BY SEA AREA						TOTAL
	ARCTIC	ATLANTIC	BALTIC SEA	BLACK SEA	MEDITERRANEAN SEA	NORTH SEA	
EUNIS (v2007-11 and v2022)	2	350	0	7	114	86	559
Habitats Directive Annex 1	0	100	76	0	90	32	298
Other Classification Systems	5	16	2	3	28	46	100

[48] https://helcom.fi/
[49] https://www.ospar.org/convention
[50] https://www.unep.org/unepmap/who-we-are/barcelona-convention-and-protocols
[51] http://www.blacksea-commission.org/_convention.asp
[52] https://www.nippon-foundation.or.jp/en
[53] https://www.gebco.net/
[54] https://seabed2030.org/
[55] https://seabed2030.org/2024/04/11/seabed-2030-announces-new-partnership-with-ocean-ledger-in-boost-to-coastal-mapping-and-ecosystems/
[56] https://emodnet.ec.europa.eu/en/seabed-habitats
[57] emodnet.ec.europa.eu
[58] EUNIS habitat classification v2007-11, EUNIS habitat classification v2022 and MSFD Benthic Broad Habitat Types
[59] HELCOM Underwater Biotopes in the Baltic and Barcelona Convention habitat types in the Mediterranean
[60] https://emodnet.ec.europa.eu/geoviewer/



Credit: EMODnet Seabed Habitats.

Figure 4.1 Examples of maps in EMODnet Seabed habitats. **(A)** OSPAR threatened and/or declining habitats in the north-east Atlantic[61]; **(B)** HELCOM underwater biotopes in the Baltic Sea[62]; **(C)** coralligenous and other calcareous bioconcretions in the Mediterranean[63] (see Martin *et al.*, 2014 and Ingrosso *et al.*, 2018 for updated data on calcareous bioconcretions not included in this map).

[61] https://bit.ly/emodnet-ospar-t-and-d-habitats
[62] https://bit.ly/emodnet-euseamap-hub
[63] https://bit.ly/emodnet-coralligenous

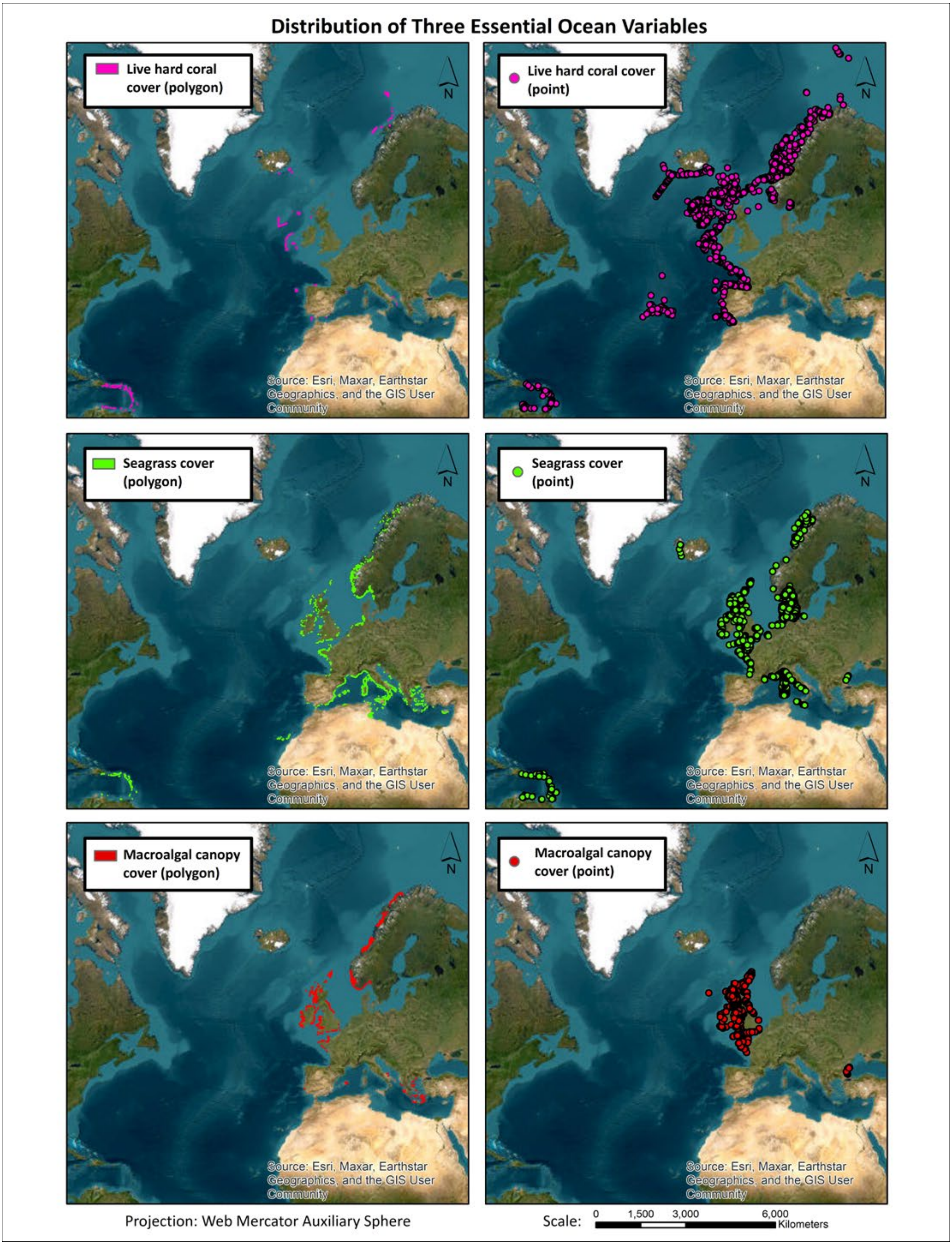


Figure 4.2 Maps showing the distribution of Essential Ocean Variables (EOVs) determined from polygon and point observations. **Top:** live hard coral cover; **middle:** seagrass cover; **bottom:** macroalgal canopy cover (i.e. kelp forests). These maps were created by interrogating and combining the marine habitat maps in EMODnet Seabed Habitats into new, composite data products.

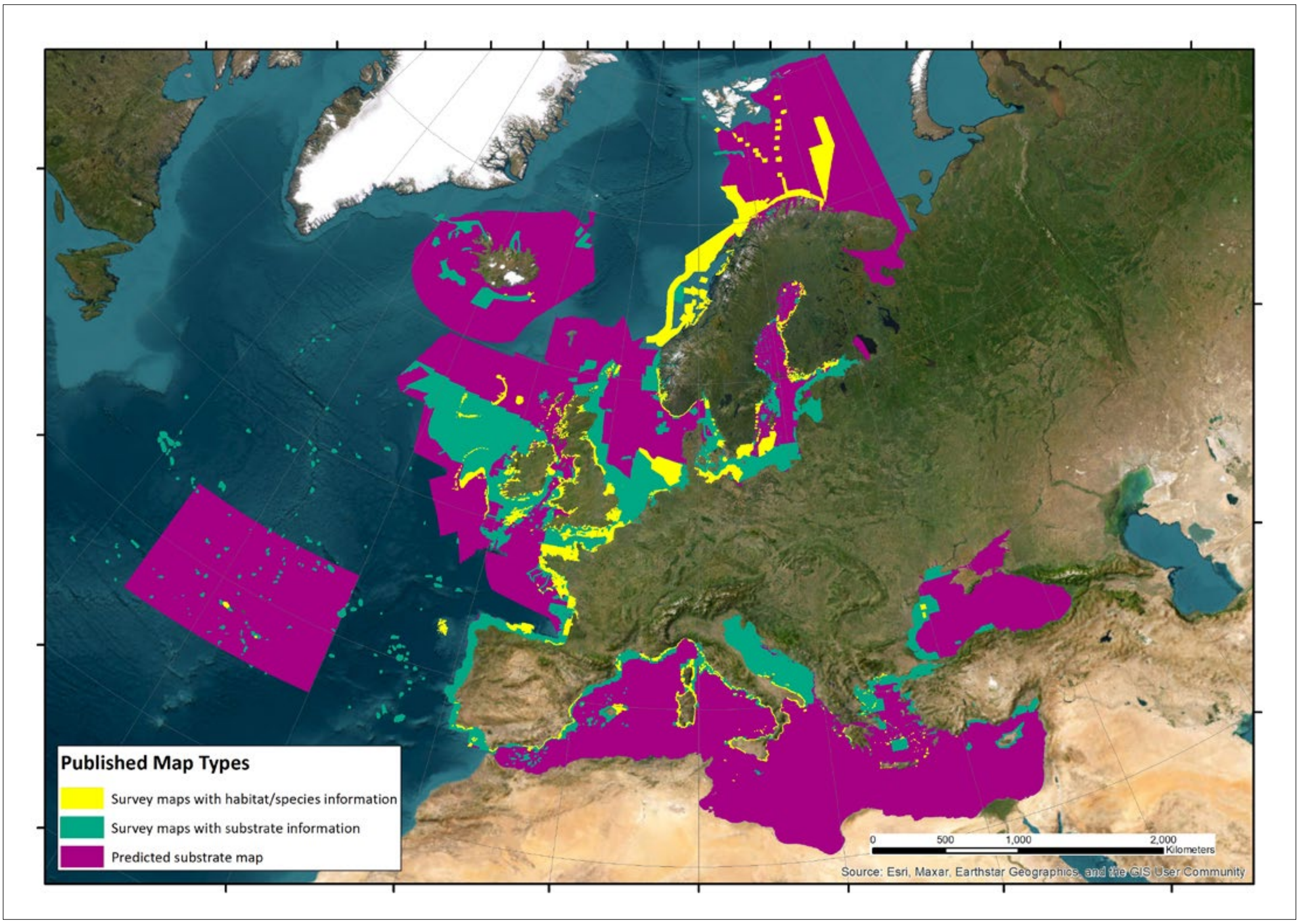


Figure 4.3 Areal extent of survey maps describing substrate only (green areas) and habitat classes with biological information (yellow areas), in Regional Sea Convention areas. Note that areas labelled as predicted substrate (purple) include maps at a range of scales, including some very coarse-scale substrate maps based on interpolation of sparse ground truthing samples and no MBES data (such as much of the deep waters of the UK) and some depth-only mapping from MBES surveys (e.g. Porcupine Abyssal Plain off the coast of Ireland). Data sourced from EMODnet Seabed Habitats[64]. Note that some data may be missing from this map (e.g. habitat map of Croatian EEZ) due to new data being published after the data in the map were collated. Future iterations will include data published from 2023 onwards.

Maps showing only substrate-level data have greater coverage. Table 4.3 provides an overview of the extent of Regional Sea Convention areas mapped for substrate and biological information. In the North Sea (OSPAR region 2) and the Celtic Sea (OSPAR region 3) over 40% of the areas have detailed substrate maps. However, maps displaying data on biology account for only 10% and 5%, respectively. The Mediterranean Sea (especially large areas off North Africa) and Black Sea maps have very low biological coverage (0.5%), however, not all survey data have been collated from all bordering countries, so these figures may improve once all data has been collated. The Norwegian Sea and parts of the Barents Sea (Arctic, OSPAR region 1) have the largest area of seabed mapped with detailed biological information (>200,000km^2). Countries that have dedicated biological sampling programmes or large repositories of biological sample data, such as Norway and Germany, generally have the most detailed MHMs. In general, there are more substrate and habitat maps available in coastal areas than in offshore areas, leaving large parts of some sea basins and Exclusive Economic Zones (EEZs) unmapped (or at least with unpublished maps). Offshore and deeper areas that have not been surveyed rely on modelling to predict habitats.

The regional differences are driven by a remarkable heterogeneity among EU countries in the compliance with targets, Directives and private uses of maps. A good example is the designation of Natura 2000 sites and nationally designated MPAs, which have different management plans, monitoring approaches, reporting and threat assessments across Europe (Mazaris *et al.,* 2019). Another key driver for these differences is the funding of national seabed mapping programmes. For example, the OSPAR area has the highest percentage map coverage in Europe due to the two state-funded national mapping programmes: MAREANO in Norway and INFOMAR, and its predecessor, the Irish National Seabed Survey (INSS) in Ireland (see Table 4.1).

[64] https://emodnet.ec.europa.eu/geoviewer/?layers=12493:1:1,9985:1:1,12615:1:1,13017:1:1,12702:1:1,12616:1:1,12701:1:1,12618:1:1&basemap=esri-gray&active=12493&bounds=-14594115.96520002,3451984.993129384,13599742.612924984,16746172.475453604&filters=&projection=EPSG:3857

Table 4.3 Percentages of Regional Sea Convention areas that have predicted seafloor substrate, mapped substrate and mapped habitat coverage. Predicted substrate includes maps at a range of scales, including some very broad-scale substrate maps based on interpolation of sparse ground truthing samples and no acoustic data. Data from EMODnet Seabed Habitats[65].

MAP TYPE	PERCENTAGE OF REGIONAL SEA CONVENTION AREA MAPPED							
	ARCTIC (OSPAR I)	NORTH SEA (OSPAR II)	CELTIC SEA (OSPAR III)	BISCAY/ IBERIA (OSPAR IV)	WIDER ATLANTIC (OSPAR V)	BALTIC SEA	BLACK SEA	MEDITERRA-NEAN SEA
Predicted substrate	32	100	100	51	35	100	100	100
Mapped substrate	6	52	43	19	11	48	14	11
Mapped habitats (including biological information)	4	10	5	4	0.3	10	0.5	0.5

4.2 What are the gaps in marine habitat mapping?

There are several gaps in mapping of key marine benthic habitats in European sea basins (even in the Norwegian and Barents Seas, which have large areas of their seabed mapped to a detailed biological level) and international waters of the North-East Atlantic. These gaps include spatial coverage (especially in the deep sea), the consistency and resolution of coverage for both common habitats and those of conservation importance, and habitat condition, as concluded by EMODnet Seabed Habitats and others (e.g. Matear *et al.*, 2023).

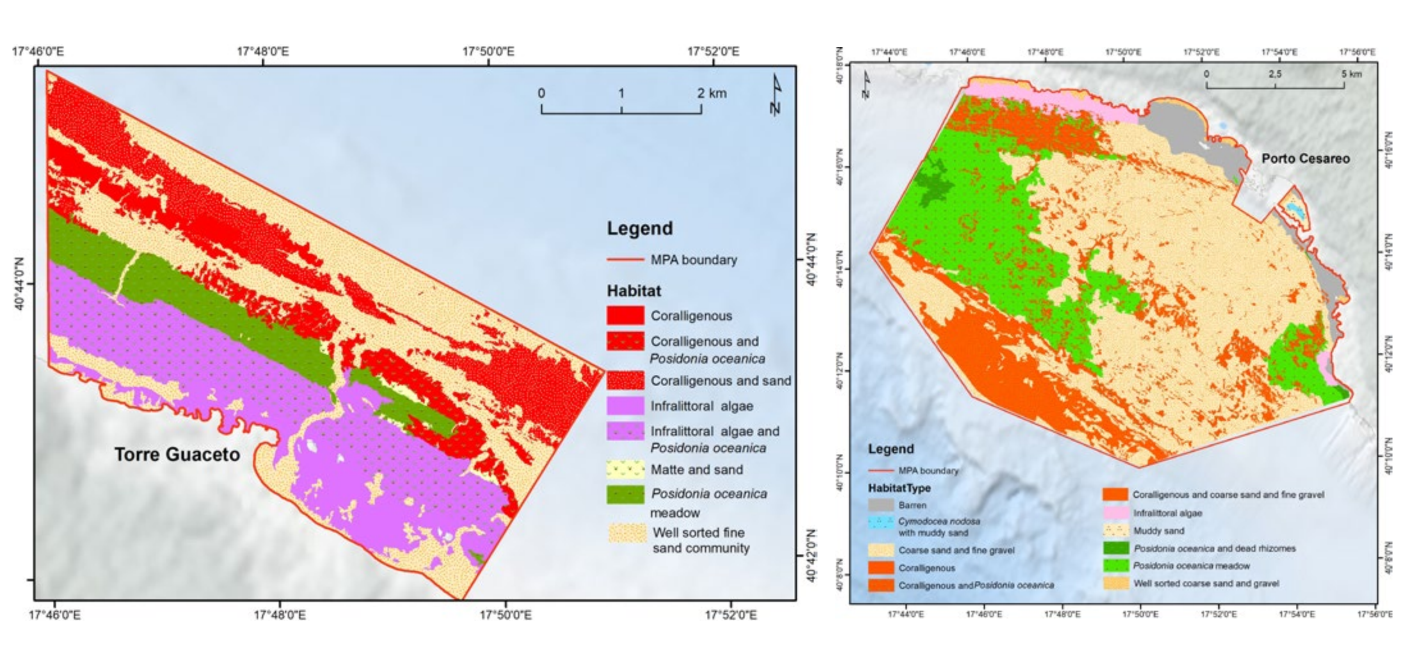
In general, the North-East Atlantic and the Baltic Sea appear to have better mapping coverage than the Mediterranean and Black Seas. Most specific habitats (e.g. seagrass meadows, coralligenous formations, maërl beds, macroalgal forests, coral gardens, sponge aggregations, seamounts, submarine canyons, mud volcanoes and hydrothermal vents) need more mapping efforts. Specific initiatives have been carried out on the distribution of Essential Fish Habitats (i.e. areas or volumes of waters or bottom substrates where fish spawn, breed, feed and grow) to minimise adverse effects from fishing activities. Some examples exist in Scotland[66], in the Baltic Sea (HELCOM, 2021) and in the Mediterranean Sea (Farrag, 2022), where these critical habitats have already been mapped.

There is a substantial lack of maps providing complete and up-to-date spatial distribution of many habitats in Natura 2000 sites. However, in Greece, where Natura 2000 sites were established mainly for protecting *Posidonia* seagrass meadows (Giakoumi *et al.*, 2013), recently produced seagrass coverage maps have quantified for the first time their extent and spatial distribution (Panayotidis *et al.*, 2022). In Italy, 400 million euro allocated from the European Green Deal will go to the Italian Institute for Environmental Protection and Research (ISPRA[67]) to map the distribution and condition of all species of seagrasses along all Italian coasts and approximately 80 seamounts to support the creation of a network of Natura 2000 deep sea sites as part of the PNRR-MER project. Several studies and projects (e.g. Interreg Med AMAre[68]) show that even in MPAs (both fully protected, where all extractive uses are forbidden, and partially protected, where some extractive uses such as fishing are permitted), knowledge about biodiversity distribution and status is often incomplete and should be updated.

Despite the EU MSFD obligation to reach GES for seabed habitats, the level of habitat degradation and loss is often not included in map records, and a low percentage of MHMs are from within MPAs (Gerovasileiou *et al.*, 2019; see Figure 4.4 for two examples). In addition, spatial information on degraded habitats is needed to plan where restoration efforts are most needed. High-quality data (i.e. with a high level of spatial resolution and classification accuracy) on the distribution of habitats that need to be restored and the distribution of human pressures are important to demonstrate the feasibility of restoration actions, to inform prioritisation and to guide the allocation of the restoration targets (Fabbrizzi *et al.*, 2023) included in the proposed EU Nature Restoration Law. Planning large-scale restoration interventions in the absence of high-resolution information can compromise their efficacy.

Finally, deep-sea ecosystems (i.e. below 200m depth) are the last large unknowns on our planet (Amon *et al.*, 2022). However, many resources crucial to society originate from these remote parts of the Ocean, such as oil and gas. In addition, deep-sea mining could become a new activity in the deepest parts of our Ocean. More biological mapping is therefore needed in the deep sea to increase knowledge and guide management actions. For more information on knowledge gaps and research priorities in the deep sea, see the EMB Working Group on Deep Sea and Ocean Health[69].

[65] https://emodnet.ec.europa.eu/geoviewer/
[66] https://www.gov.scot/publications/developing-essential-fish-habitat-maps-fish-shellfish-species-scotland-report/pages/4/
[67] https://www.isprambiente.gov.it/en
[68] https://maritime-spatial-planning.ec.europa.eu/projects/amare-actions-marine-protected-areas
[69] https://www.marineboard.eu/deep-sea-and-ocean-health



Credit: Mariacristina Prampolini & Simonetta Fraschetti (AMAre project).

Figure 4.4 Marine habitat maps are essential for management, especially within MPAs. All MPAs and Natura 2000 sites should have up-to-date, fine-scale maps. Two examples are provided above of maps from Torre Guaceto and Porto Cesareo MPAs (Italy).

4.3 Where to map first? The need for spatial prioritisation

Spatial prioritisation is required to guide the selection of priority areas for MHM. This is currently done on a use-case specific basis. Spatial prioritisation is particularly important due to the high cost of MHM activities, with the final aim to map the entire seabed. This should be considered in stakeholder discussions to mitigate preconceived ideas on which particular places should, or should not, be prioritised for MHM efforts.

Chapter 1 describes how MHM is fundamental for the successful application of EU policies and Directives e.g. to meet the ambitious targets of the MSFD to achieve GES of all BBHT, and to meet the objectives of the Maritime Spatial Planning Directive and the proposed EU Nature Restoration Law, among others. The proposed EU Nature Restoration Law sets ambitious quantitative targets for areas and habitats to restore, with targets for 2030, 2040 and 2050. However, while criteria for the allocation of conservation targets have been identified (Zhao *et al.,* 2020), deciding how to allocate restoration targets still requires considerable clarification (Fabbrizzi *et al.,* 2023). The use of decision-support tools based on scientific knowledge and considering socio-economic constraints can support this process. These are currently being used in marine spatial planning and systematic conservation planning, i.e. a multi-component, stage-wise approach to identifying conservation areas and devising management policies, with feedback, revision and reiteration, where needed, at any stage (Kukkala & Moilanen, 2013). The aim is to allocate human use and identify networks of MPAs at minimum cost. Software such as Marxan[70], one of the most widely used open-source spatial prioritisation tools (Fabbrizzi *et al.,* 2023), and others, are particularly effective in spatial planning thanks to Geographic Information System (GIS) based input of information and flexible interface that includes the costs of needed interventions. These may also be useful to prioritise areas for future restoration and MHM activities.

Regardless of the software used, fine-scale MHM (i.e. with high spatial resolution and classification accuracy) is a prerequisite for the solid background needed to design, site and start active or passive restoration interventions. Gaps in MHM have been identified in Section 4.2 and protected areas (MPAs and Natura 2000 sites) are a priority starting point for MHM. Knowledge derived from MHM is particularly important to assess the criteria for further implementing coherent networks of MPAs. These include criteria such as MPA connectivity and representativity (i.e. the need for MPAs to represent, or sample, the full variety of biodiversity, ideally at all levels of organisation). Priority should also be given to ecologically significant spatial units, such as Cells of Ecosystem Functioning (Boero *et al.,* 2019) and hot spots of ecosystem functioning (e.g. canyons, gyres, upwelling fronts). These require the definition and mapping of the significant ecological connections that define marine ecosystems, which in turn requires a holistic approach to MHM, including benthic and pelagic components, their hydrological and functional connections, and a holistic approach to their management. This process would support moving MHM towards three-dimensional volumes rather than areas (e.g. marine

[70] https://marxansolutions.org/about-marxan/

protected volumes). Areas known to be affected by the most extensive damage to the seabed (e.g. from bottom fishing) are also priorities. Sites for the installation of Blue Economy activities, such as renewable energy and aquaculture, must be properly mapped and managed to avoid significant repercussions at ecosystem level. Areas of the deep sea of interest for mining are also priority areas to be mapped in order to inform decision-making. Guidelines for the prioritisation of mapping activities at an international level could help aid in the selection of priority areas, including the consideration of both active and passive restoration criteria (Fabbrizzi *et al.*, 2023).

In parallel, collation of already existing information should be supported in order to assess what has already been mapped. Efforts already exist in terms of seagrass beds (e.g. Traganos *et al.*, 2022), macroalgal forests (e.g. Verdura *et al.*, 2023), shellfish beds (e.g. Pouvreau *et al.*, 2021), maërl beds (e.g. Illa-López *et al.*, 2023), sponge, coral and coralligenous beds (Ingrosso *et al.*, 2018), and vents and seeps (Taviani, 2014). Suitable unprocessed data can also be collated into MHMs and collated full coverage maps should be transformed into a common format and typology (e.g. EUNIS). More resources should be made available to support the collection of data that would allow the condition of habitats to be captured within maps. An example is the consultancy contract by the Specially Protected Areas Regional Activity Centre (SPA/RAC) to produce updated, standardised maps for three Mediterranean habitats (coralligenous assemblages, Posidonia meadows and marine caves) within the regional project "Empowering the legacy: Scaling up co-managed and financially sustainable no-take zones/MPAs[71]".

4.4 Who uses marine habitat maps and for what purpose?

The closest proxy for the distribution of users of MHMs in Europe is the download statistics published by EMODnet Seabed Habitats[72]. The latest published report (EMODnet Seabed Habitats, 2022) states the following users: researchers and academics (65%), private sector (16%), government/public administration (11%), non-governmental organisations (5%) and other (4%)[73] (Figure 4.5). The most downloaded product in EMODnet Seabed Habitats is the EUSeaMap (>80%). EMODnet Seabed Habitats maps are mainly used for the following applications: academic investigations (29%), implementation of the MSFD (16%), marine spatial planning (13%), studies for marine biodiversity conservation purposes (12%), research related to MPAs (11%), and baseline studies for implementing coastal management including: environmental impact assessments (9%); Blue Economy private sectors (3%); and marine ecosystem service assessments (3%) (Figure 4.5).

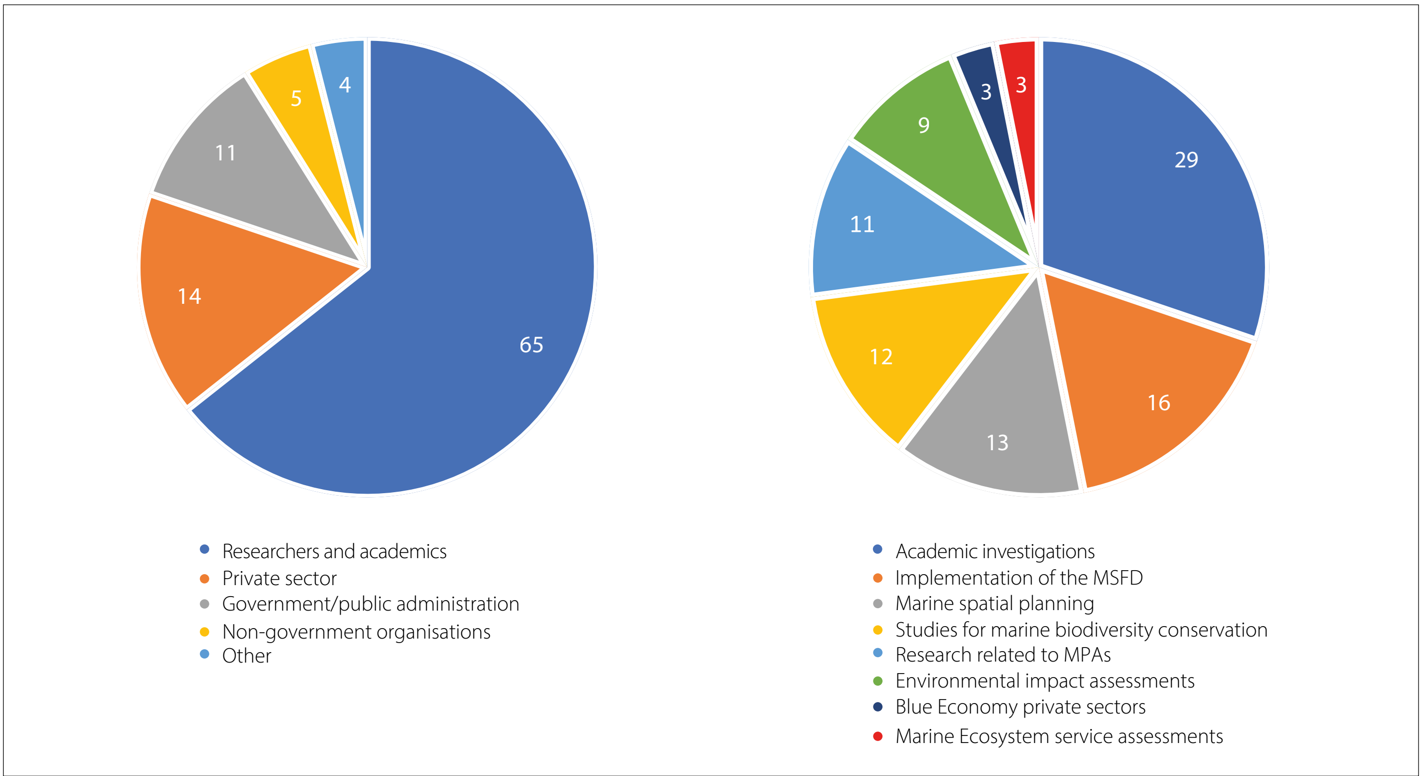


Figure 4.5 Users **(left)** and applications **(right)** for EMODnet Seabed Habitats maps. Values indicate percentages.

[71] https://www.rac-spa.org/node/2023
[72] https://emodnet.ec.europa.eu/en/seabed-habitats
[73] Note that it was not mandatory for users to supply an organisation type, so these figures are the proportions of the 79% of downloads for which an organisation type was supplied.

4.5 Bespoke, fit-for-purpose marine habitat maps

It is difficult to produce a 'one size fits all' map. Nuances in individual maps cannot always be included when carrying out large-scale analyses, especially without good understanding of the input datasets. An example of the need for bespoke maps is to evaluate the extent and distribution of *Sabellaria spinulosa* worm reefs (protected under the Habitats Directive Annex I and OSPAR) in the Southern North Sea. It may be tempting to assume that a single authoritative data product could be used for a variety of purposes. However, different mapping approaches may be required depending on the intended objective, particularly as *S. spinulosa* reefs are notorious for their short-lived nature. To understand their natural range and identify areas for protection or restoration, a compilation of all historic records and maps of the habitat may be the best approach. However, to inform management measures within MPAs, knowledge on the current extent of their habitat is best suited. Each of these use-cases would require a different map and a different estimate of the habitat's extent, all of which are equally valid.

A further example of bespoke map production is the 2023 OSPAR Quality Status Report, where the EMODnet Seabed Habitats consortium produced a bespoke map for the 'Extent of Physical Damage' indicator (Matear *et al.,* 2023), which used the best available MHMs from surveys that were compiled into a single layer, with gaps filled using EUSeaMap. Data on fishing activity was then overlaid to produce an estimate of the areas at highest risk of physical disturbance. Subsequently, it was translated into MSFD BBHTs and provided to EU Member States in the OSPAR region as an optional base layer to use for their six-yearly MSFD reporting. The key benefit of EUSeaMap, and other centrally-built composite data products, is that they are produced using consistent, and often repeatable, procedures across Member State boundaries. However, Member States often have access to additional data and expert local knowledge that can result in more accurate end products.

It would be beneficial for EMODnet Seabed Habitats to work towards producing and promoting best practice guidelines and tools to support Member States in producing their own bespoke maps and composite data products using MHMs. This would allow Member States to use their own local expert knowledge of habitats and additional available data, and to build maps at the scale, extent and level of confidence that they require for different purposes. The creation of new maps could be automated on-demand, as much of the data used to create MHMs is stored centrally, and the models used to combine this information to produce new maps, typically use the same techniques.

Bespoke marine habitat maps are useful to evaluate the extent and distribution of *Sabellaria spinulosa* reefs, particularly given their short-lived nature.

4.6 Recommendations

We recommend scientists/map producers and research funders to:

4a) Increase the spatial extent and resolution of biological information in marine habitat maps

Future MHM efforts should increase the resolution of biological information so that maps progress from predominantly presenting coarse environmental and substrate information, or broad-scale habitats, to representing greater amounts of biological information (e.g. EUNIS classes 4 – 5, and 6 for the Atlantic). This will require the use of map standards for data and modelling (see recommendations 2f and 3b), technological development of platforms and sensors (recommendations 2d and 2e) and better resourced MHM programmes. Map producers need to be tasked and resourced to tackle this critical gap, as habitat and species distribution maps are the most compatible with management and policy requirements.

4b) Develop specifications for specific types of MHMs

Map specifications should be developed for each map type intended for various purposes e.g. habitat inventories, monitoring, advice for designations, ecosystem service assessments, ecological coherence assessments. These specifications should clearly state the required spatial resolution and extent (scale), habitat types and resolution of biological information, as well as accuracy and reporting format. These need to be co-developed by scientists (i.e. advising on what is possible) and end-users (i.e. to determine what is needed and fit-for-purpose).

4c) Produce bespoke MHMs that are fit-for-purpose to better answer stakeholders' needs

Different mapping purposes often require different formats and mapped classes (i.e. potentially using different HCSs or attribution other than habitat 'identity' e.g. ecosystem services), even while using the same underlying data. The creation of new, bespoke maps that are fit-for-purpose could be automated on-demand, using criteria set by the map user and hosted on existing map platforms, such as EMODnet, using the most up-to-date information available. A best practice methodology on how to create such bespoke maps using the EMODnet Seabed Habitats resource could be provided as part of future project deliverables.

4d) Capture habitat condition in MHMs

Given the necessity of understanding condition (i.e. health), habitat mappers should collect and collate information (i.e. metrics or indicators) on habitat degradation and incorporate aspects of habitat condition within maps. This should be supported by the quantitative definition of condition levels within mapped classes (recommendation 3d) and by enabling revision and development within habitat classification schemes (recommendation 3e).

4e) Co-develop guidelines for the prioritisation of MHM activities at an international level

This is needed to help in the selection of priority areas of where to map first given the various priorities for achieving GES for degraded MSFD habitats, active and passive restoration, and maritime spatial planning for Blue Economy activities. Guidelines need to be co-developed in collaboration with a wide range of stakeholders. Decision-support tools should be employed to assist in the prioritisation of MHM activities, which should be taken into account in stakeholder discussions.

In addition, we recommend policymakers to:

4f) Strengthen national, regional, European and international strategic coordination mechanisms for interdisciplinary mapping efforts and resourcing

There is a need for enhanced cooperation on the delivery of coordinated mapping programmes. Improving strategic coordination will help mapping efforts to adhere to defined standards (recommendation 2f), the submission of data into national and European data centres and services (recommendation 5a) and the prioritisation of mapping efforts (recommendation 4e).

4g) Increase and improve map coverage of habitat types and spatial extent through national mapping programmes

Task national bodies (e.g. ISPRA or the UK Centre for Seabed Mapping[74]), which coordinate the collection, management and access of seabed mapping data, and regional (e.g. ICES) and European (e.g. EMODnet) bodies and initiatives, with maintaining oversight of MHM coverage and gap analyses for important habitats or areas. They should also update the MHM community on priority gaps annually, and should be linked to national mapping programmes that can coordinate and commission priority gap-filling surveys.

[74] https://www.admiralty.co.uk/uk-centre-for-seabed-mapping

5 Communication and dissemination

5.1 Data dissemination: increasing the value of each map

The typical format for most MHMs remains digital, to be used in specialist software packages. Efforts to collate and host these files (e.g. by EMODnet Seabed Habitats) have greatly improved their collective extent, visibility and overall value. However, beyond online browsing and the ability to download map images, downloadable files remain in specialist software formats and are generally inaccessible to the public. In addition, most available maps are images of maps and not accessible as open-access georeferenced data i.e. GIS. This should be changed. It is very expensive to produce MHMs and their value can be greatly increased by making them and the data on which they are based more easily accessible to a wider range of stakeholders, so they can be used in many different applications.

The extent to which a dataset is made accessible can be measured against the widely used FAIR data principles for scientific data management and stewardship (Wilkinson *et al.,* 2016), which state that a dataset should be:

- **Findable** – easy to find for both humans and machines;
- **Accessible** – once found, it should be clear how to access it;
- **Interoperable** – able to be combined with other datasets and/or integrated into a workflow for analysis, storage or processing; and
- **Reusable** – requiring well-described metadata about where the data came from.

The ‘collect once and use many times’ philosophy of EMODnet benefits all marine data users, including policymakers, scientists, private industry and the public. It has been estimated that an integrated marine data policy will save offshore operators at least one billion euro per year, and will open new opportunities for innovation and growth[75]. However, there is still a big gap between maps that are published in scientific papers and those available in portals. The ICES workshop[76] on the use of predictive habitat models in ICES advice found that MHMs are not yet used much in management compared to the number of available maps due to the slow uptake of the open data concept, issues of map confidence and knowing which map to use, lack of data and maps submitted to EMODnet, data management issues (e.g. formatting maps), and complex mechanisms to submit data (ICES, 2021).

An effective way to close these gaps would be to facilitate and incentivise map producers to publish MHMs in common repositories. The first step, however, is for map producers to know where the repositories are and what the process is.

5.1.1 Current situation

For some types of marine data such as geological/biological surveys and hydrographic data, national data centres are the authoritative data sources. They aggregate data on a suite of themes at a national level and set data standards. Data from these centres are then ingested by EU data infrastructures (e.g SeaDataNet[77], EurOBIS[78]), and subsequently the data is aggregated and standardised at the European level by EMODnet’s thematic groups (e.g. EMODnet Physics, Geology and Bathymetry).

Unfortunately, it is uncommon for European countries to have national data centres dedicated to MHMs. Without the national data centres aggregating national data, EMODnet Seabed Habitats (unlike most of the other EMODnet thematic groups) must first undertake this role before it can aggregate the data at European scale. This leads to bias in the MHMs that are aggregated, with the majority of MHMs coming from countries who are, or have previously been, partners in the EMODnet Seabed Habitats consortium, with data gaps elsewhere. Improving the process of getting data into EMODnet is of great importance considering the deadlines of the proposed EU Nature Restoration Law, and the need to estimate the state of play with mapping of the Habitats Directive Annex I habitats and MSFD BBHT, and assessment of their condition across EU seas.

[75] https://emodnet.ec.europa.eu/sites/emodnet.ec.europa.eu/files/public/Brochure/EMODnet_brochure_updated_11-Jan-18_Vweb.pdf
[76] https://www.ices.dk/community/groups/Archive%20for%20Community%20pages/WKPHM.aspx
[77] https://www.seadatanet.org/
[78] https://www.eurobis.org/

5.1.2 Ensuring maps produced for policy and research are submitted to EMODnet

There are repositories and portals that bring together mapping data on several marine themes for specific purposes, such as monitoring, marine spatial planning or conservation (e.g. ISPRA[79] portal and the National Biodiversity Future Centre[80] for Italy, CoCoNet spatial geoportal[81], Adriplan[82]), which have been produced by and for government agencies and departments. Map producers may perceive no added benefit in supplying data to EMODnet, despite EMODnet offering users data and web services that are interoperable with global Ocean data initiatives. In addition, the custodians of national and regional repositories do not always take responsibility for passing the data on further to ensure wider use. As a result, there are a number of different map producers and, for each map, different end-points e.g. marine planning portals, MPA portals, aggregated datasets for environmental status reporting such as for Regional Sea Conventions. What is missing is a pipeline of named organisations and repositories who are responsible for aggregation, standardisation and publication of national or sub-regional MHMs, that can feed MHMs into EMODnet.

Increasingly, researchers are encouraged to publish their data and results along with any written publications. PANGAEA[83] provides a free repository for researchers to publish spatial datasets related to Earth and environmental science and Zenodo[84] is a multidisciplinary, open repository where data can be submitted. However, more must be done to connect repositories like PANGAEA and EC marine data services e.g. EMODnet, so that data are more accessible to the public and policy communities.

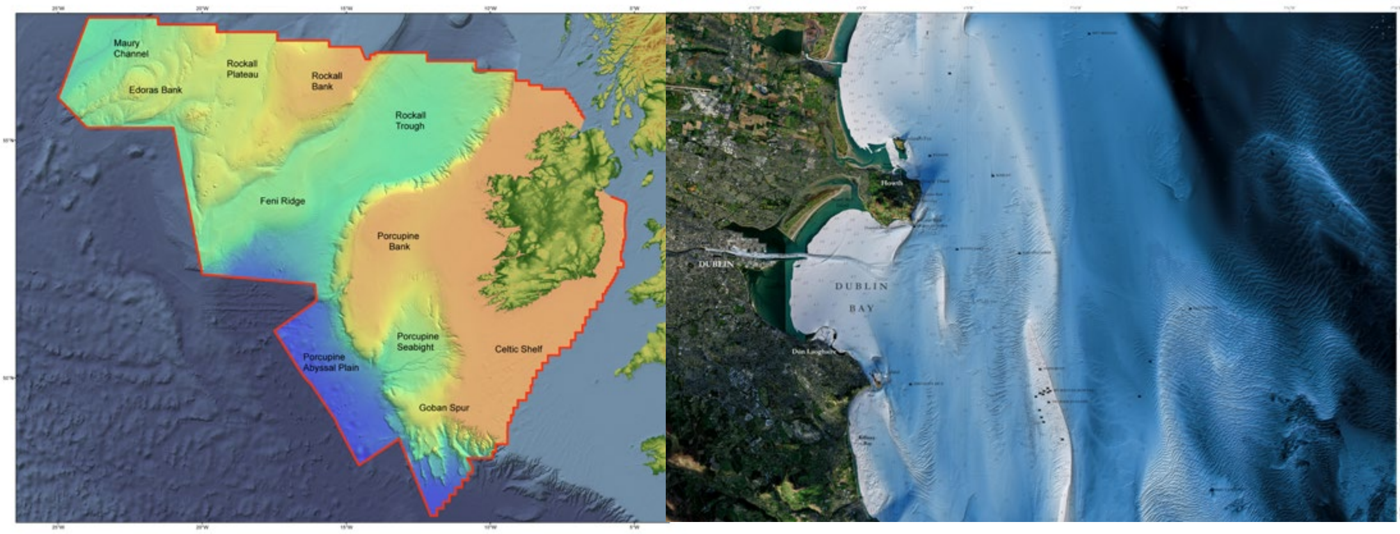
5.1.3 Industry data

Data acquired by industry provides an under-utilised source of information. To incorporate this data into MHM-based decision processes, it needs to adhere to the same standards as environmental assessment and research data and needs to be published in comparable FAIR archives e.g. in the Ocean Biodiversity Information System (OBIS[85]) or EMODnet. Quality Assurance/Quality Control plans and procedures need to be implemented to raise the information content to the level required for informative and robust MHM and for subsequent publication. To facilitate access to industry data, national licensing bodies for Blue Economy activities should require data from site investigations and monitoring to be submitted to central data repositories as a licensing condition, and agreements for mutually beneficial partnerships and data exchange formats should be activated. These data should come into national data centres first and then to EMODnet. Data need to be provided to specified standards and governments should oblige industry to provide data from environmental impact assessments and subsequent environmental monitoring in formats compatible with national databases. This might entail reduced resolution datasets for commercially sensitive areas or providing public data in formats that are compatible with industry software, e.g. bathymetric datasets that can be imported into charter plotters used by the fishing community (e.g. OLEX[86] and TimeZero[87]).

5.2 Using marine habitat maps to improve public understanding of the Ocean

Although the Ocean covers more than 70% of the Earth's surface, more than 90% of its volume and supports an estimated 90% of the life forms on our planet, marine habitats, and the species they support, remain largely inaccessible to humanity. Maps, as visual tools, provide important foundational information on marine habitats in an intuitive and recognisable format that facilitate several of the principle messages of Ocean literacy[88], namely: (i) the Earth has one big Ocean with many features; (ii) the Ocean supports a great diversity of life and ecosystems; (iii) the Ocean and humans are inextricably interconnected; and (iv) the Ocean is largely unexplored. An increase in Ocean literacy will stimulate continued interest for new or updated mapping products. MHM will undoubtedly play a major role in Ocean Literacy initiatives that bring the challenges the Ocean faces to the attention of society and when developing accessible mapping products (e.g. atlases, apps, posters and digital products) that promote public interest and knowledge of the Ocean. An example is the DONIA app[89] that targets boaters who use MHMs to avoid anchoring on sensitive seabed habitats. Ireland's national seabed mapping programme, INFOMAR, also produces story maps for bays of interest around the Irish coastline. These story maps document the natural and cultural heritage found in the area and link to the importance of managing and monitoring these features through detailed seabed maps. INFOMAR has also produced high-resolution bathymetric maps of Ireland's coastal waters (Blue Scale Map Series[90]) and the map of its offshore territory, "The Real Map of Ireland", is used as a teaching resource in primary schools[91] (Figure 5.1).

[79] http://www.db-strategiamarina.isprambiente.it/app/#/
[80] http://gismargrey.bo.ismar.cnr.it:8080/mokaApp/apps/pnrrb/index.html
[81] http://coconetgis.ismar.cnr.it/
[82] http://adriplan.eu/
[83] https://www.pangaea.de/
[84] https://zenodo.org/
[85] https://obis.org/
[86] https://olex.no/products/olex_software_en.html
[87] https://mytimezero.com/
[88] https://oceanliteracy.unesco.org/principles/
[89] https://donia.fr/en/home/
[90] https://www.infomar.ie/galleries/node/565
[91] https://www.scoilnet.ie/go-to-post-primary/geography/infomar/landscape/



Credit: INFOMAR.

Figure 5.1 Outreach products from INFOMAR used as teaching resources in Irish primary schools: "The Real Map of Ireland" (**left**) displays Ireland's offshore bathymetry in shaded relief to highlight geomorphological features and the blue scale bathymetric map of Dublin Bay (**right**) highlights complex sandbanks in the Irish Sea.

Rapidly evolving robotics, information and communication technologies hold considerable potential to help unravel the mysteries of the Ocean and allow citizens virtual access to otherwise inaccessible underwater regions. Google Streetview Underwater[92] is a good example of how citizens can view and "explore" selected areas of the underwater world. Considerable effort is being made worldwide to virtually explore the Ocean, also known as 'telepresence' or Virtual Ocean Exploration Local Area Networks (Figure 5.2), which will unleash a paradigm shift in the access that citizens have of the Ocean. The concept involves virtual explorers within the comfort of a museum or science centre auditorium being 'transported' to a given site via a satellite-based or underwater cable communications link to a support ship. The ship acts as a command unit from which robotic-based vehicles are launched to explore the underwater environment, which maintain contact with the ship via acoustic links. The movement and data gathering actions of the robots can be programmed by a virtual explorer using specially designed interfaces and the robots become the extended "arms" of the spectators, who can collectively select what type of data/information they wish to have access to or visualise. Explorers can play a double role of a general mission planner with a say on what data to acquire and where, and a mission visualiser/analyser having access to selected data acquired in almost real-time (e.g. temperature, salinity, turbidity as function of depth) and/or underwater and seabed images (e.g. photographs and acoustic-based mosaics) during and after a mission has taken place. In practice, the USA's National Oceanographic and Atmospheric Administration (NOAA) Ocean Exploration programme has made pioneering contributions in this area since the early 2000s. For example, NOAA research vessel *Okeanos Explorer* uses satellite technology to transmit data and video in real time from the ship to a shore-based hub and then to other sites via the internet (Figure 5.2) and NOAA Microbial Stowaways[93] expedition aboard *Point Sur* allowed students to telecommunicate from shore.

92 https://www.underwater.earth/
93 https://oceanexplorer.noaa.gov/explorations/19microbial-stowaways/background/plan/plan.html

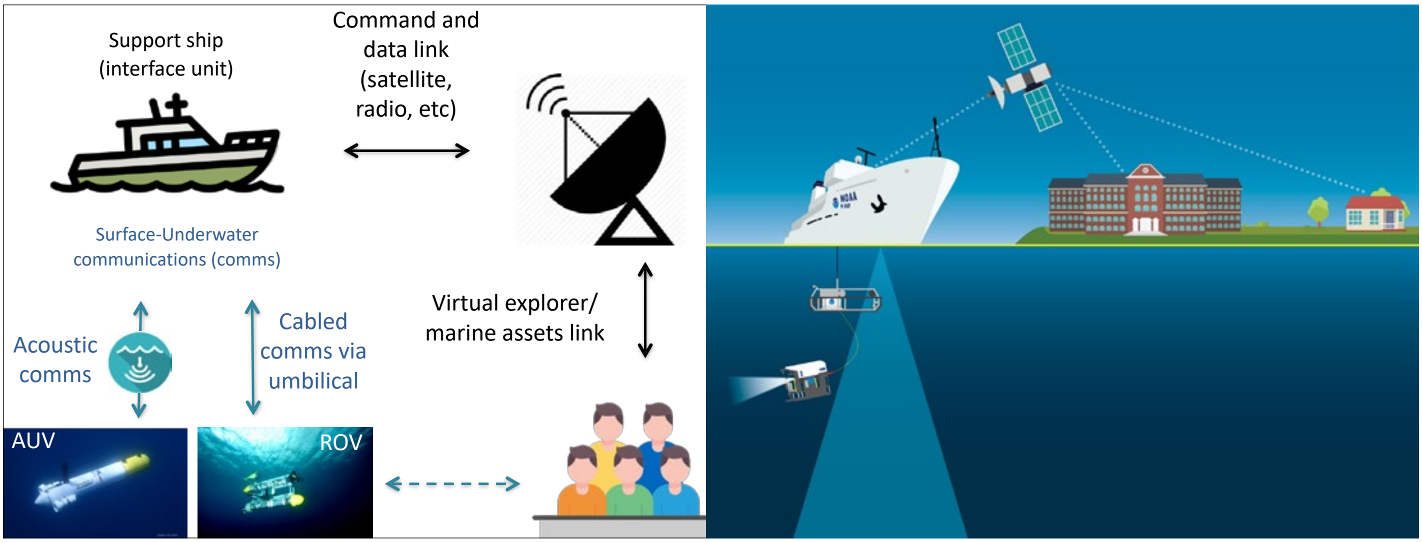


Figure 5.2 Left: Conceptual diagram of a Virtual Ocean Exploration Local Area Network (LAN; i.e. group of computers and linked devices) or 'telepresence' system, enabling virtual Ocean exploration by bringing together robotics, sensing and communications. **Right:** NOAA Ocean Exploration uses satellite technology to deliver data from sensors on their ship *Okeanos Explorer* back to shore[94].

Credit: Antonio Pascoal & Pere Ridao (left), NOAA Ocean Exploration (right).

An example of the coupling between marine robotic systems and Internet of Things (IoT[95]) as an affordable tool for Ocean Literacy is the EU project Blue Robotics for Sustainable Eco-friendly Services for innovative marinas and leisure boats (Blue RoSES[96]), where an affordable system was developed to allow non-scientific users access to the underwater world following a scientific mission as it unfolds (see Figure 5.3). Citizens were able to "connect" remotely to a station on board a small support ship to which an ROV was tethered and could issue high level instructions using a specialised application and access images. Data were transferred between the support ship and the shore station(s) using a standard telecommunication network (4G/LTE) enabling the rapid transmission of images. The ROV was able to manoeuvre in response to high level commands while keeping itself within safe vicinity of the support ship, thus removing the need for an expensive dynamic positioning system. Ultimately, it is hoped that this will become a two-way system that will allow the control or programming of underwater assets from remote locations (i.e. on shore rather than ship-based control).

Citizen science is an approach which involves members of the public in gathering scientific data and is a way to enhance awareness of the marine environment. An example is the National Biodiversity Data Centre[97] in Ireland that hosts a mapping and data portal, and runs a series of citizen science projects which allow individuals to submit their records. Other examples are the Hidden Deserts initiative[98], which includes citizen science data in mapping shallow underwater habitats, and Reef Check Mediterranean initiatives that provide citizen science data of more than 40 species collected by trained snorkelers, free divers and SCUBA divers (Turicchia *et al.*, 2021a; see Figure 5.4). Crowd sourced image annotations is another example of the contribution of citizen science to MHM. However, Assurance/Quality Control plans and procedures are required to raise citizen science data to the level required for informative and robust MHM or subsequent publication, as is done in OBIS and the Reef Check Mediterranean Underwater Coastal Environmental Monitoring Protocol (Turicchia *et al.*, 2021b).

94 https://oceanexplorer.noaa.gov/technology/telepresence/telepresence.html#
95 The internet of things is a world-wide network of smart interconnected objects with a digital entity
96 https://bluerosesproject.wixsite.com/home/about
97 https://biodiversityireland.ie/
98 https://hiddendeserts.com/

Figure 5.3 Ocean Literacy and virtual underwater exploration. **Left:** the ROV deployed in Portugal, near a shipwreck. **Right:** operator in Genova controlling the ROV while observing the shipwrecks' cannon.

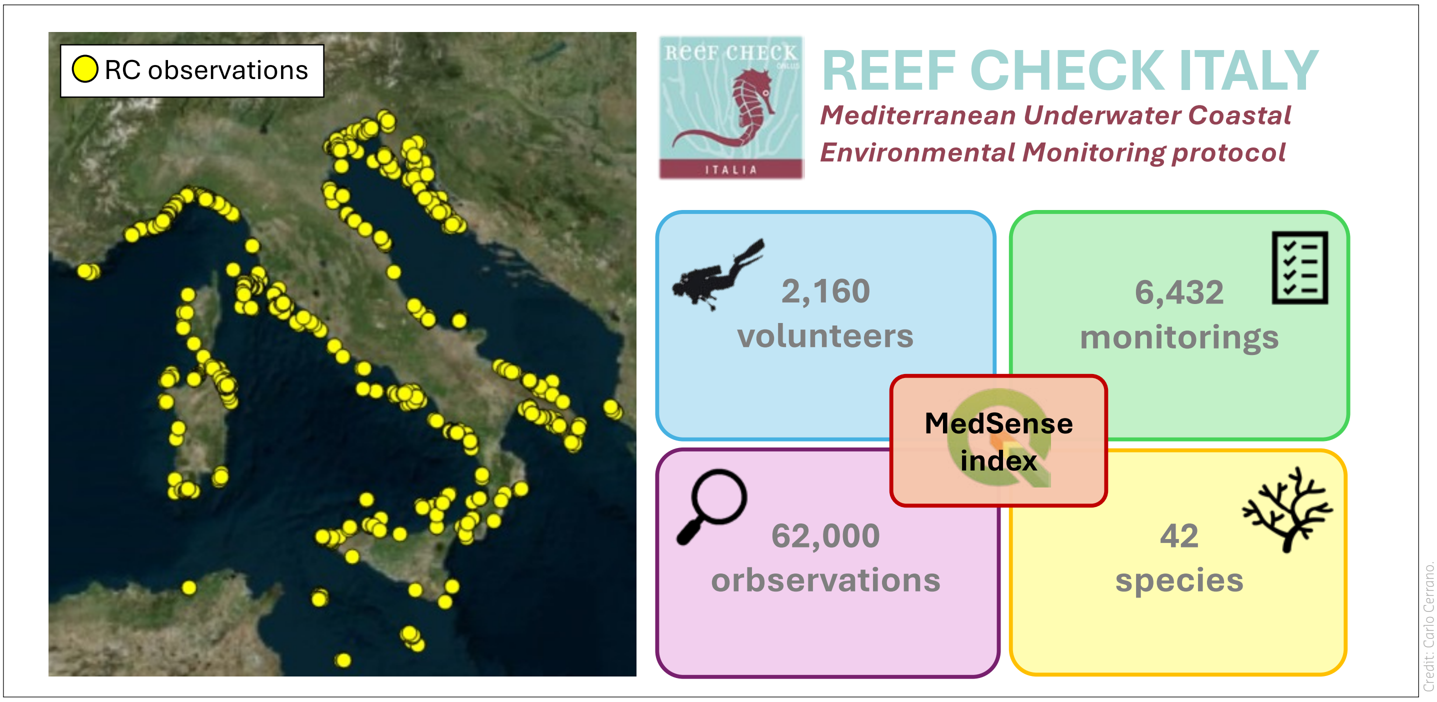


Figure 5.4 Synthesis of the activities carried out in Reef Check (RC) Mediterranean to map shallow underwater habitats.

5.3 Recommendations

We recommend research funders to:

5a) Facilitate and incentivise map producers to publish their maps according to the FAIR principles and submit data to EMODnet

MHM data should not solely be published in scientific journals or reports as PDFs, but also as FAIR data layers that allow reuse for further studies and decision-support processes. This requires open and interoperable data repositories and archives that are sustainably maintained in the long-term. No specific repositories are needed for MHM data as existing solutions like PANGAEA and Zenodo can be used. Submitted data need to adhere to FAIR standards. In addition, map producers should be incentivised and/or obliged by funding bodies to submit data and maps to EMODnet. More data repositories should be linked to EMODnet and a pipeline should be established of named organisations (e.g. national data centres) who are responsible for aggregation, standardisation and publication of national or sub-regional MHMs, that can feed into EMODnet.

We recommend policymakers to:

5b) Develop partnerships with wider stakeholders on open data

To incorporate industry and citizen science data into MHM-based decision processes it needs to adhere to the same standards as data acquired for environmental assessments and research purposes (see recommendation 2f) and needs to be published in comparable FAIR archives (see recommendation 5a). Quality Assurance/Quality Control plans and procedures need to be implemented. To facilitate access to industrial data, mutually beneficial partnerships or exchange formats need to be established and national licensing bodies for Blue Economy activities should require data from site investigations and monitoring to be submitted to central data repositories as a licensing condition.

In addition, we recommend scientists/map producers, with the support of research funders to:

5c) Develop accessible mapping products for Ocean literacy and support citizen science initiatives

Developing mapping products that promote Ocean Literacy will stimulate a continued interest in new and updated mapping products. Improvement and extension of projects that couple marine robotic systems and the Internet of Things towards the development of new affordable tools for Ocean literacy will pave the way for the development of virtual Ocean exploration missions, which are key for Ocean literacy. Additionally, citizen science projects that collect mapping data should be supported.

Credit: N Credit: NOAA Ocean Exploration.

Students telecommunicating directly with Research Vessel Point Sur during NOAA's Microbial Stowaways expedition in the Gulf of Mexico[99].

[99] https://oceanexplorer.noaa.gov/explorations/19microbial-stowaways/welcome.html

6 Overarching recommendations to advance marine habitat mapping

Marine habitat maps provide fundamental information on the 'what, where and how much' for marine habitats. Although modern sensors and autonomous platforms are revolutionising the mapping of both benthic and pelagic habitats, this requires significant resources and increased awareness of the urgent need to complete the mapping of our Ocean. Many of the gaps in mapping activities, such as substantially increasing biological information, especially in the deep sea, and mapping habitat condition, require focused investments and dedicated projects, including new mapping programmes with an ongoing duration. Meeting this need will provide a step change in improving the understanding of ecosystem patterns and processes, and will inform decision-making in areas such as marine resource management, environmental change, and Ocean conservation and restoration.

To meet these needs, we recommend scientists/map producers and research funders to:

- **Support multidisciplinary national and EU research projects to advance novel methods to increase the resolution of biological information within marine habitat mapping.**

  This will enable the step change needed to improve mapping of biological communities and species, and mapping of both the seafloor and water column as three-dimensional maps, rather than only physical habitats and substrates. This links to the increasing need to represent species and habitat distribution within marine habitat maps so they can be compatible with the new challenges posed by the spatial management of increasing human uses and policy activities. In addition, this will improve the information used in spatial models, making their outputs more robust.

- **Support national and EU research programmes that focus on repeat mapping for capturing temporal change in patterns and processes, particularly of ecologically significant spatial units, i.e. hot spots of ecosystem functioning where high rates of change are expected.**

  Repeat mapping surveys for addressing changes in habitats over time (i.e four-dimensional maps) focusing on habitat seasonality, human impacts (including long-term changes induced by climate change), recovery trajectories, and the identification of early warning signals for tipping points, will translate into scientific knowledge to support management activities. Existing mapping activities typically provide 'static' products and incorporating temporal change within marine habitat mapping is the only way to support a holistic, ecosystem approach to marine ecosystem management.

- **Promote the standardisation of mapping methods and outputs in research and mapping programmes.**

  Guidance should cover the required spatial extent and resolution of biological information and reporting format of maps for specific purposes. This includes standards for data collection and processing, and best practices on the choice, selection and parameterisation of models used in marine habitat mapping. This will help with transparency in model selection and development, and assist managers in evaluating whether a model is suitable for providing advice for spatial management. It should also include best practice methodology on the creation of bespoke maps for specific purposes.

- **Promote and incentivise research and mapping programmes to publish marine habitat mapping data according to the Findable, Accessible, Interoperable and Reusable principles and to submit data to centralised data services.**

  This will improve data sharing and includes data acquired by researchers and from a wider range of stakeholders (e.g. industry, citizen science), which are largely untapped sources of information. The value of data from stakeholders should be promoted and these data incorporated into marine habitat mapping-based decision processes. Open and interoperable FAIR data repositories, services and portals should be sustainably maintained in the long-term to handle increasing volumes of data and stakeholders incentivised to submit data.

- **Support for public-private research collaboration is needed for the development of cost-effective mapping tools.**

  This can assist in the development of innovative technologies and the collection and processing of mapping data at larger spatial scales. This includes advanced autonomous and interoperable marine robotic platforms equipped with suites of complimentary sensors for data collection "underway". Scaling-up the use of artificial intelligence can assist with cost-effective data acquisition and data analyses to deal with the large volumes of data generated by new mapping technologies.

- **Support dedicated mapping projects focusing on citizen science and reformatting mapping products that promote Ocean literacy.**

  This will stimulate continued interest for new or updated mapping products, thereby promoting the support of the public. Improvement and extension of projects that couple marine robotic systems and the Internet of Things towards the development of new affordable tools for Ocean literacy will pave the way for the development of advanced, yet affordable systems capable of executing virtual Ocean exploration missions. Additionally, citizen science projects that collect mapping data should be supported.

In addition, we recommend policymakers to:

- **Strengthen national, regional, European and international coordination mechanisms for interdisciplinary mapping efforts to ensure effective use of mapping resources and identification of gaps.**

  This will help ensure adherence to defined standards, the submission of data into national and European data centres and services, and the prioritisation of mapping efforts. Coordination bodies should identify gaps in the mapping of various habitats and the spatial coverage of marine habitat maps, and then coordinate, or commission, mapping studies to close priority gaps and to include aspects of habitat condition in the collection of mapping data and its presentation in final maps. Such efforts will support reporting for the Marine Strategy Framework Directive, Habitats and Birds Directives, 2030 Biodiversity Strategy, and the proposed EU Nature Restoration Law. This will also support the establishment and review of spatial plans, as required by the Maritime Spatial Planning Directive. National and regional coordination for shared resources and facilities is also required, as is the funding of new mapping programmes.

- **Establish an international effort to identify priority areas in need of mapping, with a focus on areas of the largely unmapped deep sea and coastal areas, which are under the greatest pressure from human activities.**

  Guidelines for the prioritisation of marine habitat mapping activities, including the use of decision-support tools, should be developed.

- **Require map producers (e.g. ICES Working Group on Marine Habitat Mapping, EMODnet, large mapping projects) or map users (e.g. the European Environment Agency, Joint Nature Conservation Committee) to produce best practice and reporting templates for the standardised assessment and reporting of map accuracy and confidence.**

  These should be widely communicated within the marine habitat mapping community to facilitate better understanding of the value of maps and their use for specific purposes. Additional guidance should be produced that assists map users in how to assess certainty and establish what is fit-for-purpose.

- **Advance habitat classification schemes, which lie at the heart of all marine habitat maps, to include quantitative characterisation of habitats to support the assessment of their condition. Habitat maps will be enriched further if these classification schemes link to other sources of information such as sensitivity to pressures and ecosystem services provision.**

  This will facilitate building a common framework and easily understood terminology for the description of habitats to be consistently adopted in initiatives aimed at marine habitat mapping, monitoring and data collation. In addition, an online tool should be developed to enable the submission of suggestions by scientists of revisions to a habitat classification system.

List of abbreviations and acronyms

3D	Three-dimensional
4G/LTE	Fourth generation long-term evolution
AI	Artificial Intelligence
AUV	Autonomous Underwater Vehicle
BBHTs	Benthic Broad Habitat Types
CBD	Convention on Biological Diversity
DNA	Deoxyribose Nucleic Acid
eDNA	Environmental DNA
EEA	European Environment Agency
EEZ	Exclusive Economic Zone
EMBRC	European Marine Biological Resource Centre
EMODnet	European Marine Observation and Data Network
EOV	Essential Ocean Variables
EU	European Union
EUNIS	European Nature Information System
EurOBIS	European Ocean Biodiversity Information System
FAIR	Findable, Accessible, Interoperable, Reusable
FP7	Seventh Framework Programme, European Union research and development funding programme
GEBCO	The General Bathymetric Chart of the Oceans
GES	Good Environmental Status
GIS	Geographic Information System
GOOS	The Global Ocean Observing System
GSI	Geological Survey Ireland
Ha	Hectare
HELCOM	The Baltic Marine Environment Protection Commission
HELCOM HUB	The HELCOM underwater biotope and habitat classification system
HCS(s)	Habitat Classification Scheme(s)
ICES	International Council for the Exploration of the Sea
INSS	Irish National Seabed Survey
ISPRA	Italian Institute for Environmental Protection and Research
LAN	Local Area Network

LiDAR	Light Detection and Ranging
MarESA	Marine Evidence-based Sensitivity Assessment
MBES	Multibeam Echosounder
MESH	Mapping European Seabed Habitats
MESSENGER	MErcury Surface, Space ENvironment, GEochemistry, and Ranging
MSC	Marine Stewardship Council
MSFD	Marine Strategy Framework Directive
MHM	Marine Habitat Mapping
MHMs	Marine Habitat Maps
MPA(s)	Marine Protected Area(s)
NASA	National Aeronautics and Space Administration
Nm	Nanometre
NOAA	National Oceanographic and Atmospheric Administration
OBIS	Ocean Biodiversity Information System
OSPAR	Oslo and Paris Conventions
PDF	Portable Document Format
PNRR MER	National Recovery and Resilience Plan, Marine Ecosystem Restoration
PwC	PricewaterhouseCoopers
RC	Reef Check
RCP	Representative Concentration Pathway
ROV	Remotely Operated Vehicles
SCUBA	Self Contained Underwater Breathing Apparatus
SDG(s)	Sustainable Development Goal(s)
SPA/RAC	Specially Protected Areas Regional Activity Centre
SSS	Side-Scan Sonar
UAV	Unmanned Aerial Vehicle
UK	United Kingdom
USA	United States of America
UN	United Nations
UNEP MAP- RAC/SPA	United Nations Environment Programme Mediterranean Action Plan Specially Protected Areas Regional Activity Centre
VIAME	Video and Image Analytics for Marine Environments
WGMHM	Working Group Marine Habitat Mapping

Glossary

Abiotic - Non-living components of an ecosystem or environment.

Absence data - Observational data on where a species of interest and habitats are not present.

Accuracy - Certainty within a map in terms of location and the quality of labelling for mapped units. Accuracy is diminished by the cumulative influence of all errors (total error) within a map. Estimates of map error rate are derived from cross-validation between observed versus predicted classes.

Artificial Intelligence - The theory and development of computer systems that are able to perform tasks or exhibit behaviour normally requiring human intelligence.

Autonomous surface platforms - Uncrewed vehicles designed to operate on the surface of water without direct human intervention.

Autonomous underwater vehicle - An underwater sensor platform that undertakes a programmed survey without input from an operator and without a cabled connection to the surface. AUVs can carry a variety of sensors and cameras to collect data over large spatial extents and at relatively low cost.

Backscatter data - Data on the intensity of sound waves released from Multibeam Echosounder (MBES) devices reflected back from the seabed, used to measure substrate softness and texture.

Bathymetry - Underwater topography and physical features derived from depth data.

Benthic crawler - A robot that moves independently, carrying scientific instrumentation for scanning a continuous track of the seabed for prolonged periods.

Benthic habitat - A habitat associated with or occurring at the seafloor.

Benthic landers - Static seabed platforms containing sensors able to provide high-resolution time-series data at fixed locations.

Biocenosis - A group of living organisms that, through their composition, number of species and individuals, reflects the average conditions of their environment. These organisms are interconnected through mutual dependence and permanently live and reproduce in a specific location. The term is synonymous with a biological community.

Bioconcretion - Hardened biological structures formed by the accumulation and cementation of mineral materials within a biological environment.

Biogenic habitat - Habitats formed by living organisms, which provide a habitat for other organisms. Typical examples include mussel beds, coral reefs, coralligenous concretions and *Posidonia oceanica* meadows and algal-animal forests.

Biological assemblage - A group of species that coexist in a specific habitat.

Biological community - A group of interacting organisms coexisting in a specific habitat.

Biological habitat map - A map that illustrates the spatial distribution of living organisms within that area, providing insights into biodiversity, species composition or ecological interactions.

Biotope - A distinct habitat or environment where particular types of organisms live.

Chlorophyll-a - A green pigment found in plants, algae and some cyanobacteria. It plays a crucial role in photosynthesis.

Circalittoral - The region extending from the low tide mark to the maximum depth at which photosynthesis is possible.

Condition - The ecological health of a mapped unit in terms of environmental conditions (e.g. anthropogenic modification of key environmental properties or concentrations) and biological disturbance (i.e. impacts on the structure or functioning of a community of species within a habitat).

Confidence - The fitness of a map for a specific use. Confidence is determined both by the accuracy of a map and the intended purpose of the map by the end-user.

Connectivity - The extent to which populations in different parts of the species' range are linked by the movement of eggs, larvae or other propagules, juveniles or adults.

Contiguous data - Data that is continuous across a geographic area.

Continuous data - Data with variables that can take on an infinite number of values within a certain range e.g. salinity.

Convolutional neural networks - A type of artificial neural network that is well-suited for analysing visual data such as images and videos. They are designed to automatically and adaptively learn spatial hierarchies of features from input data.

Coralligenous formations - A hard surface made mostly from the buildup of calcareous coralline algae.

Correlative models - Models that relate known probabilities of species presence to environmental variables.

Corer - A device that retrieves a physical sample of the uppermost layers of the seabed.

Cultural ecosystem services - Ecosystem services that provide non-material benefits derived from nature such as recreation and tourism, beauty, as well as spiritual, intellectual and cultural benefits.

Deep learning - Capable of learning patterns directly from data.

Digital twins - Coupled observation and simulation data frameworks for human and AI-based scenario interpretation.

Direct observations - Data collected close to the object of interest.

Discrete data - Categorical data with values that are separate, with no possible values in between e.g. substrate.

Distribution models / habitat suitability models / species distribution models - Models that typically predict the probability of the presence, or the habitat suitability, for a given species, or selection of species when applying joint species distribution modelling.

Dredge - A tool used for collecting samples from the seabed. It typically consists of a metal frame with an attached net or basket, which is dragged along the seabed to scoop up sediment, rocks and biological organisms.

Drop camera - A type of underwater camera that is lowered into the water column from a boat, buoy, or other platform and attached to a cable.

Ecosystem-based approach - An approach to management where all interactions within an ecosystem, including human interactions, are considered holistically.

Ecosystem services - The social and economic benefits obtained by society from its use of the ecological functions of ecosystems.

Environmental DNA - Genetic material collected directly from environmental samples such as sediments or seawater.

Epibenthic communities - Biological communities on or just above benthic habitats.

Essential Fish Habitats - Areas or volumes of water or bottom substrate that are crucial for fish life stages i.e. areas where they spawn, breed, feed and mature.

Essential Ocean Variables - A series of variables to monitor and map the Ocean consistently and cost-effectively.

Eulittoral - The area of the shore between the highest and lowest tides.

Geomorphology - The shape of the seabed.

Georeferenced data - Data that are associated with a location or physical space.

Gliders - A type of autonomous underwater vehicle that is deployed from vessels for survey missions at remote distances from the vessel. They typically do not have an engine, and instead use changes in buoyancy to move up and down through the water.

Grab - A device that retrieves a physical sample of the uppermost layers of the seabed.

Ground truthing - The process of validating or verifying data collected via remote sensing methods or from modelling. This is done by direct, *in situ* observations.

Habitat - A recognisable space which can be distinguished by its abiotic characteristics and associated biological assemblage, assessed at particular spatial and temporal scales.

Habitat classification scheme - A set of instructions that identify, delimit, and describe the habitats of distinct species and communities by categorising them into "classes".

Hyperspectral imaging - Optical camera technology that records in the visible portion of the electromagnetic spectrum (390-700nm) at up to 1nm resolution.

Infralittoral - A specific depth range within the marine environment extending from the lowest tide limit to the the limit at which enough light penetrates to support photosynthetic organisms.

***In situ* observations** - Samples and observations collected in the water, close to the object of interest.

Internet of Things - A world-wide network of smart interconnected objects with a digital entity.

Light detection and ranging (LiDAR) - A method for determining distances by targeting an object or a surface with a laser and measuring the time for the reflected light to return to the receiver.

Littoral - The part of a sea or Ocean that is close to the shore.

Local area network - A network of interconnected computers and devices within a limited geographical area. They allow computers and devices to communicate and share resources.

Machine learning - Algorithms that automatically learn to recognise complex patterns in new datasets, improve their performance from experience and produce models that have predictive power.

Machine vision - Machines that are able to autonomously perceive, interpret and understand visual data.

Maërl bed - A biogenic structure composed of unattached calcareous red algae living on sedimentary bottoms.

Mechanistic models - Models that relate physiological information about a species gained from literature or laboratory experiences to environmental variables for assessing their fitness at specific locations.

Megaripple bedforms - Large wave-like features on the seabed typically formed by the interaction between strong currents and mobile sediments.

Mosaic - A representation of the seabed composed of multiple habitat types or classes arranged in a spatially contiguous manner.

Multibeam Echosounder (MBES) - An acoustic device that uses sonar to map seabed bathymetry, morphological characteristics and substrate types.

Multispectral MBES - Sensors that acquire several MBES data using different acoustic frequencies simultaneously.

Pelagic habitats - Habitats associated with the water column.

Photogrammetry - A technique using multiple overlapping photographs to determine the size, shape and position of objects.

Photophilic - Algae or plants that grow best in strong light.

Physical habitat map - A map delineating the environmental characteristics and features of a given area, such as substrate type, depth, seafloor morphology and water flow.

Phytoplankton - Microscopic algae that live in the water column.

Process-oriented models - Models used to estimate species distribution based on processes such as ability to disperse and biotic interactions.

Provisioning ecosystem services - Ecosystem services that provide tangible, harvestable goods such as fish, shellfish and seaweed for food, raw materials, algae and minerals.

Proxy - An observable variable that is used as a substitute or indicator for a specific habitat type or ecological feature. Proxies are often derived from remotely-sensed data and are used to infer the presence or characteristics of different habitat types across the marine environment.

Pseudo-absence data - Proxy observations suggesting that a species of interest is highly unlikely to be present e.g. observations of other species that are known not to co-occur with the target species.

Reflectivity - The acoustic energy reflected from the seabed or an object in the water column.

Regulating ecosystem services - Ecosystem services that regulate natural processes and maintain ecological balance, such as coastal protection, prevention of erosion, water purification and carbon storage.

Remotely operated vehicle - An underwater platform equipped with sensors, cameras and/or manipulator arms remotely controlled from the surface via a cable.

Remote sensing - Collecting data at a distance from the mapped area.

Resilience - The capacity of systems to persist, adapt or transform when faced with disturbances whilst maintaining their essential functions.

Resistance - A system's ability to actively change while retaining its identity or to passively maintain system performance following one or more adverse events.

Satellite altimetry - A technique used to measure the height of the Ocean's surface from space, which varies depending on bathymetry therefore indirectly providing information about the seabed.

Sensitivity - The degree to which marine features respond to stressors, which are deviations of environmental conditions beyond the expected range.

Sessile - An organism that is fixed in one place i.e. immobile.

Side-scan sonar - A type of sonar that emits acoustic pulses across a wide angle perpendicular to the path of the sensor through the water. Stacking the responses along the track line creates an image of reflection strength. It is used to create images of large areas of the seabed and bathymetric features.

Status - A broad, composite assessment of various aspects of multiple habitats, used by marine managers to capture overall ecosystem health.

Substrate - Bottom type, also known as substrata/substratum.

Substrate map - A map depicting the sediment and rock type of the seabed with little or no information on the biological communities present.

Super-resolution - Enhanced resolution.

Systematic conservation planning - A multi-component, stage-wise approach to identifying conservation areas and devising management policies, with feedback, revision and reiteration, where needed, at any stage.

Three-dimensional marine habitat mapping - Mapping that includes multiple depth ranges of the distribution of biodiversity and includes species distributions by incorporating their life cycle, trophic interactions and exchanges between the water column and the seafloor.

Tipping points - The critical point at which a rapid and unexpected shift is triggered and an ecosystem transitions to a new state with altered composition and functioning.

Towfish - An underwater vehicle, usually carrying instrumentation such as a side-scan sonar, that is towed behind a surface vessel.

Trawl - A type of sampling device used to collect benthic samples. Trawls are dragged along the seabed by a vessel, scooping up sediment, rocks and benthic organisms.

Underway data - Opportunistic data collected during transits or non-mapping voyages.

Unmanned aerial vehicle - An aircraft without any human pilot, crew, or passengers on board, commonly referred to as a drone.

Virtual research environments - Immersive virtual reality displays of complex data streams.

Vulnerability - The probability that a feature will be exposed to a stressor to which it is sensitive.

Water column - The vertical column of water extending from the surface of the Ocean to the seabed.

References

Al-Hamdani, Z., & Reker, J. (2007). Towards marine landscapes in the Baltic Sea. *BALANCE interim report #10.* http://balance-eu.org/

Amon, D. J., Gollner, S., Morato, T., Smith, C. R., Chen, C., Christiansen, S., Currie, B., Drazen, J. C., Fukushima, T., Gianni, M., Gjerde, K. M., Gooday, A. J., Grillo, G. G., Haeckel, M., Joyini, T., Ju, S.-J., Levin, L. A., Metaxas, A., Mianowicz, K., … Pickens, C. (2022). Assessment of scientific gaps related to the effective environmental management of deep-seabed mining. *Marine Policy, 138*, 105006. https://doi.org/https://doi.org/10.1016/j.marpol.2022.105006

Andersen, J. H., Manca, E., Agnesi, S., Al-Hamdani, Z., Lillis, H., Mo, G., Populus, J., Reker, J., Tunesi, L., & Vasquez, M. (2018). European Broad-Scale Seabed Habitat Maps Support Implementation of Ecosystem-Based Management. *Open Journal of Ecology, 08*(02), 86–103. https://doi.org/10.4236/oje.2018.82007

Angeletti, L., Bargain, A., Campiani, E., Foglini, F., Grande, V., Leidi, E., Mercorella, A., Prampolini, M., & Taviani, M. (2019). 16 Cold-Water Coral Habitat Mapping in the Mediterranean Sea: Methodologies and Perspectives. In C. Orejas & C. Jiménez (Eds.), *Mediterranean Cold-Water Corals: Past, Present and Future: Understanding the Deep-Sea Realms of Coral* (pp. 173–189). Springer International Publishing. https://doi.org/10.1007/978-3-319-91608-8_16

Asjes, A., González-Irusta, J., & Wright, P. (2016). Age-related and seasonal changes in haddock Melanogrammus aeglefinus distribution: Implications for spatial management. *Marine Ecology Progress Series,* 553. https://doi.org/10.3354/meps11754

Bargain, A., Foglini, F., Pairaud, I., Bonaldo, D., Carniel, S., Angeletti, L., Taviani, M., Rochette, S., & Fabri, M. C. (2018). Predictive habitat modeling in two Mediterranean canyons including hydrodynamic variables. *Progress in Oceanography, 169,* 151–168. https://doi.org/10.1016/j.pocean.2018.02.015

Beca-Carretero, P., Teichberg, M., Winters, G., Procaccini, G., & Reuter, H. (2020). Projected Rapid Habitat Expansion of Tropical Seagrass Species in the Mediterranean Sea as Climate Change Progresses. *Frontiers in Plant Science, 11*. https://doi.org/10.3389/fpls.2020.555376

Bevilacqua, S., Guarnieri, G., Farella, G., Terlizzi, A., & Fraschetti, S. (2018). A regional assessment of cumulative impact mapping on Mediterranean coralligenous outcrops. *Scientific Reports, 8*(1), 1757. https://doi.org/10.1038/s41598-018-20297-1

Boero, F., De Leo, F., Fraschetti, S., & Ingrosso, G. (2019). Chapter Four - The Cells of Ecosystem Functioning: Towards a holistic vision of marine space. In C. Sheppard (Ed.), *Advances in Marine Biology* (Vol. 82, pp. 129–153). Academic Press. https://doi.org/10.1016/bs.amb.2019.03.001

Boero, F., Foglini, F., Fraschetti, S., Goriup, P. D., Macpherson, E., Planes, S., & Soukissian, T. H. (2016). CoCoNet: Towards coast to coast networks of marine protected areas (From the shore to the high and deep sea), coupled with sea-based wind energy potential. *SCIRES-IT: SCIentific RESearch and Information Technology, 6,* 1–95. https://api.semanticscholar.org/CorpusID:54783314

Brown, C. J., Beaudoin, J., Brissette, M., & Gazzola, V. (2019). Multispectral Multibeam Echo Sounder Backscatter as a Tool for Improved Seafloor Characterization. *Geosciences, 9*(3). https://doi.org/10.3390/geosciences9030126

Brown, C. J., Smith, S. J., Lawton, P., & Anderson, J. T. (2011). Benthic habitat mapping: A review of progress towards improved understanding of the spatial ecology of the seafloor using acoustic techniques. *Estuarine, Coastal and Shelf Science, 92*(3), 502–520. https://doi.org/10.1016/j.ecss.2011.02.007

Bulleri, F., Batten, S., Connell, S., Benedetti-Cecchi, L., Gibbons, M., Nugues, M., & Gribben, P. (2020). *Human pressures and the emergence of novel marine ecosystems* (pp. 441–493). https://doi.org/10.1201/9780429351495-9

Burgos, J. M., Buhl-Mortensen, L., Buhl-Mortensen, P., Ólafsdóttir, S. H., Steingrund, P., Ragnarsson, S. Á., & Skagseth, Ø. (2020). Predicting the Distribution of Indicator Taxa of Vulnerable Marine Ecosystems in the Arctic and Sub-arctic Waters of the Nordic Seas. *Frontiers in Marine Science, 7.* https://doi.org/10.3389/fmars.2020.00131

Casal, G., Sánchez-Carnero, N., Sánchez-Rodríguez, E., & Freire, J. (2011). Remote sensing with SPOT-4 for mapping kelp forests in turbid waters on the south European Atlantic shelf. *Estuarine, Coastal and Shelf Science, 91*(3), 371–378. https://doi.org/10.1016/j.ecss.2010.10.024

Castellan, G., Angeletti, L., Correggiari, A., Foglini, F., Grande, V., & Taviani, M. (2020). Visual Methods for Monitoring Mesophotic-to-Deep Reefs and Animal Forests: Finding a Compromise Between Analytical Effort and Result Quality. In S. Rossi & L. Bramanti (Eds.), *Perspectives on the Marine Animal Forests of the World* (pp. 487–514). Springer International Publishing. https://doi.org/10.1007/978-3-030-57054-5_15

CBD. (1992). *Convention on Biological Diversity*. https://www.cbd.int/convention/text/

CBD/COP/DEC/15/4. (2022). *Kunming-Montreal Global Biodiversity Framework*. https://www.cbd.int/doc/decisions/cop-15/cop-15-dec-04-en.pdf

COM/2007/574 final. (2007). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions - An Integrated Maritime Policy for the European Union (COM/2019/6 final)*. http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52007DC0575

COM/2019/640 final. (2019). *Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions: The European Green Deal*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2019%3A640%3AFIN

COM/2020/380 final. (2020). *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: EU Biodiversity Strategy for 2030 Bringing nature back into our lives*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52020DC0380

COM/2021/240 final. (2021). COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS on a new approach for a sustainable blue economy in the EU Transforming the EU's Blue Economy for a Sustainable Future. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021DC0240

COM/2022/304 final. (2022). Proposal for a Regulation of the European Parliament and of the Council on nature restoration. https://environment.ec.europa.eu/publications/nature-restoration-law_en

Cooper, K. M., & Barry, J. (2020). A new machine learning approach to seabed biotope classification. *Ocean & Coastal Management, 198,* 105361. https://doi.org/10.1016/j.ocecoaman.2020.105361

Council Directive 92/43/EEC. (1992). Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora. *Official Journal of the European Union, 11*, 0114. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A31992L0043

Danovaro, R., Bianchelli, S., Brambilla, P., Brussa, G., Corinaldesi, C., Del Borghi, A., Dell'Anno, A., Fraschetti, S., Greco, S., Grosso, M., Nepote, E., Rigamonti, L., & Boero, F. (2024). Making eco-sustainable floating offshore wind farms: Siting, mitigations, and compensations. *Renewable and Sustainable Energy Reviews, 197,* 114386. https://doi.org/10.1016/j.rser.2024.114386

de la Torriente, A., González-Irusta, J. M., Aguilar, R., Fernández-Salas, L. M., Punzón, A., & Serrano, A. (2019). Benthic habitat modelling and mapping as a conservation tool for marine protected areas: A seamount in the western Mediterranean. *Aquatic Conservation: Marine and Freshwater Ecosystems, 29*(5), 732–750. https://doi.org/https://doi.org/10.1002/aqc.3075

Directive 2000/60/EC. (2000). Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. *Official Journal of the European Union, 327,* 0001–0037. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32000L0060

Directive 2008/56/EC. (2008). Directive 2008/56/EC of the European Parliament and of the Council 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, L164/19*. http://data.europa.eu/eli/dir/2008/56/oj

Directive 2009/147/EC. (2009). Directive 2009/147/EC of the European Parliament and of the Council of 30 November 2009 on the conservation of wild birds (Codified version). *Official Journal of the European Union, 20*, 7. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32009L0147

Directive 2014/89/EU. (2014). Directive 2014/89/EU of the European Parliament and of the Council of 23 July 2014 establishing a framework for maritime spatial planning. *Official Journal of the European Union, 257,* 135. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32014L0089

Durden, J. M., Hosking, B., Bett, B. J., Cline, D., & Ruhl, H. A. (2021). Automated classification of fauna in seabed photographs: The impact of training and validation dataset size, with considerations for the class imbalance. *Progress in Oceanography, 196,* 102612. https://doi.org/10.1016/j.pocean.2021.102612

Effrosynidis, D., Arampatzis, A., & Sylaios, G. (2018). Seagrass detection in the mediterranean: A supervised learning approach. *Ecological Informatics, 48,* 158–170. https://doi.org/10.1016/j.ecoinf.2018.09.004

Elith, J., & Leathwick, J. R. (2009). Species Distribution Models: Ecological Explanation and Prediction Across Space and Time. *Annual Review of Ecology, Evolution, and Systematics, 40*(1), 677–697. https://doi.org/10.1146/annurev.ecolsys.110308.120159

Ernst, C. M., Chabot, N. L., Klima, R. L., Kubota, S., Rogers, G., Byrne, P. K., Hauck, S. A., Vander Kaaden, K. E., Vervack, R. J., Besse, S. & Blewett, D. T. (2022). Science goals and mission concept for a landed investigation of Mercury. *The Planetary Science Journal, 3*(3), 68. https://doi/10.3847/PSJ/ac1c0f

European Commission. (2017). *Commission Decision (EU) 2017/848 of 17 May 2017 laying down criteria and methodological standards on good environmental status of marine waters and specifications and standardised methods for monitoring and assessment, and repealing Decision 2010/477/EU*. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32017D0848&from=EN

European Marine Board. (2019). Navigating the Future V: Marine Science for a Sustainable Future. In J. J. Heymans, B. Alexander, A. Muniz Piniella, P. Kellett, J. Coopman, & K. Larkin (Eds.), *EMB Position Paper 24*. https://doi.org/10.5281/zenodo.2809392

Fabbrizzi, E., Giakoumi, S., De Leo, F., Tamburello, L., Chiarore, A., Colletti, A., Coppola, M., Munari, M., Musco, L., Rindi, F., Rizzo, L., Savinelli, B., Franzitta, G., Grech, D., Cebrian, E., Verdura, J., Bianchelli, S., Mangialajo, L., Nasto, I., … Fraschetti, S. (2023). The challenge of setting restoration targets for macroalgal forests under climate changes. *Journal of Environmental Management, 326*, 116834. https://doi.org/10.1016/j.jenvman.2022.116834

Fabbrizzi, E., Scardi, M., Ballesteros, E., Benedetti-Cecchi, L., Cebrian, E., Ceccherelli, G., De Leo, F., Deidun, A., Guarnieri, G., Falace, A., Fraissinet, S., Giommi, C., Mačič, V., Mangialajo, L., Mannino, A. M., Piazzi, L., Ramdani, M., Rilov, G., Rindi, L., … Fraschetti, S. (2020). Modeling Macroalgal Forest Distribution at Mediterranean Scale: Present Status, Drivers of Changes and Insights for Conservation and Management. *Frontiers in Marine Science, 7*. https://doi.org/10.3389/fmars.2020.00020

Farrag, M. M. S. (2022). Towards the identification of essential fish habitats for commercial deep-water species. In M. Otero & C. Mytilineou (Eds.), *Deep-sea Atlas of the Eastern Mediterranean Sea*. IUCN. https://www.semanticscholar.org/paper/Towards-the-identification-of-essential-fish-for/547c8c34b73fc5a20628ec57a96f6fcdf047f2dc

Ferrier, S., & Guisan, A. (2006). Spatial modelling of biodiversity at the community level. *Journal of Applied Ecology, 43,* 393–404. https://api.semanticscholar.org/CorpusID:85000606

Fraschetti, S., Pipitone, C., Mazaris, A. D., Rilov, G., Badalamenti, F., Bevilacqua, S., Claudet, J., Carič, H., Dahl, K., D'Anna, G., Daunys, D., Frost, M., Gissi, E., Göke, C., Goriup, P., Guarnieri, G., Holcer, D., Lazar, B., Mackelworth, P., … Katsanevakis, S. (2018). Light and Shade in Marine Conservation Across European and Contiguous Seas. *Frontiers in Marine Science, 5*. https://doi.org/10.3389/fmars.2018.00420

Galparsoro, I., Borja, A., & Uyarra, M. C. (2014). Mapping ecosystem services provided by benthic habitats in the European North Atlantic Ocean. *Frontiers in Marine Science, 1*. https://doi.org/10.3389/fmars.2014.00023

Galparsoro, I., Connor, D. W., Borja, Á., Aish, A., Amorim, P., Bajjouk, T., Chambers, C., Coggan, R., Dirberg, G., Ellwood, H., Evans, D., Goodin, K. L., Grehan, A., Haldin, J., Howell, K., Jenkins, C., Michez, N., Mo, G., Buhl-Mortensen, P., … Vasquez, M. (2012). Using EUNIS habitat classification for benthic mapping in European seas: Present concerns and future needs. *Marine Pollution Bulletin, 64*(12), 2630–2638. https://doi.org/10.1016/j.marpolbul.2012.10.010

Gerovasileiou, V., Smith, C. J., Sevastou, K., Papadopoulou, N., Dailianis, T., Bekkby, T., Fiorentino, D., McOwen, C. J., Amaro, T., Bengil, E. G. T., Bilan, M., Boström, C., Carreiro-Silva, M., Cebrian, E., Cerrano, C., Danovaro, R., Fraschetti, S., Gagnon, K., Gambi, C., … Scrimgeour, R. (2019). Habitat mapping in the European Seas - is it fit for purpose in the marine restoration agenda? *Marine Policy, 106,* 103521. https://doi.org/10.1016/j.marpol.2019.103521

Giakoumi, S., Sini, M., Gerovasileiou, V., Mazor, T., Beher, J., Possingham, H. P., Abdulla, A., Çınar, M. E., Dendrinos, P., Gucu, A. C., Karamanlidis, A. A., Rodič, P., Panayotidis, P., Tačkın, E., Jaklin, A., Voultsiadou, E., Webster, C., Zenetos, A., & Katsanevakis, S. (2013). Ecoregion-Based Conservation Planning in the Mediterranean: Dealing with Large-Scale Heterogeneity. *PLoS ONE, 8*. https://api.semanticscholar.org/CorpusID:10861874

Greathead, C., González-Irusta, J., Boulcott, P., Blackadder, L., Weetman, A., & Wright, P. (2014). Environmental requirements for three sea pen species: Relevance to distribution and conservation. *ICES Journal of Marine Science, 72*. https://doi.org/10.1093/icesjms/fsu129

Guidi, L., Guerra, A. F., Bakker, D. C. E., Canchaya, C., Curry, E., Foglini, F., Irisson, J.-O., Malde, K., Marshall, C. T., Obst, M., Ribeiro, R. P., & Tjiputra, J. (2020). Big Data in Marine Science. In J. J. Heymans, B. Alexander, A. Muniz Piniella, P. Kellett, & J. Coopman (Eds.), *EMB Future Science Brief 6*. https://doi.org/10.5281/zenodo.3755793

Halpern, B. S., Walbridge, S., Selkoe, K. A., Kappel, C. V, Micheli, F., D'Agrosa, C., Bruno, J. F., Casey, K. S., Ebert, C., Fox, H. E., Fujita, R., Heinemann, D., Lenihan, H. S., Madin, E. M. P., Perry, M. T., Selig, E. R., Spalding, M., Steneck, R., & Watson, R. (2008). A Global Map of Human Impact on Marine Ecosystems. *Science, 319*(5865), 948–952. https://doi.org/10.1126/science.1149345

HELCOM. (2021). *Essential fish habitats in the Baltic Sea - Identification of potential spawning, recruitment and nursery areas*. https://helcom.fi/wp-content/uploads/2021/09/Essential-fish-habitats-in-the-Baltic-Sea.pdf

Hering, D., Schürings, C., Wenskus, F., Blackstock, K., Borja, A., Birk, S., Bullock, C., Carvalho, L., Dagher-Kharrat, M. B., Lakner, S., Lovrič, N., McGuinness, S., Nabuurs, G.-J., Sánchez-Arcilla, A., Settele, J., & Pe'er, G. (2023). Securing success for the Nature Restoration Law. *Science, 382*(6676), 1248–1250. https://doi.org/10.1126/science.adk1658

Hill, N. A., Foster, S. D., Duhamel, G., Welsford, D., Koubbi, P., & Johnson, C. R. (2017). Model-based mapping of assemblages for ecology and conservation management: A case study of demersal fish on the Kerguelen Plateau. *Diversity and Distributions, 23*(10), 1216–1230. https://doi.org/10.1111/ddi.12613

Howell, K., Holt, R., Endrino, P., & Stewart, H. (2011). When the species is also a habitat: Comparing the predictively modelled distributions of Lophelia pertusa and the reef habitat it forms. *Biological Conservation, 144*. https://doi.org/10.1016/j.biocon.2011.07.025

ICES. (2005). *Report of the Working Group on Habitat Mapping (WGMHM), 5–8 April, Bremerhaven, Germany*. https://www.ices.dk/sites/pub/CM%20Doccuments/2005/E/WGMHM05.pdf

ICES. (2021). *Workshop on the Use of Predictive Habitat Models in ICES Advice (WKPHM)*. https://doi.org/10.17895/ices.pub.8213

Illa-López, L., Cabrito, A., de Juan, S., Maynou, F., & Demestre, M. (2023). Distribution of rhodolith beds and their functional biodiversity characterisation using ROV images in the western Mediterranean Sea. *Science of The Total Environment, 905,* 167270. https://doi.org/10.1016/j.scitotenv.2023.167270

Ingrosso, G., Abbiati, M., Badalamenti, F., Bavestrello, G., Belmonte, G., Cannas, R., Benedetti-Cecchi, L., Bertolino, M., Bevilacqua, S., Bianchi, C. N., Bo, M., Boscari, E., Cardone, F., Cattaneo-Vietti, R., Cau, A., Cerrano, C., Chemello, R., Chimienti, G., Congiu, L., … Boero, F. (2018). Chapter Three - Mediterranean Bioconstructions Along the Italian Coast. In C. Sheppard (Ed.), *Advances in Marine Biology* (Vol. 79, pp. 61–136). Academic Press. https://doi.org/10.1016/bs.amb.2018.05.001

Korpinen, S., Laamanen, L., Bergström, L., Nurmi, M., Andersen, J. H., Haapaniemi, J., Harvey, E. T., Murray, C. J., Peterlin, M., Kallenbach, E., Klančnik, K., Stein, U., Tunesi, L., Vaughan, D., & Reker, J. (2021). Combined effects of human pressures on Europe's marine ecosystems. *Ambio, 50*(7), 1325–1336. https://doi.org/10.1007/s13280-020-01482-x

Kukkala, A. S., & Moilanen, A. (2013). Core concepts of spatial prioritisation in systematic conservation planning. B*iological Reviews, 88*(2), 443–464. https://doi.org/10.1111/brv.12008

Levin, N., Kark, S., & Danovaro, R. (2018). Adding the Third Dimension to Marine Conservation. *Conservation Letters, 11*(3), e12408. https://doi.org/10.1111/conl.12408

Lurton, X. (2010). *An introduction to Underwater Acoustics: Principles and Applications. 2nd edition.* Springer Praxis Books & Praxis Publishing.

Lurton, X., Lamarche, G., Brown, C. J., Lucieer, V., Rice, G., Schimel, A. C. G., & Weber, T. C. (2015). *Backscatter measurements by seafloor- mapping sonars: guidelines and recommendations.* https://api.semanticscholar.org/CorpusID:129508402

Maes, J., Teller, A., Erhard, M., Condé, S., Vallecillo, S., Barredo, J. I., Paracchini, M. L., Abdul Malak, D., Trombetti, M., Vigiak, O., Zulian, G., Addamo, A. M., Grizzetti, B., Somma, F., Hagyo, A., Vogt, P., Polce, C., Jones, A., Marin, A. I., ... Santos--Martín, F. (2020). *Mapping and Assessment of Ecosystems and their Services: An EU ecosystem assessment, EUR 30161 EN.* https://doi.org/10.2760/757183

Malde, K., Handegard, N. O., Eikvil, L., & Salberg, A.-B. (2020). Machine intelligence and the data-driven future of marine science. *ICES Journal of Marine Science, 77*(4), 1274–1285. https://doi.org/10.1093/icesjms/fsz057

Marlow, J., Halpin, J. E., & Wilding, T. A. (2024). 3D photogrammetry and deep-learning deliver accurate estimates of epibenthic biomass. *Methods in Ecology and Evolution, n/a*(n/a). https://doi.org/10.1111/2041-210X.14313

Martin, C., Giannoulaki, M., De Leo, F., Scardi, M., Salomidi, M., Knittweis, L., Pace, M. L., Garofalo, G., Gristina, M., Ballesteros, E., Bavestrello, G., Belluscio, A., Cebrian, E., Gerakaris, V., Pergent, G., Pergent-Martini, C., Schembri, P. J., Terribile, K., Rizzo, L., ... Fraschetti, S. (2014). Coralligenous and maërl habitats: predictive modelling to identify their spatial distributions across the Mediterranean Sea. *Scientific Reports, 4*, 5073. https://doi.org/10.1038/srep05073

Matear, L., Vina-Herbon, C., Woodcock, K. A., Duncombe-Smith, S. W., Smith, A. P., Schmitt, P., Kreutle, A., Marra, S., Curtis, E. J., & Baigent, H. N. (2023). *Extent of Physical Disturbance to Benthic Habitats: Fisheries. In: OSPAR, 2023: The 2023 Quality Status Report for the Northeast Atlantic.* https://oap.ospar.org/en/ospar-assessments/quality-status-reports/qsr-2023/indicator-assessments/phys-dist-habs-fisheries/

Mayer, L., Jakobsson, M., Allen, G., Dorschel, B., Falconer, R., Ferrini, V., Lamarche, G., Snaith, H., & Weatherall, P. (2018). The Nippon Foundation—GEBCO Seabed 2030 Project: The Quest to See the World's Oceans Completely Mapped by 2030. *Geosciences, 8*(2). https://doi.org/10.3390/geosciences8020063

Mazaris, A. D., Kallimanis, A., Gissi, E., Pipitone, C., Danovaro, R., Claudet, J., Rilov, G., Badalamenti, F., Stelzenmüller, V., Thiault, L., Benedetti-Cecchi, L., Goriup, P., Katsanevakis, S., & Fraschetti, S. (2019). Threats to marine biodiversity in European protected areas. *Science of The Total Environment, 677,* 418–426. https://doi.org/10.1016/j.scitotenv.2019.04.333

Melo-Merino, S. M., Reyes-Bonilla, H., & Lira-Noriega, A. (2020). Ecological niche models and species distribution models in marine environments: A literature review and spatial analysis of evidence. *Ecological Modelling, 415,* 108837. https://doi.org/10.1016/j.ecolmodel.2019.108837

Miesner, A. K., & Payne, M. R. (2018). Oceanographic variability shapes the spawning distribution of blue whiting (Micromesistius poutassou). *Fisheries Oceanography, 27*(6), 623–638. https://doi.org/10.1111/fog.12382

Mitchell, P. J., Downie, A.-L., & Diesing, M. (2018). How good is my map? A tool for semi-automated thematic mapping and spatially explicit confidence assessment. *Environmental Modelling & Software, 108*, 111–122. https://doi.org/10.1016/j.envsoft.2018.07.014

Montefalcone, M., Tunesi, L., & Ouerghi, A. (2021). A review of the classification systems for marine benthic habitats and the new updated Barcelona Convention classification for the Mediterranean. *Marine Environmental Research, 169,* 105387. https://doi.org/10.1016/j.marenvres.2021.105387

Montes-Herrera, J. C., Cimoli, E., Cummings, V., Hill, N., Lucieer, A., & Lucieer, V. (2021). Underwater Hyperspectral Imaging (UHI): A Review of Systems and Applications for Proximal Seafloor Ecosystem Studies. *Remote Sensing, 13*(17). https://doi.org/10.3390/rs13173451

Mora, C., Tittensor, D., Adl, S., Simpson, A., & Worm, B. (2011). How Many Species Are There on Earth and in the Ocean? *PLoS Biology, 9*, e1001127. https://doi.org/10.1371/journal.pbio.1001127

Moritz, C., Lévesque, M., Gravel, D., Vaz, S., Archambault, D., & Archambault, P. (2013). Modelling spatial distribution of epibenthic communities in the Gulf of St. Lawrence (Canada). *Journal of Sea Research, 78*, 75–84. https://doi.org/10.1016/j.seares.2012.10.009

Morris, K., Epstein, G., Kaiser, M. J., Porter, J., & Johnson, A. F. (2023). Adapting the marine stewardship council's risk-based framework to assess the impact of towed bottom fishing gear on blue carbon habitats. *PLOS ONE, 18*(11), e0288484-. https://doi.org/10.1371/journal.pone.0288484

Murillo, F. J., Weigel, B., Bouchard Marmen, M., & Kenchington, E. (2020). Marine epibenthic functional diversity on Flemish Cap (north-west Atlantic)—Identifying trait responses to the environment and mapping ecosystem functions. *Diversity and Distributions, 26*(4), 460–478. https://doi.org/10.1111/ddi.13026

Panayotidis, P., Papathanasiou, V., Gerakaris, V., Fakiris, E., Orfanidis, S., Papatheodorou, G., Kosmidou, M., Georgiou, N., Drakopoulou, P., & Loukaidi, V. (2022). Seagrass Meadows in The Greek Seas. In SEANOE (Ed.), *SEANOE*. https://doi.org/10.17882/87740

Piechaud, N., & Howell, K. L. (2022). Fast and accurate mapping of fine scale abundance of a VME in the deep sea with computer vision. *Ecological Informatics, 71*, 101786. https://doi.org/10.1016/j.ecoinf.2022.101786

Pouvreau, S., Cochet, H., Bargat, F., Petton, S., Le Roy, V., Guillet, T., & Potet, M. (2021). Current distribution of the residual flat oysters beds (Ostrea edulis) along the west coast of France. In *SEANOE*. https://doi.org/10.17882/79821

Prampolini, M., Angeletti, L., Castellan, G., Grande, V., Le Bas, T., Taviani, M., & Foglini, F. (2021). Benthic Habitat Map of the Southern Adriatic Sea (Mediterranean Sea) from Object-Based Image Analysis of Multi-Source Acoustic Backscatter Data. *Remote Sensing, 13*(15). https://doi.org/10.3390/rs13152913

Prampolini, M., Savini, A., Foglini, F., & Soldati, M. (2020). Seven Good Reasons for Integrating Terrestrial and Marine Spatial Datasets in Changing Environments. *Water, 12*(8). https://doi.org/10.3390/w12082221

PricewaterhouseCoopers. (2008). *INFOMAR Marine Mapping Study. Options Appraisal Report: Final Report 30 June 2008*. Marine Institute. http://hdl.handle.net/10793/1652

Pulido Mantas, T., Roveta, C., Calcinai, B., di Camillo, C. G., Gambardella, C., Gregorin, C., Coppari, M., Marrocco, T., Puce, S., Riccardi, A., & Cerrano, C. (2023). Photogrammetry, from the Land to the Sea and Beyond: A Unifying Approach to Study Terrestrial and Marine Environments. *Journal of Marine Science and Engineering, 11*(4). https://doi.org/10.3390/jmse11040759

Ramiro-Sánchez, B., González-Irusta, J. M., Henry, L.-A., Cleland, J., Yeo, I., Xavier, J. R., Carreiro-Silva, M., Sampaio, Í., Spearman, J., Victorero, L., Messing, C. G., Kazanidis, G., Roberts, J. M., & Murton, B. (2019). Characterization and Mapping of a Deep-Sea Sponge Ground on the Tropic Seamount (Northeast Tropical Atlantic): Implications for Spatial Management in the High Seas. *Frontiers in Marine Science, 6*. https://doi.org/10.3389/fmars.2019.00278

Regulation 691/2011. (2011). European environmental economics accounts. Official Journal of the European Union, L 192/1. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex%3A32011R0691

Regulation EU 1380/2013. (2013). Regulation (EU) No 1380/2013 of the European Parliament and of the Council of 11 December 2013 on the Common Fisheries Policy (2013). *Official Journal of the European Union, 354*, 22. http://data.europa.eu/eli/reg/2013/1380/oj

Rindi, L., Mintrone, C., Ravaglioli, C., & Benedetti-Cecchi, L. (2024). Spatial signatures of an approaching regime shift in Posidonia oceanica meadows. *Marine Environmental Research, 198*, 106499. https://doi.org/10.1016/j.marenvres.2024.106499

Robinson, C. L. K., & Levings, C. D. (1995). *An overview of habitat classification systems, ecological models, and geographic information systems applied to shallow foreshore marine habitats. Canadian Manuscript Report of Fisheries and Aquatic Sciences 2322.* https://publications.gc.ca/site/fra/464405/publication.html

Rodríguez-Basalo, A., Ríos, P., Arrese, B., Abad Uribarren, A., Cristobo, J., Patrocinio Ibarrola, T., Ballesteros, M., Prado, E., & Sánchez, F. (2022). Mapping the habitats of a complex circalittoral rocky shelf in the Cantabrian Sea (south Bay of Biscay). Estuarine, *Coastal and Shelf Science, 273,* 107912. https://doi.org/10.1016/j.ecss.2022.107912

Salman, A., Jalal, A., Shafait, F., Mian, A., Shortis, M., Seager, J., & Harvey, E. (2016). Fish species classification in unconstrained underwater environments based on deep learning. *Limnology and Oceanography: Methods, 14*(9), 570–585. https://doi.org/10.1002/lom3.10113

Saunders, R. S., Spear, A. J., Allin, P. C., Austin, R. S., Berman, A. L., Chandlee, R. C., Clark, J., Decharon, A. V., De Jong, E. M., Griffith, D. G. & Gunn, J. M. (1992). Magellan mission summary. *Journal of Geophysical Research: Planets, 97*(E8), 13067-13090. https://doi.org/10.1029/92JE01397

Sidiropoulos, P. & Muller, J. P. (2015). On the status of orbital high-resolution repeat imaging of Mars for the observation of dynamic surface processes. *Planetary and Space Science, 117,* 207-222. https://doi.org/10.1016/j.pss.2015.06.017

Stevens, T., & Connolly, R. M. (2004). Testing the utility of abiotic surrogates for marine habitat mapping at scales relevant to management. *Biological Conservation, 119*(3), 351–362. https://doi.org/10.1016/J.BIOCON.2003.12.001

Strong, J. A. (2020). An error analysis of marine habitat mapping methods and prioritised work packages required to reduce errors and improve consistency. *Estuarine, Coastal and Shelf Science, 240,* 106684. https://doi.org/10.1016/j.ecss.2020.106684

Strong, J. A., Clements, A., Lillis, H., Galparsoro, I., Bildstein, T., & Pesch, R. (2019). A review of the influence of marine habitat classification schemes on mapping studies: inherent assumptions, influence on end products, and suggestions for future developments. *ICES Journal of Marine Science, 76*(1), 10–22. https://doi.org/10.1093/icesjms/fsy161

Taviani, M. (2014). Marine Chemosynthesis in the Mediterranean Sea. In Z. Goffredo Stefano and Dubinsky (Ed.), *The Mediterranean Sea: Its history and present challenges* (pp. 69–83). Springer Netherlands. https://doi.org/10.1007/978-94-007-6704-1_5

Teague, J., Willans, J., Allen, M., Scott, T., & Day, J. (2019). *Hyperspectral imaging as a tool for assessing coral health utilising natural fluorescence. 8*. https://doi.org/10.1255/jsi.2019.a7

Thomsen, P. F., & Willerslev, E. (2015). Environmental DNA – An emerging tool in conservation for monitoring past and present biodiversity. *Biological Conservation, 183,* 4–18. https://doi.org/10.1016/j.biocon.2014.11.019

Tozer, B., Sandwell, D.T., Smith, W.H., Olson, C., Beale, J.R. & Wessel, P., (2019). Global bathymetry and topography at 15 arc sec: SRTM15+. *Earth and Space Science, 6*(10), 1847-1864. https://doi.org/10.1029/2019EA000658

Traganos, D., Lee, C. B., Blume, A., Poursanidis, D., čižmek, H., Deter, J., Mačič, V., Montefalcone, M., Pergent, G., Pergent-Martini, C., Ricart, A. M., & Reinartz, P. (2022). Spatially Explicit Seagrass Extent Mapping Across the Entire Mediterranean. *Frontiers in Marine Science, 9.* https://doi.org/10.3389/fmars.2022.871799

Turicchia, E., Ponti, M., Rossi, G., & Cerrano, C. (2021a). The Reef Check Med Dataset on Key Mediterranean Marine Species 2001–2020. *Frontiers in Marine Science, 8*. https://doi.org/10.3389/fmars.2021.675574

Turicchia, E., Ponti, M., Rossi, G., Milanese, M., Di Camillo, C. G., & Cerrano, C. (2021b). The Reef Check Mediterranean Underwater Coastal Environment Monitoring Protocol. *Frontiers in Marine Science, 8*. https://doi.org/10.3389/fmars.2021.620368

Tyler-Walters, H., Tillin, H. M., d'Avack, E. A. S., Perry, F., & Stamp, T. (2023). *Marine Evidencebased Sensitivity Assessment (MarESA) – Guidance Manual. Marine Life Information Network (MarLIN).* https://www.marlin.ac.uk/publications

United Nations. (2015). Transforming Our World: The 2030 Agenda for Sustainable Development. In *A/RES/70/1*. https://doi.org/10.1007/s13398-014-0173-7.2

Vasquez, M., Ségeat, B., Condingley, A., Tilby, E., Wikstrom, S., Ehrnsten, E., Al Hamdani, Z., Agnesi, S., Andresen, M. S., Annunziatellis, A., Askew, N., Bekkby, T., Bentes, L., Daniels, E., Doncheva, V., Drakopoulou, V., Ernsten Verner, B., Goncalves, J., Karavinen, V., ... Woods, H. (2023). *EUSeaMap 2023, A European broad-scale seabed habitat map, Technical Report*. https://archimer.ifremer.fr/doc/00859/97116/

Verdura, J., Rehues, L., Mangialajo, L., Fraschetti, S., Belattmania, Z., Bianchelli, S., Blanfuné, A., Sabour, B., Chiarore, A., Danovaro, R., Fabbrizzi, E., Giakoumi, S., Iveša, L., Katsanevakis, S., Kytinou, E., Nasto, I., Nikolaou, A., Orfanidis, S., Rilov, G., ... Cebrian, E. (2023). Distribution, health and threats to Mediterranean macroalgal forests: defining the baselines for their conservation and restoration. *Frontiers in Marine Science, 10*. https://doi.org/10.3389/fmars.2023.1258842

Wilkinson, M. D., Dumontier, M., Aalbersberg, Ij. J., Appleton, G., Axton, M., Baak, A., Blomberg, N., Boiten, J.-W., da Silva Santos, L. B., Bourne, P. E., Bouwman, J., Brookes, A. J., Clark, T., Crosas, M., Dillo, I., Dumon, O., Edmunds, S., Evelo, C. T., Finkers, R., ... Mons, B. (2016). The FAIR Guiding Principles for scientific data management and stewardship. *Nature Scientific Data, 3*. https://www.nature.com/articles/sdata201618

Wright, D., & Heyman, W. (2008). Introduction to the Special Issue: Marine and Coastal GIS for Geomorphology, Habitat Mapping, and Marine Reserves. *Marine Geodesy, 31*, 223–230. https://doi.org/10.1080/01490410802466306

Zapata-Ramírez, P. A., Huete-Stauffer, C., Scaradozzi, D., Marconi, M., & Cerrano, C. (2016). Testing methods to support management decisions in coralligenous and cave environments. A case study at Portofino MPA. *Marine Environmental Research, 118,* 45–56. https://doi.org/10.1016/j.marenvres.2016.04.010

Zhang, Y., Bellingham, J. G., Ryan, J. P., Kieft, B., & Stanway, M. J. (2015). Autonomous Four-Dimensional Mapping and Tracking of a Coastal Upwelling Front by an Autonomous Underwater Vehicle. *Journal of Field Robotics, 33*(1), 67–81. https://doi.org/https://doi.org/10.1002/rob.21617

Zhao, Q., Stephenson, F., Lundquist, C., Kaschner, K., Jayathilake, D., & Costello, M. J. (2020). Where Marine Protected Areas would best represent 30% of ocean biodiversity. *Biological Conservation, 244,* 108536. https://doi.org/10.1016/j.biocon.2020.108536

Annex 1

Members of the European Marine Board Working Group on Marine Habitat Mapping

NAME	INSTITUTION	COUNTRY
Working Group Chairs		
Simonetta Fraschetti	University of Naples Federico II Stazione Zoologica Anton Dohrn (SZN) National Biodiversity Future Centre	Italy
James Strong	National Oceanography Centre (NOC)	United Kingdom
Working Group Members		
Lene Buhl-Mortensen	Institute of Marine Research (IMR)	Norway
Federica Foglini	Institute of Marine Science (CNR-ISMAR)	Italy
Jorge M.S. Gonçalves*	Centre of Marine Sciences of the Algarve (CCMAR)	Portugal
José Manuel González-Irusta	Spanish Institute of Oceanography (IEO-CSIC)	Spain
Helen Lillis*	Joint Nature Conservation Committee (JNCC)	United Kingdom
Mats Lindegarth	University of Gothenburg	Sweden
Georg Martin	Estonian Marine Institute, University of Tartu	Estonia
Lenaick Menot	The French Research Institute for Exploitation of the Sea (Ifremer)	France
Eimear O'Keeffe*	Marine Institute (MI)	Ireland
António Pascoal	Instituto Superior Técnico (IST), University of Lisbon	Portugal
Maria Salomidi	Hellenic Centre for Marine Research (HCMR)	Greece
Timm Schoening	GEOMAR Helmholtz Centre for Ocean Research Kiel	Germany

*Member of EMODnet Seabed Habitats Consortium

Annex 2

Data driven approaches to the use of distribution models in marine habitat mapping

TYPE OF OBSERVATION	DESCRIPTION	ADVANTAGES	DISADVANTAGES	OUTPUT AND EXAMPLES
Presence only data	Models use presence records and pseudo-absences randomly generated to replace the lack of directly available absences. Predict the suitability of the area for the target species or habitat by measuring how similar the area is to the area with the presence records.	Can be used with data from public repositories (e.g. OBIS). Some algorithms are user friendly (i.e. have specific software provided).	Do not offer information on prevalence or density. Limited proxy to biogenic habitat distribution. Sensitive to sampling bias.	Frequently used as a proxy of the distribution of biogenic habitats such as *Desmophyllum pertusum* coral reefs (Howell *et al.*, 2011) or sea pen fields (Greathead *et al.*, 2014).
Presence and absence data	Correlative models use both presences and absences obtained from sampling data. Predict the probability of finding the species or community in space.	Provide information on prevalence and is less sensitive to sampling bias.	No information on density. Limited proxy to biogenic habitats distribution. Sometimes real absences are not available (e.g. public repositories).	Used as a proxy to the distribution of biogenic habitats e.g. deep-sea sponge grounds, (Ramiro-Sánchez *et al.*, 2019).
Abundance of the target species, measured as density or biomass	Abundance models measured as biomass or number of individuals.	Used to model essential fish habitats with information on aggregations. Good proxy to biogenic habitats formed by only one species.	Data demanding and more complex than presence/absence models.	Usually applied to identify essential fish habitats such as spawning grounds (Miesner & Payne, 2018) or nursery areas (Asjes *et al.*, 2016). Recently used to model the distribution of biogenic habitats (Rodríguez-Basalo *et al.*, 2022).
Community data, ranging from only presence records of several taxa to abundance matrices of several species	**Predict first - assemblage later:** First the distribution of indicator species (habitat forming species) is predicted using Community models and presence-only or presence-absence models. Then the assemblages are computed using the prediction maps of these models. The analysis provided the predicted distribution of stacked species.	Can be applied using only presence-data (thus using data from public repositories).	The outputs can generate assemblages that do not occur. Accuracy is not computed for the whole process only for each step separately (prediction and assemblages).	Burgos *et al.*, (2020) used MAXENT and only presence data to model the distribution of 44 vulnerable marine ecosystem indicator species. In a second step they analysed the co-occurrence of these species using a cluster analysis of the predicted maps.

TYPE OF OBSERVATION	DESCRIPTION	ADVANTAGES	DISADVANTAGES	OUTPUT AND EXAMPLES
Community data, ranging from only presence records of several taxa to abundance matrices of several species	**Assemblage first - Predict later:** First, the assemblages are defined by using multivariate techniques (e.g. cluster analysis) to analyse the biological samples. Then, the assemblage distribution is modelled using a presence/absence approach. The analysis provides the distribution of biological communities (assemblages) previously defined using multivariate techniques.	Good proxy to biogenic habitats. Allows modification of assemblage definition to better cover specific biogenic habitats.	Accuracy cannot be computed for the whole process only for each step separately (prediction and assemblages). The sum of the probability of all assemblages does not necessarily equal 1.	Used to model the distribution of epibenthic communities in the Gulf of St Lawrence, Canada (Moritz *et al.*, 2013). Deep-sea biogenic habitats in the Galicia and Seco de los Olivos Banks, Spain (de la Torriente *et al.*, 2019)
	Assemblage and predict together: Describes assemblages and predicts their distribution within the same model framework. The output type differs slightly depending on the type of model used: Joint species distribution models include co-occurrence matrices as latent variables to model community data. Region common profiles delineate geographic areas where the probabilities of observing a group of species remains approximately constant.	Powerful models which overcome most of the limitations of previous approaches.	Very data demanding and technically very complex.	Relatively new in marine ecosystems, but have been used extensively in terrestrial ecosystems (Ferrier & Guisan, 2006). Joint species distribution models used in the marine ecosystems (Murillo *et al.*, 2020). Region common profile models (Hill *et al.*, 2017).

European Marine Board

Advancing Seas & Ocean Science

European Marine Board IVZW
Belgian Enterprise Number: 0650.608.890

Jacobsenstraat 1 I 8400 Ostend I Belgium
Tel: +32 (0)59 56 98 00
E-mail: info@marineboard.eu
www.marineboard.eu