

WP 3	Deliverable No. 3.2
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MARBEFES Project

<p>Title: Handbook on Assessing Human Multi-impacts on Seascape Ecosystems Delivery date: M40</p>
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<p>Submission date December 31st, 2025</p>



MARBEFES Project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no 101060937 and UKRI under Grant Agreements 10040216, 10048815 and 10041354'



Document Version Control			
Version	Date	Comment	Modified by
1.0	26.11.2025	First draft	All authors
2.0	17.12.2025	Second and final draft pre-EC submission	Garcia, Bremner and Nordström



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Summary

European Member States, like other countries, need to understand and sustain biodiversity and ecosystem functions to ensure continued supply of ecosystem services on which human well-being relies. Effective environmental management depends on valuing coastal and marine biodiversity and their benefits through ecological and societal measures. MARBEFES aims to improve understanding of biodiversity and develop methods for ecological, economic and cultural valuation. Specifically, MARBEFES WP3 provides the structure for the project work on biodiversity and ecosystem tools. It develops and appraises a suite of tools for assessing ecosystems - physical conditions, biogeochemical cycles, habitats, biodiversity, ecosystem function and ecosystem services - from primary producers to higher trophic levels. It aims to:

- Develop analytical and conceptual tools to better understand rules on biodiversity and ecosystem functioning across seascapes and the physico-chemical factors that shape them, in order to clarify patterns and processes across taxa and environments and through time, spanning surface, water column and seafloor
- Develop tools to enable prediction of the impacts of multiple human activities, future scenarios and management options on ecosystem biodiversity, structure, function and production of ecosystem services
- Develop new methods and a toolbox to better inventory and monitor seascape biodiversity, ecological functioning and ecosystem services

WP3 developed and tested 16 different tools or knowledge generation initiatives, of which the majority are operational tools for practitioners to use in the context of their specific environment-related problems (biodiversity links to ecosystem services and options to manage them).

The Handbook on Assessing Multi-impacts on Seascape Ecosystems presents the suite of tools developed in MARBEFES for integrated assessment of the impacts of multiple human pressures, both contemporary and future, on biodiversity, function and ecosystem services. The handbook is designed to ensure clarity and usability and is organised for easy navigation by tool category or remit. Each tool section gives a concise overview accessible to non-specialists. As a technical handbook for assessing human impact on ecosystems, it delivers expert-reviewed, reliable information. Each tool is covered in a few pages, offering consistency, practical examples, and standardised content throughout.

The handbook is structured around 4 themes human-impact related: spatial planning, single and multi-impact and current or future scenario. Out of the 16 different tools and knowledge-generation initiatives developed by WP3, 6 were specifically developed with the aim to describe human multi-impact on biodiversity, function and ecosystem services. The tool section of this report presents the 6 tools, which address all or a subset of these themes (see the main introduction of this report and the Handbook on Seascape Biodiversity, Function and Ecosystem Services for details regarding the



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other tools). The tools were further categorised and colour coded by approach (molecular, trait-based, network or decision-support), as well as star-coded by the anticipated level of practitioner usability (from direct to indirect). In the tool section, each tool is presented succinctly, and a worked example is provided to illustrate the type of outputs expected. The final section provides an overview of how to use the tools in an integrated manner to complement their strengths.



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1 Project Background

MARBEFES: European Member States, as with countries worldwide, have a fundamental need to understand how biodiversity and ecosystem functioning must be maintained to ensure the delivery of ecosystem services and societal goods and benefits, which must in turn be sustainably utilised by humankind. Critically, this calls for valuation of coastal and marine biodiversity and the ecosystem services they provide, as a basis for cost-effective environmental management. Above all, this requires ecological, economic, and cultural valuation to fully capture the diversity of ways in which biodiversity contributes to the healthy functioning of ecosystems and the supply of ecosystem services. MARBEFES set itself the objectives to ensure an increase in understanding of biodiversity, and the delivery of methods for ecological, cultural and economic valuation. As such, it dedicates several work packages (WPs) to deliver fully developed methods and tools, and in parallel test and validate them in diverse environmental settings across Europe (from the Arctic to semi-tropical areas) through a series of case study areas stretching from the coast to the open sea, termed Broad Belt Transects (BBTs). In this way, MARBEFES aims at showing the way to describe, assess, and value different nature components (habitats, species, ecosystems), to explore different alternative scenarios for policymakers.

Workpackage 3 (WP3): In this project context, MARBEFES WP3 provides the structure for the project work on biodiversity and ecosystem tools. It develops and appraises a suite of tools for assessing ecosystems - physical conditions, biogeochemical cycles, habitats, biodiversity, ecosystem function and ecosystem services - from primary producers to higher trophic levels. In practice, WP3 is built upon four main tasks:

- **Geo-physical drivers of biodiversity across seascapes** focusing on developing and validating regional models of ecosystem dynamics and biodiversity drivers, linking riverine, estuarine and coastal processes to shelf sea environments;
- **Tools for exploring ecological phenomena** developing tools to explore ecological connectivity and the links between biodiversity and function across seascapes;
- **Impacts of multi-pressures on ecological systems** developing tools for integrated impact assessment, considering the biodiversity, ecological processes and function and how these translate to ecosystem services;
- **Innovation in biodiversity inventory and monitoring** focusing on improved inventory and monitoring of marine and coastal biodiversity, the use of the latest remote monitoring methods and developing new tools for characterising biodiversity, collecting functional data and detecting the ecological effects of environmental change.

Collectively, these four tasks from WP3 aim at:

- Developing analytical and conceptual tools to better understand processes underlying biodiversity patterns and ecosystem functioning across seascapes and the physical-chemical factors that shape them



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- Developing tools to enable prediction of the impacts of multiple human activities, future scenarios and management options on ecosystem biodiversity, structure, function and supply of ecosystem services
- Developing new methods and toolboxes to better inventory and monitor seascape biodiversity, ecological functioning and ecosystem services

Biodiversity an ecosystem tools: MARBEFES WP3 presided over the development and testing of sixteen (16) different tools or knowledge generation initiatives, the majority of which are presented as operational tools for practitioners to use in the context of their specific environment-related problems (biodiversity links to ecosystems services and options to manage them) within WP3 deliverable reports (see below). In parallel, WP3 initiatives also aimed at advancing the capabilities of its tools by increasing the quality and the diversity of available evidence that the tools build on. In the activity called “*The viability of indicators of functional change*”, it sought to comprehensively describe the state-of-the-art of established, empirically measured links between functional identity (functional trait expression) and ecosystem functioning (flow of energy and matter). In the activity called “*Exploring the potential of citizen science to support BBTs*”, with respect to identifying under-used, potentially difficult, sources of evidence, WP3 also endeavoured to explore pathways for the uptake of citizen science programmes that monitor biodiversity by reviewing existing projects and developing approaches to integrate the information generated by the projects to support decision making . Another pathway for new sources of evidence was explored by WP3 through non-traditional methods to generate trait data by developing a framework for collecting so-called informal trait information from *e.g.* researchers or student lab or field projects that are only recorded in difficult-to-access grey literature in multiple languages (activity “*New tools for the inventory of ecological function*”). These initiatives are not included in here as they are knowledge-generation activities and not suited for a Handbook on Assessing Multi-impacts on Seascapes ecosystems, and are, as such, reported as part of other outputs within MARBEFES.

D3.2 Deliverable: Handbook on Assessing Multi-impacts on Seascape Ecosystems. The handbook presents the suite of tools developed in MARBEFES for integrated assessment of the impacts of multiple human pressures, both contemporary and future, on biodiversity, function and ecosystem services. Together with the **Handbook on Seascape Biodiversity, Function and Ecosystem Services**, this deliverable comprises the final MARBEFES reports on biodiversity and ecosystem tools, providing first-level guidelines. The purpose of this report is to provide an overview of the tools developed in WP3, allowing the reader to conduct a quick assessment as to whether any of the tools on the list could be of help for their specific objectives before delving deeper into the tool’s functioning and methodology, and the report hence aims at being a “first port of call” in guiding this choice. Each tool is presented with a short case study to provide an example of outcomes and help with the decision. The two WP3 Handbooks (D3.1 and D3.2) should be considered together with the WP4 Deliverable **Handbook on the Ecological, Economic and Socio-Cultural Valuation of Biodiversity** (D4.1) for a full suite of MARBEFES tools. The full testing and validation of each tool



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within MARBEFES case-studies (BBTs), alongside recommendations, are described and reported within the WP2 Deliverable **Final Assessment Report from Tests** (D2.2). Finally, the most up-to-date material and methods for applying each of the tools presented here are stored in the WP6 Deliverable **Marine Biodiversity and Valuation Toolbox** (D6.1), a web-based collection of the tools developed within MARBEFES.

2 Purpose of the Handbook on assessing human multi-impacts on Seascape Ecosystem

2.1 Human multi-impacts on seascape ecosystem structure function and services

The Handbook on Seascape Biodiversity, Function and Ecosystem Services presents the tool options that describe marine biodiversity at selected areas in Europe to understand the links between ecological structure and functioning across biological organizational levels from the molecular, individual and population to the community and ecosystem and the service they deliver. However, the way society decide to use those services (including conserving and restoring them) requires a solid understanding on how the links between biodiversity and ecosystem services is impacted (magnitude and direction) by human cumulated impact on the marine ecosystems. This is the objectives of the present handbook. It showcases a set of tools which present options to evaluate how human activities may change the expected level of services derived from the marine system. Applications of those tools (or a complementary subset thereof) can provide helpful recommendations on how management interventions should be directed and addressed to maximise and optimise the ecological and economical values respectively.

2.2 Handbook objectives and organisation

The handbook was designed around seven (7) principles. In order to (i) **provide a concise overview of the tools**, each tool section focusses on a few key characteristics, which are (ii) **organised for easy navigation** either by tool broad category, remit or ease of access to non-specialists. The handbook is defined as a (iii) **technical handbook** for the assessment of seascape biodiversity, function and ecosystem services and each tool description contained therein is (iv) **authoritative and reliable** having been developed, written and reviewed by experts in the field. This handbook is meant to be a concise overview of each tool (one page with a fundamental tool description followed by short examples of tool implementation) so that it is (v) **easy to dip in and out of**, each tool section is (vi) **consistent and standardised** with the same type of information provided for each and all contain (vii) **practical examples** for a tangible application and example outcome of respective tool.

3 Tool Overview

WP3 developed 16 tools or knowledge generation initiatives, which all can be used for describing seascape structure, function and services. Applied in different settings and for different purposes, the tools can also be useful for assessing human impact. In the interest for each of the handbooks to guide the user to the most relevant tool, tools are here listed and divided according to their primary focus under the MARBEFES project. Therefore, out of the 16 tools or knowledge generation



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initiatives that WP3 developed, 3 constitute activities outside the scope of the handbooks (an overview of citizen science, informal trait approaches and a literature review of indicators of functional change) and will be reported elsewhere, 3 were primarily developed to assess human impacts and are therefore presented in the present report (D3.2) and 7 were primarily developed to describe seascape structure, function and services are presented in the other handbook (D3.1). Finally, 3 of the tools ('Multi-Scale Trait-Based Approaches Linking Biological Structure to Ecosystem Function', 'Assessing Functional Trait-Based Species Vulnerability Against Environmental and Human Drivers', and 'Metric of Habitat Function') were developed for both objectives and are therefore presented in both handbooks with the example of application in each tailored to the purpose of respective handbook. For example, the "Assessing Functional Trait-Based Species Vulnerability Against Environmental and Human Drivers" tool presents an application describing the vulnerability assessment from anthropogenic impacts in the present handbook (D3.2) and one describing describing the change of functional trait structure according to an environmental gradient in the other handbook (D3.1). Overall, the present Handbook on Assessing Multi-impacts on Seascape Ecosystems (D3.2) presents 6 tools (3 specific, 3 in common with D3.1) and the Handbook on Seascape Biodiversity, Function and Ecosystem Services (D3.1) presents 10 tools (7 specific, 3 in common with D3.2) (Table 1).

For ease of cross-reference, each of the WP3 tools has been classified according to the tool's main categories or themes (first principle upon which the tool is based), the relevance of each tool for research questions aimed at assessing biodiversity, and whether the tool focuses on ecosystem components or assesses ecosystem functioning or ecosystem services (Table 2).

Tools were assigned a colour-coded category (common across D3.1 and D3.2):

- Physical-chemical approaches [blue] are hydrodynamic or biogeochemical models.
- Molecular approaches [fuchsia] are techniques using sub-organism methods (e.g. DNA/RNA) as a primary assessment method.
- Imaging approaches [coral] rely on methodologies based on deriving information out of images.
- Trait-based approaches [green] are tools built upon the use of functional traits to inform either a response of the biological community to the environment or an effect on ecosystem functioning.
- Network approaches [orange] are tools that use a diagram or a network-based approach as a basis for their implementation (e.g., food web, path diagram).
- Decision-support tools [grey] (not presented in D3.1) are integrated tools with an interface for entering scenario parameters



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Table 1 Classification of the 13 WP3 tools (excluding the 3 knowledge generation initiatives – see text) across the two handbooks, based on whether they are used for describing seascape structure, function and services (D3.1), for assessing human impacts (D3.2), or both. The tools that are not described in this handbook are greyed and in italics.

Tool name	D3.1	D3.2
Multi-Scale Trait-Based Approaches Linking Biological Structure to Ecosystem Function	✓	✓
TeloStress – Telomere Length as an Indicator of Physiological Stress		✓
A Bayesian Belief Network Framework for Testing Management Scenario Effects on Ecosystem Services		✓
Assessing Functional Trait-Based Species Vulnerability Against Environmental and Human Drivers	✓	✓
Metric of Habitat Function	✓	✓
Food-Web-Informed Cumulative Effects Assessment to Evaluate Ecosystem Functioning Across Human-Use Scenarios		✓
<i>Genetic Tools for Environmental Monitoring</i>	✓	
<i>Methodological Framework for Seascape Scale Benthic Ecosystem Functioning Research: Integrating Current Practices and Emerging Technologies</i>	✓	
<i>Deriving Faunal Function from Benthic Samples Using the ZooScan - an Automated Imaging System</i>	✓	
<i>Assessing Morphological Traits of Marine Invertebrates Related to Ocean Acidification and Climate Change Using Micro-Computed Tomography (Micro-CT)</i>	✓	
<i>Biogeochemical Modelling: Linking Marine Physics, Chemistry and Biology</i>	✓	
<i>Modelling Ecosystem Service Dynamics Using Structural Equation Modelling</i>	✓	
<i>Assessing Food Web Structure and Function Using Ecological Interaction Network Approaches and Bioenergetic Modelling</i>	✓	

Finally, each tool has also been categorised for whether non-specialist practitioners are likely to engage with or use the tool in a direct, semi-direct, or indirect way. One star (*) indicates a direct level of engagement, the tool is interactive or partially interactive and allows for current and future scenarios that can be directly implemented and tested by stakeholders. Two stars (**) indicates a semi-direct level of engagement, the tool is highly specialised but does benefit from non-specialist engagement in setting the right questions and identifying suitable outputs. Finally, three stars (***) indicates an indirect level engagement, where the tool is still at a research and development stage and is likely to benefit non-specialists only indirectly (for example, by exploring new sources of data that could be used through other tools).



Table 2 Tools and their assigned category (molecular [fuchsia], trait-based approaches [green], imagery [coral], physical-biogeochemical [blue] and network approaches [orange]). Note that tools are not restricted to a single category but, here, the most representative for the implementation was chosen. Green checkmarks, red crosses and amber question marks, respectively, indicate whether the tool addresses, does not address or could address the category with a little amendment. Stars indicate the level of non-specialist engagement, * = direct; ** = semi-direct, and *** = indirect.

Tool name	Category	Spatial Planning	Single impact	Cumulative/ Multi-Impact	Current Scenario	Future Scenario
Multi-scale trait-based approach to link biological structure to ecosystem function**	Traits	✓	✓	✓	✓	✗
TeloStress – Telomere length as an indicator of physiological stress***	Molecular	✗	✓	✓	?	✗
A Bayesian Belief Network framework for testing management scenario effects on ecosystem services*	Network	✗	✓	✓	✓	✓
Assessing Food Web Structure and Function Using Ecological Interaction Network Approaches and Bioenergetic Modelling **	Network	✓	✓	✓	✓	?
Assessing functional trait-based species vulnerability against environmental and human drivers**	Traits	✓	✓	✓	✓	✓
Metric of Habitat Function*	Traits	✓	✓	✓	✓	✓
Food-web–informed cumulative effects assessment to evaluate ecosystem functioning across human-use scenarios*	Decision-Support	✓	✓	✓	✓	✓



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4 Tool List

Multi-scale trait-based approach to link biological structure to ecosystem function **	
Tool focus:	Spatial planning, Single and cumulative impact, current scenario
Tool type:	Stepwise data analysis guidance, primer on trait-based approaches
Tool category:	Trait-based approach
Main users:	Scientists, planners (with more advanced knowledge of data analysis)
<p>Tool description: Biodiversity is often assessed by the number of species and their abundance or biomass, using indices of <i>e.g.</i> species richness or diversity. However, in recent decades a need for an improved insight on how the ecosystem is functioning, or the functional roles of species, have led to the development of different types of trait-based approaches (TBAs). Common for all of these, are the use of traits, or characteristics of an organism. A trait is defined as any morphological, physiological, life-history or behavioural characteristic measurable an individual level, such as size, longevity, feeding or movement type. In trait-based approaches that focus on assessing biodiversity patterns in space and time, the trait(s) of an organism is(are) often combined with the density of the organism, with assessments often conducted on a community level. The “Multi-scale trait-based approach to link biological structure to ecosystem function” tool (Multi-scale TBA tool) was developed to i) advance such trait-based approaches across taxonomic (<i>e.g.</i>, benthic organisms, fish, phytoplankton) and organisational scales (<i>e.g.</i>, species, communities, habitats, seascapes), and to ii) provide step-wise guidance, concrete examples and code of analysis, as well as primer on trait-based assessments. It was also developed with the potential to support, for example, identification of functionally important areas, and informing marine spatial planning and management in coastal areas regarding functional patterns.</p>	
<p>Data needs: Community data (abundance or biomass or presence/absence) for an ecosystem component, such as macrozoobenthos, fish, macrophytes, or phytoplankton, trait data for the included organisms, and depending on the analysis of interest, habitat data in the study area (<i>e.g.</i>, EUNIS habitat information). The level of expertise needed to apply the tool include knowledge in preparation and data analysis of marine biological community data, basic knowledge of GIS (<i>e.g.</i>, ArcGIS or QGIS), and basic knowledge in the R programming language. These are skills primarily possessed by scientists, experts or marine planners. However, the accompanying primer on trait-based approaches also informs on why and how to apply trait-based approaches on a more general level.</p>	
<p>Key references: Frelat <i>et al.</i> (2022). Tutorial for analysing trait-environment relationships, Zenodo, 10.5281/zenodo.6712534 and https://github.com/rfrelat/TraitEnvironment; De Juan & Demestre (2012). A Trawl Disturbance Indicator to Quantify Large Scale Fishing Impact on Benthic Ecosystems. Ecological Indicators 18: 183–190. Green <i>et al.</i> 2022. Trait-based approaches to global change ecology: moving from description to prediction. Proceedings of the Royal Society B. 289. 20220071. Hamilton <i>et al.</i> (2019). Limitations of trait-based approaches for stressor assessment: The case of freshwater invertebrates and climate drivers. Global Change Biology 26: 364-379. Verberk <i>et al.</i> (2013). Delivering on a promise: Integrating species traits to transform descriptive community ecology into a predictive science. Freshwater Science, 32, 531–547.</p>	



Multi-scale trait-based approach to link biological structure to ecosystem function

Example of implementation: Marine ecosystems are subjected to multiple human-derived stressors such as climate change and habitat degradation through e.g. bottom-trawling and coastal constructions, as well as pollution, e.g. of excessive nutrient inputs or toxic substances. As traits also describe the role or function of an organism in the system, they enable valuable insights into the impacts of human pressures on functioning of the ecosystem (Figure 1). Several analyses have been developed to assess a community's functional dynamics across space and time. Today, these are often based on average values in the community by combining the biomass- or abundance of species with the traits expressed. This in turn allows for investigations of individual traits in the community or explorations through different functional metrics. When studying functioning or functional structure in general, incorporation of all traits and functions present in the community, of as many, or at least the dominant species is optimal. However, to evaluate an individual species', taxonomic group's or community's vulnerability to a specific stressor or set of stressors, a better approach may be to include the most sensitive species. In addition to a species' sensitivity (the degree to which it is affected by a stressor), it's vulnerability to a stressor is also a function of its adaptive capacity (ability to adapt to or recover from a stressor), as well as exposure. Included in the tool "Multi-scale trait-based approach to link biological structure to ecosystem function" (Multi-scale TBA tool), is a primer on trait-based approaches, which may serve as a first point of contact for anyone interested in applying trait-based approaches. The primer outlines what trait-based approaches are, where to find information on traits and references to previous studies, as well as types of analysis. The examples of applying the Multi-scale TBA tool do not specifically evaluate human impacts, but could, depending on availability of e.g. pollution gradients, environmental status or other data on human-related pressure, be considered in the analysis. For example, the trait-based assessment of habitats within the EUNIS framework, could also be linked with e.g. an eutrophication gradient or other data on the status of the habitats, not only providing information on functional differences between habitats per se, but also how the status of them affects the functional structure. In addition, if data on human-related is available, this can be assessed in relation to trait biogeographies through e.g. trait biogeographic modelling. The example of this application in the Multi-scale TBA tool includes only three traits, which may be applicable also in a vulnerability assessment, but can easily be extended to additional traits relevant for the sensitivity to a pressure, if trait information is available.

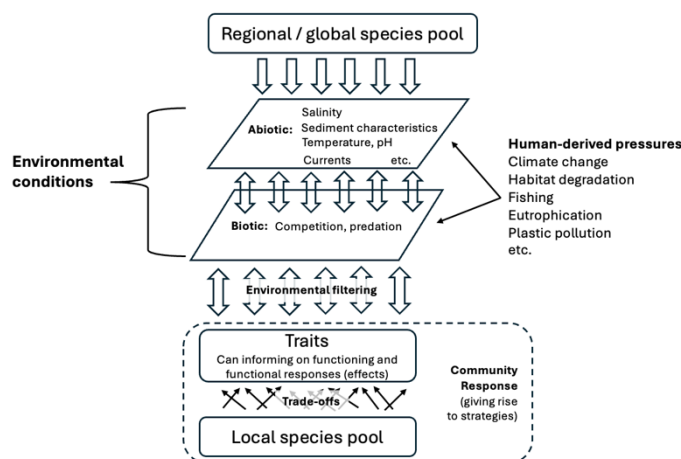


Figure 1 Trait-based approaches and the link to human impacts. Illustration of environmental filtering (biotic and abiotic) and species sorting in a marine environment, which in turn underpin trait-based approaches and assessments of environmental change and human impact. Human-derived pressures affect the environmental conditions, which in turn determine the species' response or strategies, in line with their expressed traits (adapted from Verberk et al. 2013, Hamilton et al. 2019).

TeloStress – Telomere length as an indicator of physiological stress ***	
Tool focus:	Environmental single and cumulative impacts
Tool type:	Biomarker of physiological stress (protocol)
Tool category:	Molecular
Main users:	Scientists
<p>Tool description: Telomeres are molecular tools acting as relevant proxies of individual quality, lifestyle and lifespan of living organisms. Telomeres are non-coding DNA-protein complexes located at the end of linear chromosomes playing critical roles in maintaining and ensuring genomic integrity and stability. They progressively shorten along life, but their attrition is accelerated by a wide range of environmental stressors. When telomere length reaches a critical lower threshold, cell division can damage coding DNA leading to apoptosis or cellular senescence. Chronic stress, including changes in environmental conditions and demanding biological processes, has been shown to speed up telomere shortening thus reflecting the physiological stress. In that context, their use as stress proxy in ecology and environmental science has exponentially increased over the past years with numerous successful applications on vertebrates. They have been shown to be a strong indicator of individual fitness and even promising proxy for early warnings of population extinction risks. Applications in marine invertebrates are sparse and MARBEFES aims to bring this potent tool into the realms of the marine environment, especially on sensitive species such as corals located in vulnerable marine ecosystems. Sub-lethal stress indicators capable of distinguishing intermediate stress status are essential for early intervention and thus preservation and sustainable management of vulnerable marine ecosystems forming species.</p>	
<p>Data needs: The equipment needed for the collection of biological samples depends on the species of interest. For deep-sea corals, the use of the ROV technology is required. Determination of telomere length from biological samples (i.e., DNA) requires both basic and more advanced molecular laboratory facilities and equipment, including a spectrophotometer, qPCR machine, incubator, centrifuge, agarose gel electrophoresis system, restriction enzymes, blotting equipment, hybridization oven, chemiluminescence imager, and software for data analysis (e.g., ImageJ, R).</p>	
<p>Key references:</p> <p>Angelier <i>et al.</i> (2018). Do glucocorticoids mediate the link between environmental conditions and telomere dynamics in wild vertebrates? A review. <i>General and comparative endocrinology</i>, 256: 99-111.</p> <p>Blévin <i>et al.</i> (2016). Exposure to oxychlorane is associated with shorter telomeres in arctic breeding kittiwakes. <i>Science of the Total Environment</i>, 563: 125-130.</p> <p>Dupoué <i>et al.</i> (2024). Reproductive aging weakens offspring survival and constrains the telomerase response to herpesvirus in Pacific oysters. <i>Science Advances</i>, 10: eadq2311.</p> <p>Rouan <i>et al.</i> (2021). Telomere dysfunction is associated with dark-induced bleaching in the reef coral <i>Stylophora pistillata</i>. <i>Molecular Ecology</i>, 31: 6087-6099.</p>	



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TeloStress – Telomere length as an indicator of physiological stress

Example of implementation: A recent published example of implementation is provided by Rouan et al. (2021) – see key references –, with a coral-reef case study. Coral reefs are under threat due to global climate change and anthropogenic activities. Coral bleaching occurs when environmental stressors—such as rising sea temperatures, pollution, or ocean acidification—cause corals to expel the symbiotic algae that give them color. To mitigate coral loss, there is currently an urgent need to understand the mechanisms involved in the response of corals to environmental stressors. Telomeres are non-coding DNA-protein complexes located at the end of linear chromosomes playing critical roles in maintaining and ensuring genomic integrity and stability. They progressively shorten along life, but their attrition is accelerated by a wide range of environmental stressors. When telomere length reaches a critical lower threshold, cell division can damage coding DNA leading to apoptosis or cellular senescence. Chronic stress, including changes in environmental conditions and demanding biological processes, has been shown to speed up telomere shortening thus reflecting the physiological stress. In that context, their use as stress proxy in ecology and environmental science has exponentially increased over the past years with numerous successful applications on marine vertebrates such as fish and seabirds. They have been shown to be a strong indicator of individual fitness and even promising proxy for early warnings of population extinction risks. Telomeres are relevant molecular tools acting as relevant proxies of individual quality, lifestyle and lifespan of living organisms. Applications in marine invertebrates are sparse, especially on sensitive species such as corals located in vulnerable marine ecosystems. Rouan et al. (2021) investigated the telomere changes occurring in a symbiotic coral, *Stylophora pistillata*, that has experienced continuous darkness over 6 months. The study showed that continuous darkness was associated with telomere length shortening, suggesting that telomere length is a relevant indicator of physiological stress in corals.

Stylophora pistillata

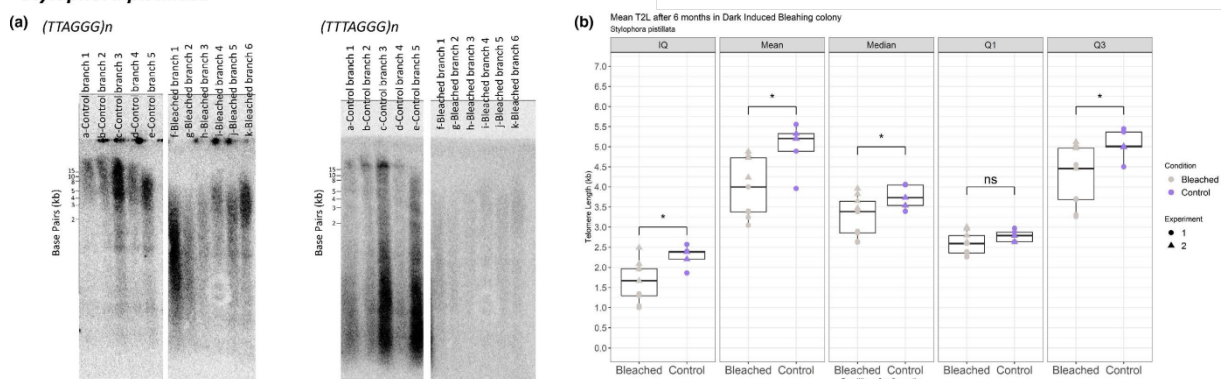


Figure 2 *Stylophora pistillata* dark-induced bleaching telomere length measured by a telomeric restriction fragment assay. (a) Telomeric restriction fragment assay from experiment D1; the left panel shows the membrane labelled with the (TTAGGG)*n* host coral DNA telomeric sequence complementary probe and the right panel shows the membrane labelled with the radioactive (TTTAGGG)*n* symbionts DNA telomeric sequence complementary probe. Five control branches and six bleached branches are displayed. Bleached branches after 6 months of darkness exposure exhibit a shorter telomeric smear signal with the (TTAGGG)*n* coral telomere probe labelling and no signal with the (TTTAGGG)*n* symbiont telomere probe. (b) Boxplot of (TTAGGG)*n* coral telomere smear measurements: IQ (interquartile distance between first quartile Q1 and third quartile Q3), mean and median telomere length between bleached and control samples from experiment D1 (circles) and D2 (triangles); TL IQ, mean, median and Q3 were significantly shorter in bleached conditions except for Q1 that was not significantly different between the two conditions (Rouan et al. 2021).

A Bayesian Belief Network Framework for testing Management Scenarios effects on Ecosystem Services *	
Tool focus:	Single and cumulative impact, current and future scenario
Tool type:	Statistical analysis, Conceptual path diagram, Bayesian inference, proprietary software, R environment
Tool category:	Network analysis
Main users:	Scientist, Environmental practitioner, Decision-maker
<p>Tool description: A Bayesian Belief Network (BBN) is a visual tool that shows how different things (events, conditions) are related and how likely they are to influence each other. BBNs are based on two structural model components: (1) a directed acyclic graph (DAG) that denotes dependencies and independencies between the model's variables and (2) conditional probability tables (CPTs) informing the strengths of the links in the graph. The DAG consists of a network of variables or nodes which represent the modelled system. The relationships between different nodes are indicated by directed arrows which represent cause-effect relations within system (parent node -> child node); DAGs are "acyclic" which means that no feedback is allowed. Each network variable contains a limited number of states to which their realized value can belong, this is called discretisation (continuous variable are not allowed in BBNs), a probability distribution defines whether a variable is expressed in a particular state. The strengths of the causal relations between the networks variables are quantified through conditional probabilities tables (CPTs). Bayesian inference is used to propagate these probabilities through the network. Due to their high adaptability in dealing with multiple data source combined with a highly visual components, BBNs are ideal to conceptualise the full chain of service delivery allowing for building in management scenarios options the effects of which can be visually seen throughout the ES chain (Figure 3).</p>	
<p>Data needs: The amount of information needed will be conditional on the complexity of the DAG, BBNs can accommodate field or experimental data, experts' judgement, modelled data and even hybrid sources. They work well even with incomplete data which is one of their strengths.</p>	
<p>Key references: Landuyt <i>et al.</i> (2013). A review of Bayesian belief networks in ecosystem service modelling, <i>Environ. Model. Softw.</i> 46: 1–11. Uusitalo (2007). Advantages and challenges of Bayesian networks in environmental modelling. <i>Ecological modelling</i>, 203: 312-318. Uusitalo <i>et al.</i> (2023). Modelling framework to evaluate societal effects of ecosystem management. <i>Science of the Total Environment</i>, 898: 165508.</p>	

Figure 3 General layout of a BBN embedded in the Ecosystem Service cascade with a decision node added.



A Bayesian Belief Network Framework for testing Management Scenarios effects on Ecosystem Services

Example of implementation: A recent example of BBN implementation undertaken in the context of ecosystem service management can be found in Uusitalo *et al.* 2023 (see key references). This work aimed at demonstrating a transparent framework to evaluate how different ecosystem management options, under different climate change scenarios would affect the people who are using the sea. The model used existing (modelled) data simulating the ecosystem response to management and climate scenarios (nutrient loading, climate and fishing policy), which resulted in different predicted biomass for important marine taxa group, in combination with a stakeholders' questionnaire data informing on what aspect of the marine ecosystem they value the most (or the least). The BBN strength was to combine those two sources of data into one single framework (Figure 4) to illustrate which management options bring the highest benefits to stakeholders, and whether different stakeholder groups benefit differently from different management choices. In this specific case study, the more moderate climate scenario and strict fisheries and nutrient loading management brought the highest benefits to all stakeholders. This work demonstrates a method to numerically integrate and analyse the long path from scenarios and management alternatives to the realised utilities (benefits and harms) that different groups may perceive. This approach can be used in a variety of studies where it is important to estimate how potential human activities will feed back to human well-being through their ecosystem effects. The approach also allows the evaluation of whether the effects will benefit or harm all stakeholder groups in equal manner, or if the benefits or harms will be felt by one group more than the others. This allows decision-making to consider the societal effects of ecosystem use and environmental management in a transparent way

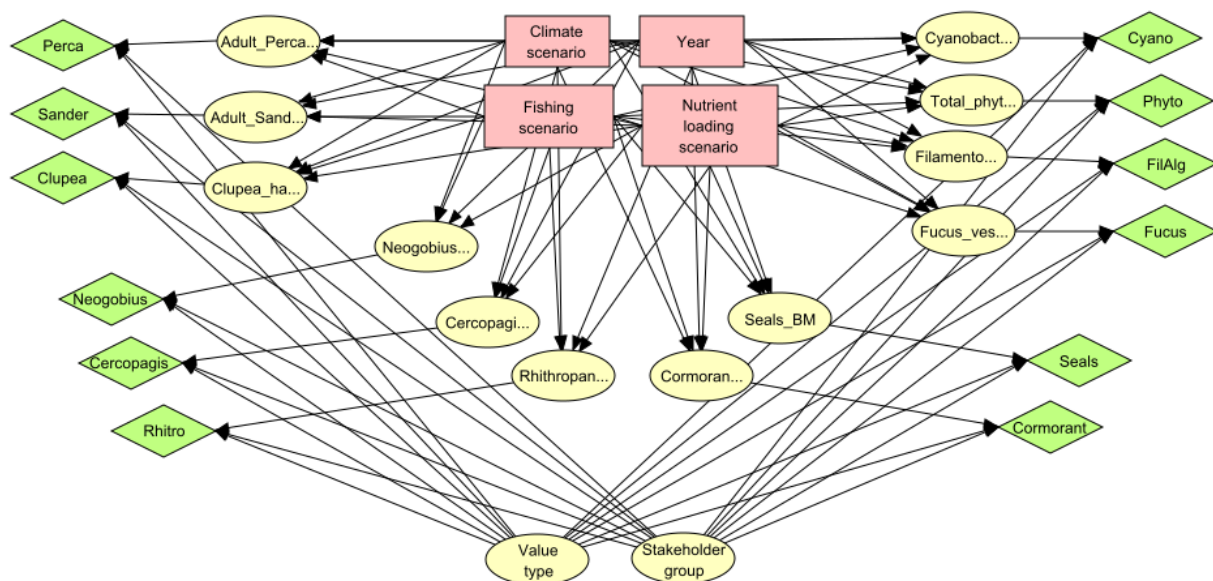


Figure 4 DAG representing the ecosystem service management developed by Uusitalo *et al.* 2023. The 4 management or climate options (pink square) would inform the biomass change of each marine taxa group (top yellow oval) while the stakeholder's value (bottom yellow oval) would "weigh" each of those group according to their preferences, the integration of which would be realised in the utility nodes (green lozenge).

Assessing Functional Trait-Based Species Vulnerability Against Environmental and Human Drivers **	
Tool focus:	Single and multi-impact, trait-based vulnerability assessment, current scenarios of pressures
Tool type:	Statistical analysis process, Correlative model, Multivariate Analysis, R Environment
Tool category:	Trait-based approach
Main users:	Scientists, Environmental practitioner
Tool description:	<p>The tool for “Assessing functional trait-based species vulnerability against environmental and human drivers” is also described in the Handbook D3.1 on Seascape Biodiversity, Function and Ecosystem Services please refer to this document for a full description. The RLQ is a multivariate analysis used to connect different types of data (namely environmental, species distribution and functional traits), therefore, incorporating human pressures into the table R allows for the quantification of relationships between trait, pressures and environment. The methods can show which pressures are most strongly related to environmental variables and how these alter species composition through traits. The association of the RLQ with the 4th Corner method (which tests for individual trait-environment/pressure relationships) can be harnessed to both identify the main relationships between pressures and traits (RLQ) and the most significant association between the two (4th corner). Used for vulnerability assessment, the RLQ/4th corner method can pinpoint which functional traits are strongly selected for (or against) human disturbance. The analysis can further reveal which community function are the most likely to be affected (for example, in a contaminated area, the analysis might show an increase in species with traits for tolerance). The results are highly visual where a 2-dimensional plot show how environment, pressure and species traits are positioned to show their co-relationships, making the results easier to interpret and communicate to stakeholders. By understanding how human pressures change ecosystems at a functional level, researchers and managers can develop more effective conservation and management plans, such as understanding effects of MPA beyond preserving biodiversity.</p>
Data needs:	<p>Similar to the data needs indicated in the Deliverable D3.1. Additionally, the RLQ/4th Corner can accommodate any types of human pressures data. Continuous: for example, fishing pressure, contaminant/eutrophication gradient, temperature or acidification change; categorical: for example, in and out of (or before/after) aggregate extraction zone, offshore windfarm or dredge material disposal. A combination of both continuous and categorical is also possible, the method is not limited by the number of variables just by the fact that the information needs to be available for each site.</p>
Key references:	<p>MARBEFES R tutorial and example data: https://github.com/Clem2012/MARBEFESWP3_VA <u>Araújo et al. (2024)</u>. Trait–environment relationship of riverine fish assemblages across a human footprint mosaic. <i>Hydrobiologia</i> 851: 1135–1151. https://doi.org/10.1007/s10750-023-05370-9. <u>Beauchard et al. (incl. Garcia) (2023)</u>. Trawling-induced change in benthic effect trait composition – A multiple case study. <i>Frontiers in Marine Sciences</i> 10: 1303909. https://dx.doi.org/10.3389/fmars.2023.1303909 <u>Dray et al. (2014)</u>. Combining the fourth-corner and the RLQ methods for assessing trait responses to environmental variation. <i>Ecology</i>, 95: 14-21. DOI 10.1890/13-0196.1 <u>Rao et al. (2021)</u>. Responses of Functional Traits of Macrobenthic Communities to Human Activities in Daya Bay (A Subtropical Semi-Enclosed Bay), China. <i>Front. Environ. Sci.</i> 9:766580. doi: 10.3389/fenvs.2021.766580</p>



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Assessing Functional Trait-Based Species Vulnerability Against Environmental and Human Drivers

Example of implementation: Bottom trawl fisheries is a ubiquitous threat to benthic ecosystem functions the full extent of which remain unclear and vary with environmental context. Indeed, direct mortality of benthic species does not always translate to loss of functions or functional diversity, and trait-based vulnerability analysis has been shown to be a helpful tool to assess the direct or indirect effect of bottom trawling on ecosystem functioning. In their 2023 study, Beauchard et al. used the RLQ/4th Corner approach to explore the consequence of bottom trawling on benthic trait composition using 13 case-studies spanning across different European waters (from the Mediterranean through the Bay of Biscay to the North and Baltic Sea). The combined analyses found that bottom trawling was significant selective force for benthic trait distribution. Tube-dwelling traits were found to be the most vulnerable to the pressure, only found at low trawling intensity whereas deep burrowing species were more resistant to high trawling intensity (figure 5). The finding emphasised the key role of burrowing depth and mobility (escape ability) and body size to explain the vulnerability of species to trawling intensity.

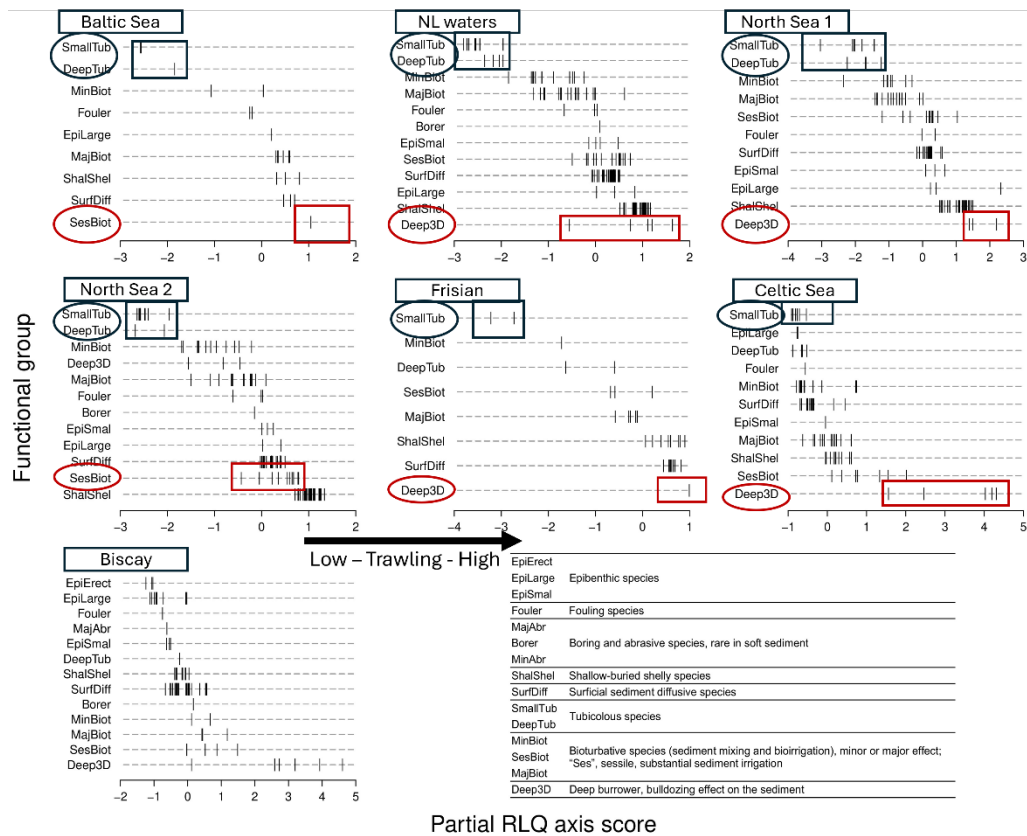


Figure 5 Trait distribution along the RLQ axis expressing an increase of trawling intensity from left to right, vertical segments indicate species position within trait composition and are arranged according to mean species position. As the RLQ controls for environmental drivers, species position is solely determined by trawling intensity.



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Metric of Habitat Function *	
Tool focus:	Single and multi-impact, trait-based vulnerability assessment, current scenarios of pressures
Tool type:	Conceptual model, GIS, map of functions
Tool category:	Trait-based approach
Main users:	Scientists
<p>Tool description: The tool for assessing Habitat Function Metric (HFM) is described in detail in the Handbook D3.1 on Seascape Biodiversity, Function and Ecosystem Services; please refer to that document for the full methodological framework. The HFM maps the capacity of benthic habitats to support key ecosystem functions and provides a basis for assessing functional losses from habitat degradation. The assessment of impacts can be achieved by comparing habitat function under different environmental conditions or scenarios. In the HFM current development, this can be operationalized in two complementary ways:</p> <ol style="list-style-type: none"> 1. Through the environmental status weighting—where lower condition scores (<i>e.g.</i>, 0.5 for degraded habitats) directly reduce the functional potential attributed to each spatial unit. 2. Through modified habitat baselines—by altering the input habitat map to represent degradation or loss of specific habitat types (<i>e.g.</i>, decline of seagrass cover), and recalculating the resulting functional output. <p>Both approaches allow the tool to simulate the consequences of human pressures (<i>e.g.</i>, trawling, coastal construction, eutrophication) on the delivery of ecosystem functions such as nutrient cycling, carbon storage, and structural habitat provision. The output expresses the relative loss or maintenance of function across the seascape. Used for impact assessment, the HFM thus acts as a diagnostic and predictive tool: by linking habitat integrity to ecological functioning, it enables managers to visualize how pressures alter functional capacity and to identify priority areas for conservation or restoration.</p>	
<p>Data needs:</p> <ul style="list-style-type: none"> • Habitat data: EUNIS 2022 maps (\geqLevel 2). • Environmental data: MSFD indicators or other spatial assessments of ecological status; or cumulative impact maps. • Functional data: Expert-derived functional scores, literature-based function–habitat linkages, and empirical measures (<i>e.g.</i>, bioturbation, carbon fluxes, habitat complexity indicators). • Spatial framework: High-resolution (250 m) hexagonal grid for GIS integration. 	
<p>Key references:</p> <p><u>Bevilacqua <i>et al.</i> (2018)</u>. A regional assessment of cumulative impact mapping on Mediterranean coralligenous outcrops. <i>Scientific Reports</i>, 8: 1757.</p> <p><u>de Juan <i>et al.</i> (2015)</u>. Standardising the assessment of Functional Integrity in benthic ecosystems. <i>Journal of Sea Research</i>, 98: 33-41.</p> <p><u>de Juan <i>et al.</i> (2022)</u>. Biological traits approaches in benthic marine ecology: Dead ends and new paths. <i>Ecology and Evolution</i>, 12: e9001.</p> <p><u>Hinz <i>et al.</i> (2021)</u>. Trait-based indices to assess benthic vulnerability to trawling and model loss of ecosystem functions. <i>Ecological Indicators</i>, 126: 107692.</p>	



Metric of Habitat Function

Example of implementation: In the Menorca Channel, currently a *Site of Community Importance (Natura 2000)*, the HFM has been applied to quantify the functional role of benthic habitats under current protection. However, this conceptual framework could be applied to simulate potential impacts under degradation scenarios. The main historical pressures in this area were recreational boat anchoring, which can damage *Posidonia oceanica* meadows in the coastal zone, and bottom trawling affecting maërl beds on continental shelves. Trawling was fully banned from the Channel in 2016, and the area now maintains a generally good ecological status.

To explore a regression scenario, the HFM can simulate a loss of maërl beds, replacing areas with 100% rhodolith cover by detritic bottoms with dispersed rhodoliths. This change in the habitat map would result in a measurable decline in habitat functions, particularly in carbon storage capacity and structural habitat provision, as rhodolith beds are key biogenic habitats supporting high biodiversity and carbon sequestration. By comparing the current and degraded scenarios, the tool highlights the magnitude and spatial distribution of functional losses, demonstrating how the HFM can be used to quantify and visualize ecosystem impacts linked to specific pressures or management actions.

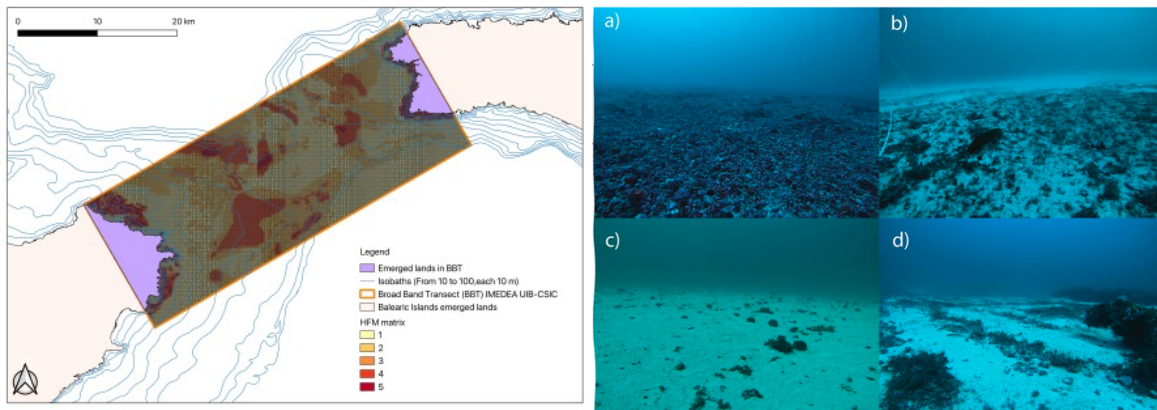


Figure 6 Metric of Habitat Function in BBT10. The potential functions provided by habitats (right) are scaled and aggregated to produce a normalized measure of functional potential across spatial units in the area.

Food-web-informed cumulative effects assessment to evaluate ecosystem functioning across human-use scenarios (EcoFunMAP + PlanWise4Blue) *	
Tool focus:	Biodiversity, ecosystem, ecosystem functioning and services
Tool type:	Bioenergetic and food web models, species distribution models, cumulative effects assessment algorithms, web- and desktop-based applications
Tool category:	Decision support tool
Main users:	Scientists, decision makers

Tool description: Effective marine spatial planning increasingly requires understanding not just how human activities affect individual species or habitats, but how these impacts propagate through whole ecosystems and influence key ecological processes. While existing cumulative effects assessment (CEA) tools in Europe support planning and environmental assessment, they typically overlook ecosystem functioning and food-web-level responses. Recent advances in food-web and bioenergetic modelling allow quantifying energy and matter flows across multi-trophic systems, offering strong metrics for ecosystem functioning, resilience, and stability. Building on these advances, MARBEFES developed EcoFunMAP, a web application that scales up bioenergetic food-web analyses for spatial planning (Food Web-based **E**cosystem **F**unctioning **M**apping and **A**ssessment Platform). Using species interaction networks (metawebs) and spatial biomass or abundance layers, EcoFunMAP reconstructs local food webs for every grid cell and computes energy fluxes and ecosystem functioning indicators. Specifically, the MARBEFES tool development allowed for linking EcoFunMAP with the CEA tool PlanWise4Blue (PW4B) (Figure 7). PW4B models how human activities change species biomass, and these updated biomass layers feed directly into EcoFunMAP. This integration enables planners to evaluate how human-use scenarios affect food-web structure, stability, energy and matter fluxes, and overall ecosystem functioning. Both tools are now available through the Blue Bio Sites geoportal.

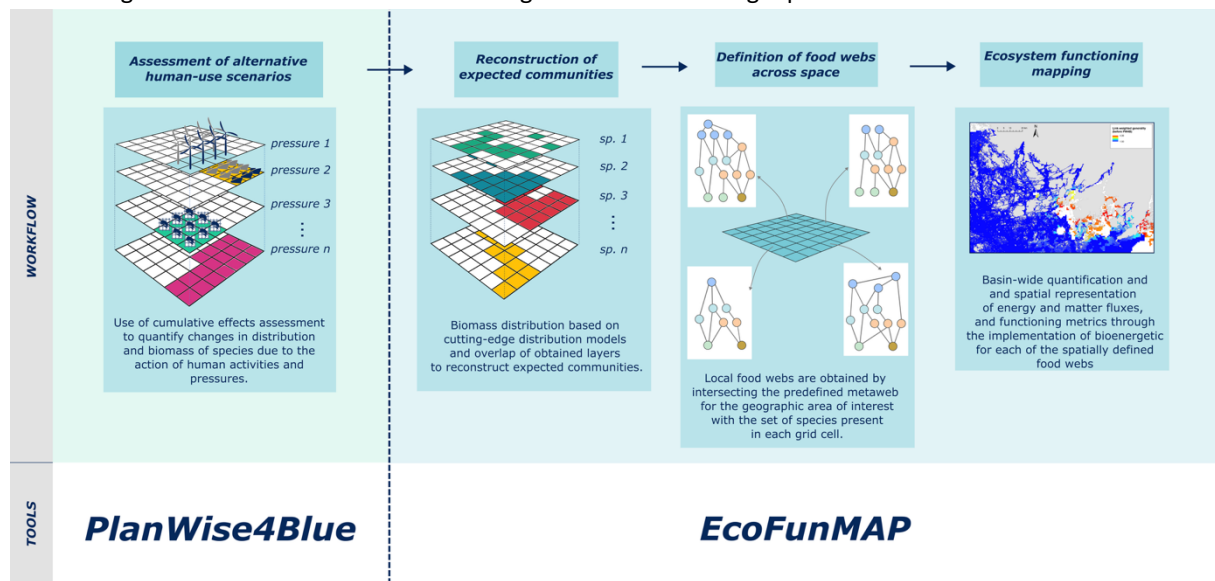


Figure 7 Schematic representation of the combined use of EcoFunMAP and PlanWise4Blue to scale up bioenergetic food web analyses to spatial scales relevant for marine spatial planning, and to quantify and map energy and matter fluxes, food web stability indices and derived ecosystem-functioning metrics, under alternative human-use scenarios.



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Data needs: List of species and feeding interactions for reconstructing a metaweb for the geographic area of interest. Biomass or abundance distribution layers for species included in the metaweb. Spatial distribution (and, where available, intensity) layers of human activities and pressures to be included in the cumulative effects assessment.

Key references: [Antunes et al. \(2024\)](#). Linking biodiversity, ecosystem function, and Nature’s contributions to people: a macroecological energy flux perspective. *Trends in Ecology & Evolution*, 39: 427-434.

[Kortsch et al. \(2021\)](#). Disentangling temporal food web dynamics facilitates understanding of ecosystem functioning. *Journal of Animal Ecology*, 90: 1205-1216.

[Kotta et al. \(2020\)](#). Online tool to integrate evidence-based knowledge into cumulative effects assessments: Linking human pressures to multiple nature assets. *Environmental Advances*, 2: 100026.

[Olivier et al. \(2024\)](#). A network of biological traits: Profiling consumer-resource interactions. *Food Webs*, 38: e00333.



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Food-web-informed cumulative effects assessment to evaluate ecosystem functioning across human-use scenarios (EcoFunMAP + PlanWise4Blue)

Example of implementation: As EcoFunMAP and its integration with PW4B have only recently been completed, their overall implementation is still at a preliminary stage. The first coupled application of the tools carried out within MARBEFES focused on the Eastern Baltic Sea. This implementation relies on biomass distribution data produced by the Estonian Marine Institute (University of Tartu), derived from the integration of information generated by national monitoring programmes and modelling efforts initiated under the ADRIENNE project. The metaweb for the area was reconstructed based on previous bibliographic work by Åbo Akademi University and the University of Helsinki (see Kortsch *et al.*, 2021; Olivier *et al.*, 2024) and was further refined through species-targeted revisions conducted within MARBEFES.

This initial application was run using the desktop versions of EcoFunMAP and PW4B on the University of Tartu's supercomputer cluster. Dredging and dumping, fishing, eutrophication, and coastal modification were included as key human activities and pressures for performing CEA in PW4B. EcoFunMAP was applied using both the original biomass layers and those resulting from the changes imposed by the cumulative action of the considered human activities and pressures, allowing exploration of how gradients of human impact translate into spatial changes in food web structure and stability, and energy and matter fluxes across the Eastern Baltic Sea (Figure 8 for an example of the type of outputs expected from the couple application of EcoFunMAP and PW4B).

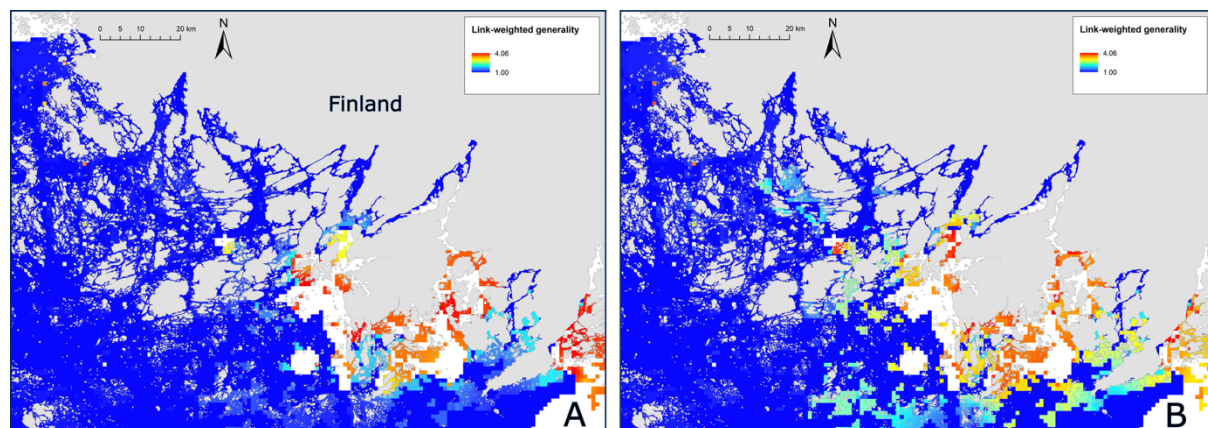


Figure 8 Example of EcoFunMAP outputs based on (A) baseline biomass layers of species and (B) biomass layers resulting from the assessment of the cumulative effects of human activities and pressures using PW4B. In this case, the maps show the spatial distribution of link-weighted generality, a food web-related metric which, together with link-weighted connectance and vulnerability, provides insight into the distribution and magnitude of energy flows and aspects of system stability and resilience (Kortsch *et al.*, 2021).

5 Tool integration

The WP3 tools have generally been designed to answer specific questions but MARBEFES WP3 has fostered a cross-tools development environment aiming for a better integration so that the complementary use of a carefully calibrated subset would allow to bring more than “the sum of its part”. This possible integration of multiple tools to answer bigger questions is illustrated in Figure 9. This illustration only relates to aspect of human impact and should be considered together with its counterpart from D3.1 on biodiversity, ecosystem function and services.

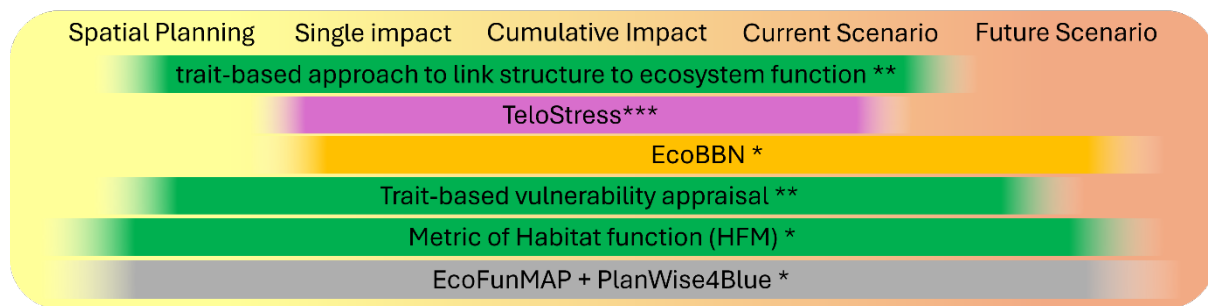


Figure 9 Tools and their assigned category (trait-based approaches [green], network approaches [orange], physical-biogeochemical approaches [blue], molecular approaches [fuchsia], and imaging approaches [coral]). Note that tools are not necessarily restricted to a single category but, here, the most representative for the implementation was chosen. Stars indicate the level of possible stakeholder engagement and usability * = direct, ** = semi-direct, *** = indirect.

All the tools described in this report can address single and cumulative impacts for current scenarios. They do so in different ways, while the molecular approach TeloStress (fuchsia) evaluate the net effect of all stress, endured by a community, accumulated at molecular level and derive a level of risk out of it, the trait-based approaches (green) generally proceed from an *a priori* assumption that the chosen traits to be investigated against a pressure gradient do indeed reflect an ecological reality in the community response to those stressors. Taken together, this means that the TeloStress tool is able to reveal an objective stress within the community through changes happening at molecular level but the respective contribution of the various impacts causing that stress is difficult to ascertain. On the other hand, while the trait-based approaches are less certain that the potential change in trait distribution do indeed reflect a stress, those methods have generally better control over the respective contribution of each impact in the case of cumulative impacts. The strength of those categories of analysis is that they have very limited logistic and only necessitate the relevant data to be adapted in any geographical regions.

The EcoBBN tool (using BBN for assessing human impact on ecosystem services) is greedier in data and logistic as it needs a prior construction of a conceptual model that explain how the system works and how impacts may propagate through that system (generally built by consulting experts, undertaking literature review or organising workshop). A strength of this approach, however, is that it remains somewhat adaptable to any geographic setting (but would take a little more time and efforts than the two previous tool categories) and can accommodate multiple data sources which means that many of the other tool categories can be fed into an EcoBBN quite rapidly. It is a particularly strong tool for Future Scenario as a “Future Scenario” node can be implemented with a high level of details and any outcome from those scenarios will be fully documented, visually



assessable through change in the network and will have a Bayesian uncertainty associated to it therefore ideal when it comes to stakeholder engagement and what it might mean for the future of a resource they might be interested in.

The EcoFunMap & PW4B integration is moving one step towards a better integration of various impacts and consequences on ecosystem service delivery and has a particularly strong spatial component. It renders this tool very powerful for spatial planning scenario design current or future that involves one or multiple impacts. The weakness of this tool however is that it is heavy in logistic. The current working system is mostly developed for the Eastern Baltic Sea, but the essential components and workflow are in place for an application to a different location. A new application for this tool will however take the longest time to implement out of all the tool categories presented in this report.

A hypothetical case-study requiring a full tool integration (Figure 10) would start with the application of TeloStress which would define an objective and measurable molecular-based level of risk for a community. This molecular risk could be fed into one of the trait-based tools (broadscale and vulnerability in the first instance) which could relate that change of risk according to pressure gradient and within the context of a wider suite of traits, thereby informing a possible ecosystem function-related risk overall. The input of that information into the metric of Habitat Function would allow to consider other functional metrics (not trait related) and render the outcome spatially explicit strengthening the outcome on function-related risk. In parallel, feeding the output from TeloStress and the Trait-based approach into an EcoBBN would allow for a better discrimination of the effect of multiple impacts and allow the user to implement stronger current and future management scenarios with an associated uncertainty in the outcome. Finally, the spatial layers from HFM together with the probability distribution of the relationship between variable from EcoBBN could be further integrated to EcoFunMap & PW4B for a much stronger and confident outcome across all human impact categories, spatial planning, single and cumulative impact, current and future scenario.

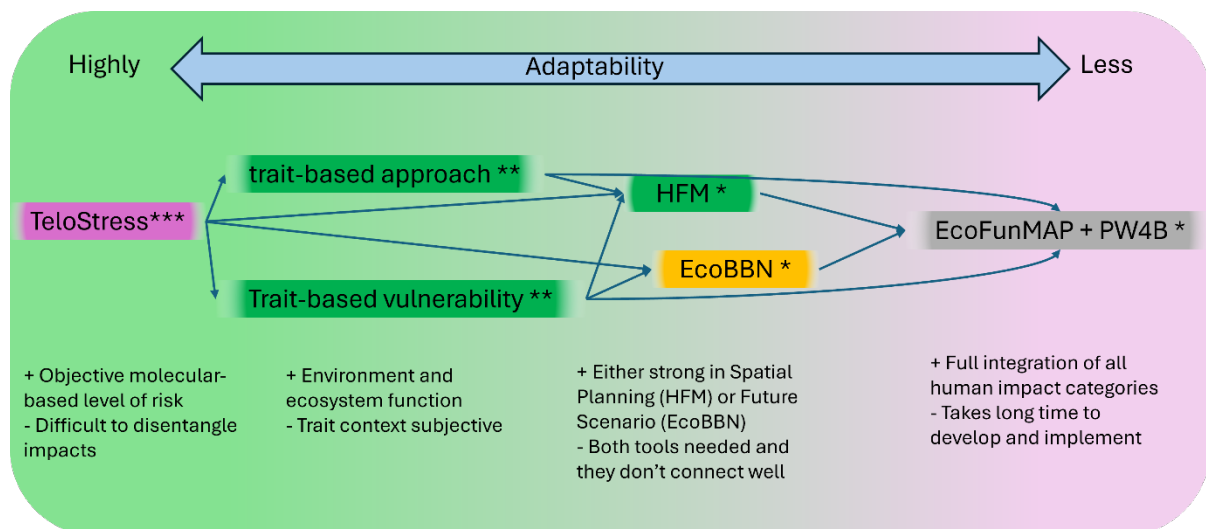


Figure 10 Possible workflow that would connect all of the WP3 tool dedicated to assessing human impact and presented within this deliverable presented in a gradient of local adaptability. See text for fuller explanation.



6 Conclusion

This Deliverable reports on the MARBEFES WP3 activities biodiversity and ecosystem tools specifically designed to assess human multi-impacts on seascapes ecosystems. It forms the final deliverables from WP3 together with its counterpart the Handbook on Seascape Biodiversity, Function and Ecosystem Services (D3.1). The document is designed as a technical handbook for the assessment of human multi-impact on ecosystem function and services. It was designed around 4 themes human-impact related: spatial planning, single and multi-impact and current or future scenario. The tool section presented 6 tools which are addressing all or a subset of these themes, these tools were further categorised by types (molecular, trait-based, network or decision-support) and colour coded, as well as star-coded by the anticipated level of direct stakeholders' engagement (from direct to indirect). In the tool section, each tool is presented succinctly, and a worked example is provided to illustrate the type of outputs expected. The final section provides an overview of how to use those tools in an integrated manners so that their weaknesses are counteracted and their strengths complemented.



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