A COMMON HANDBOOK

# Cumulative effects assessment in the marine environment

JPI OCEANS

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# JPI OCEANS KNOWLEDGE HUB ON CUMULATIVE EFFECTS OF HUMAN ACTIVITIES IN THE MARINE ENVIRONMENT

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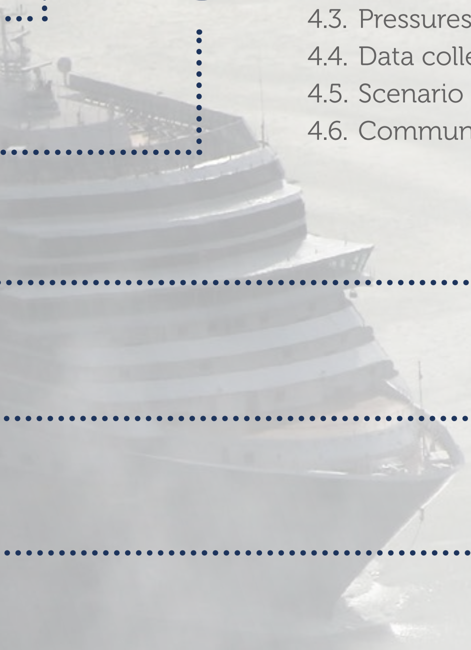



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# 1.0 INTRODUCTION

**Understanding and assessing the cumulative effects of human activities on ecosystems, including seas and oceans, is crucial for effective management and to ensuring sustainability goals of healthy and productive seas and oceans. Cumulative effects refer to the combined impacts of multiple activities or projects on a given environment or ecosystem. Here we aim to present some methods, tools and examples taken from scientific and grey literature.**

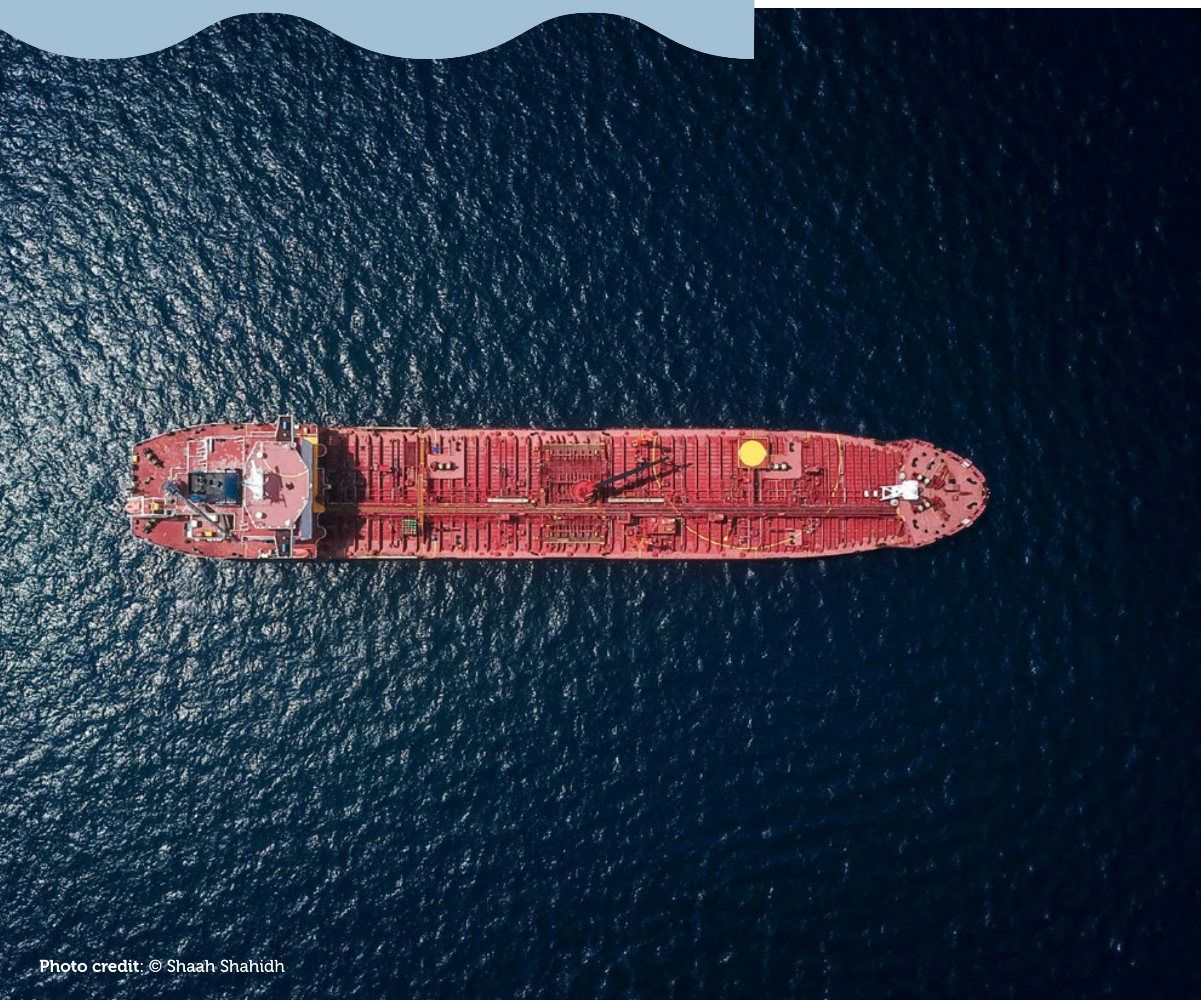
These combined impacts can be difficult to assess and mitigate because they can occur over a long period of time, can occur at larger spatial scales, involve multiple actors, and interact with other environmental stressors. Some activities may have local impacts, while others may have regional or even global impacts. Similarly, some impacts may be immediate, while others may have delayed or long-term effects. Some externalities cannot be controlled locally but must be considered on larger scales. This means that management decisions for marine environments must consider both ocean processes and external factors such as ocean currents, global biogeochemical cycles, transboundary pollution, and pressures.

With the acknowledgement of a need for more holistic, ecosystem-based management of sea basins rather than managing each ecosystem component (fish species, sea birds, mammals etc) and each human activity separately, a new set of approaches to evaluate the cumulative impact of human activities have been proposed. Existing methods for cumulative effects assessment (CEA) vary widely, both in the underlying assumptions and to which regional scale, activities, and ecosystem components they are appropriate. There are no internationally agreed and routinely applied methodologies to do assessments combining multiple pressures, and there are differences and in some cases inconsistencies in the language used to describe cumulative effect assessments, starting from its definition which is "cumulative effects assessments, CEAs" in some cases, and "cumulative impacts assessment, CIA" in others (Halpern et al., 2008a Stock and Micheli, 2016). Here we regard both terms as synonymous.

As deeply investigated by Steltzenmüller et al. (2018), the plethora of approaches has led to large variation of research agendas of CEAs (Foley et al., 2017) and makes comparisons among methods and the results they deliver difficult (Stock and Micheli, 2016). Some differences and apparent inconsistencies pertain to the level of focus and scale of the different CEA. For example, in Halpern et al. (2008) the assessment is conducted at a global spatial scale, with a focus on identifying and mapping the spatial distribution of multiple human activities and stressors in the ocean. The Judd et al. (2015)

approach is focused on the assessment of cumulative impacts on ecosystems at a smaller spatial scale, such as a river basin or a local area. This scale is suitable for integration of the principles of environmental risk assessment to identify and evaluate potential risks associated with the interactions between multiple activities, pressures, and ecosystem components.

Cumulative Effects Assessment offers a holistic approach, and the consideration of pathways and the likelihood of exposure can help to prioritize the most significant and relevant interactions and components, based on their potential impact and sensitivity. The use of risk-based decision-making can help to identify the best course of action for managing and minimizing environmental risks.



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# 2.0 WHAT IS CUMULATIVE EFFECTS ASSESSMENT?

**Cumulative effect assessments (CEAs) are defined as holistic evaluations of the combined effects of human activities and natural processes on the environment and are a specific form of environmental impact assessment (EIA) (Jones, 2016).**

The European Union, in its recently updated guidance document on wind energy development and conservation legislation, established procedures for identifying cumulative effects that are consistent with relevant directives (European Commission, 2020). One approach described in this document is the Common Environmental Assessment Framework (CEAF), developed under the North Seas Energy Cooperation (NSEC), a voluntary collaboration of 11 North Sea littoral states to promote offshore energy development. CEAF provides an online toolkit for considering the environmental impacts of Offshore Wind at North Sea scale and represents collaboration underpinned by a policy statement. It defines cumulative impacts as "impacts resulting from incremental changes caused by other past, present, or reasonably foreseeable actions along with the project" (CEAF, 2019).

In the United States, the Council on Environmental Quality (CEQ) previously defined cumulative effects as the "impact on the environment which results from the incremental impact of the action when added to other past, present, and reasonably foreseeable future actions regardless of what agency (federal or non-federal) or person undertakes such other actions. Cumulative impacts can result from individually minor, but collectively significant, actions taking place over time" (CEQ, 1997). In 2020, the CEQ published a final rule that amended regulations for the National Environmental Policy Act (1969) and removed references to direct, indirect, and cumulative effects (Federal Register, 2020).

Other methodological approaches have been developed in the frame of Tools4MSP (Menegon et al, 2018b).

# 3.0 WHY DO WE NEED CEA?

**Globally, there is an increased awareness that we need to move from managing single species and single pressures to a more holistic ecosystem-based management. This has led to recommendations to include holistic cumulative effects or impacts assessments in global, regional, and national conventions and legislation.**

Many international organizations, including the United Nations Environment Programme (UNEP), the World Health Organization (WHO), and the International Union for Conservation of Nature (IUCN), recognize the importance of considering cumulative effects in environmental assessments. For example, the UNEP Guidelines for Environmental Impact Assessment in the Arctic (2019) specifically require that cumulative effects be considered in all Arctic EIAs. Additionally, the Convention on Biological Diversity (CBD) requires its member states to assess and mitigate the cumulative effects of human activities on biodiversity. The CBD has also established guidelines for conducting SEAs that explicitly require consideration of cumulative effects.

Regionally, cumulative impact assessments in the European Union are required by the Environmental Impact Assessment Directive (Directive 2014/52/EU), the Strategic Environmental Assessment (Directive 2001/42/EC), the Water Framework Directive and the Marine Strategy Framework Directive (Directive 2008/56/EC). Furthermore, the Barcelona Convention (Mediterranean Sea), OSPAR (the North-east Atlantic) and HELCOM (the Baltic Sea) all aim at developing cumulative effects assessments. Individual countries may also have legislation that involves additional or complementary CEA requirements (see Annex for more in-depth description).

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CASE STUDY

## ESTIMATING MARINE-BIRD HABITATS IN GERMANY

Mercker et al. (2021) present an integrative statistical approach for estimating the current conditions of marine-bird habitats affected by human activities. This approach allows the assessment of the cumulative influence of several anthropogenic pressures. This approach has been used for different marine bird species located in the German section of the Baltic Sea and in the German-Dutch-Belgian part of the North Sea. A pilot assessment of this candidate indicator is part of the latest OSPAR Quality Status Report 2023 (Dierschke, Merkcker, 2022).

First, the influence of multiple human offshore activities on the species of interest using integrative regression techniques is estimated. Then these models are used to predict the distribution and abundance of the species throughout the study area, in both the current situation, with human activities, and in a hypothetical situation without the effects of the studied human activities. Finally, different measures related to the comparison between these two scenarios are developed. This approach highlights critical regions where locally high abundance is co-localized with large declines in abundance due to human activities, as well as a global metric quantifying the overall condition of the marine-bird habitat in the study area in relation to human disturbance. This approach allows us to assess the cumulative influence of several anthropogenic pressures, in this case offshore wind farms, bottom-trawling fishery, and ship traffic (Mercker et al., 2021).

# 4.0 HOW TO CONDUCT A CEA

**There are several different methods for performing CEA. In this chapter we summarise the main steps (see Figure 1) and present some of the available tools.**

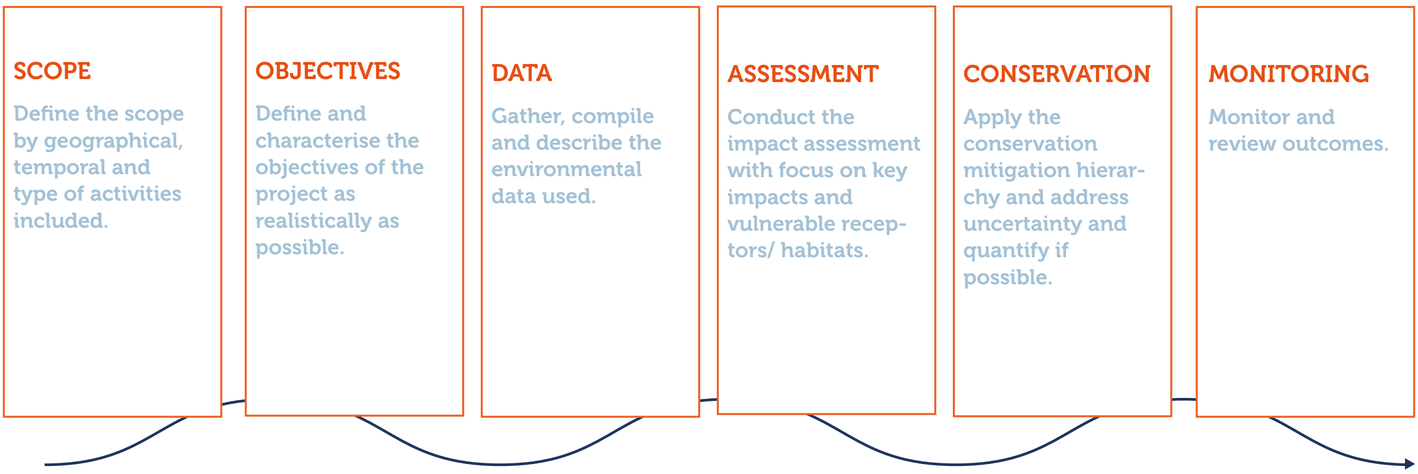


**Figure 1. The workflow of a Cumulative Effects Assessment (Milner-Gulland et al., 2021).**

When conducting a Cumulative Effects Assessment, the scope of the assessment must first be defined. The geographical and temporal extent, and activities to include influence which method to use. Then the project must be characterised and the data gathered and described. At this point the assessment itself can be done, while addressing the uncertainties of the methodology. Only at this point can we apply the conservation measures.

## MARINE SPATIAL PLANNING (MSP) AT STRATEGIC AND PROJECT LEVEL

At the strategic level, the goal is to look at the big picture and assess the cumulative impacts of multiple uses of the marine system in a given area or region. Project-based CEA considers the impacts of a particular project in the marine area relative to other existing and future projects that are anticipated or reasonably foreseeable.

The marine space referred to herein is a specific location or site where a proposed or planned activity is to occur, or a geographic scale on which the spatial analysis will be conducted, depending on the scope of the analysis.

## MARINE SYSTEM DEFINITION

In order to assess the potential impacts of the activity on the environment and surrounding community, it is necessary to define the zone of interest of the sea and its spatial and temporal boundaries. It is important to use an ecosystem-based approach that considers both the biotic and abiotic components of the ecosystem as well as the social and economic components. The ecosystem of the area includes the characteristics of circulation properties, depth, and any other relevant physical factors that may affect the ecosystem. Boundary conditions and inputs should also be considered, including the coastal zone, atmospheric inputs, and any other marine processes occurring in the surrounding systems.

Existing impacts or activities in the area should be identified, including any sources of pollution or runoff from nearby activities. The Marine Strategy Framework Directive (MSFD, 2008/56/EC, Annex III) provides a useful framework for the identification of the Pressures and Impacts related to human activities. Relevant information can be obtained from local, regional, and national authorities, as well as from existing impact assessments (EAS), studies and literature. This means measuring the spatial and temporal impacts of exposures from the above activities, determining the magnitude, duration, and frequency of exposures, weighting the various impacts in space and time, and understanding the impacts on all receptors. It is also important to recognize that a CEA refers to "all impacts of all activities" and to determine if there is a tipping point or threshold when all impacts are taken together. The use of multi-criteria tools and the integration of dynamic and statistical models can help manage this complexity. Proposed new activities should also be considered, and the type of data needed will depend on the specific activity being suggested. Data sources may include sectoral agencies, such as those responsible for tourism, agriculture, fisheries, aquaculture, ports, docks, maritime activities, land-based transportation, and environmental concerns.

## PRESSURES, IMPACTS AND EFFECTS IDENTIFICATION

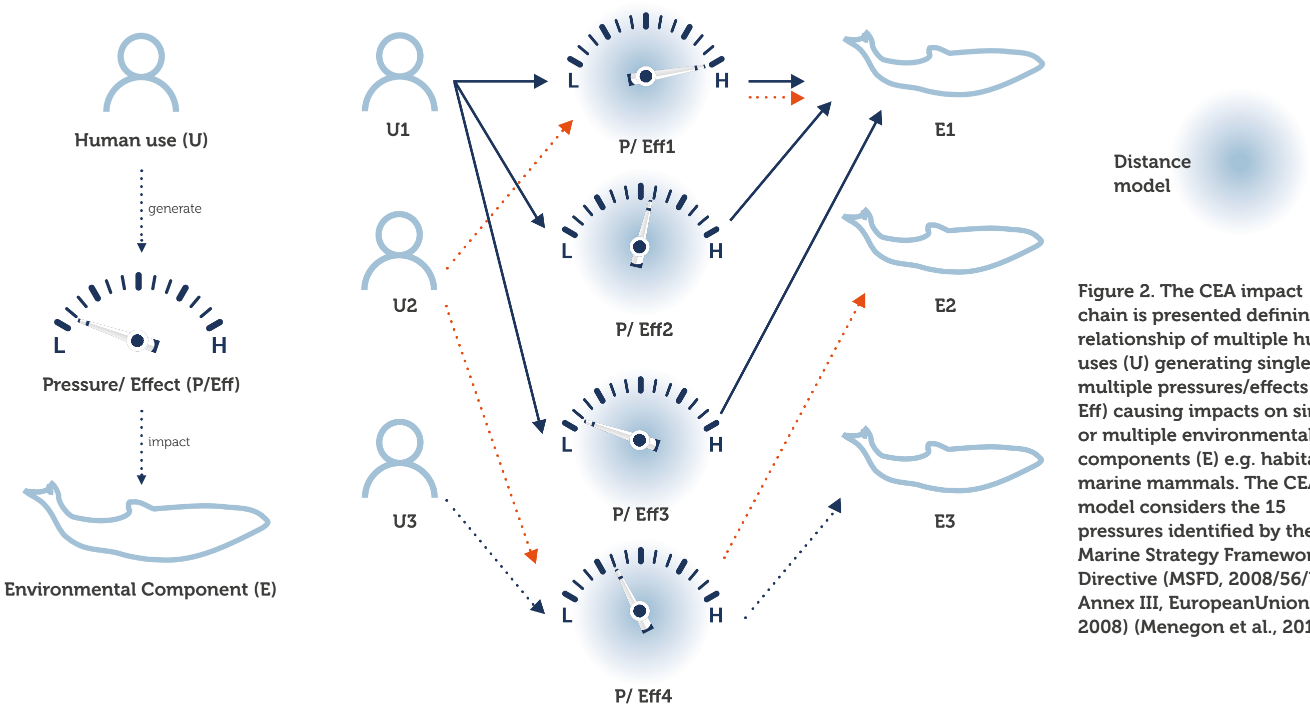


Figure 2. The CEA impact chain is presented defining the relationship of multiple human uses (U) generating single or multiple pressures/effects (P/Eff) causing impacts on single or multiple environmental components (E) e.g. habitats, marine mammals. The CEA model considers the 15 pressures identified by the Marine Strategy Framework Directive (MSFD, 2008/56/EC, Annex III, EuropeanUnion, 2008) (Menegon et al., 2018a).

## DATA COLLECTION

Several types of data may be required, including baseline data, spatial data, environmental monitoring data, human activity data, social and economic data, and model simulation results. Sources for these data include local, regional, and national agencies, as well as previous reports and the knowledge and experience of locals, experts, and other stakeholders.

To conduct a comprehensive CEA, it is essential to have access to high-quality data on the various stressors and ecosystem components. However, data availability can vary widely across different marine areas, making it challenging to conduct a standardized CEA. In well-surveyed areas, researchers may have access to detailed data on the various stressors and ecosystem components, which can be used to conduct a comprehensive CEA. Moreover, data relevant for cumulative effects assessments are often hidden in resource management agency reports, environmental consultant files, or unpublished or unshared data from scientific publications. This can make it difficult to access and use data, further complicating the process of conducting a CEA. In areas with limited data availability, researchers may need to rely on less-detailed data or models to conduct a CEA.

The use of dynamic models and machine learning tools can support a deeper understanding of how, where, why, and when particular responses occur and to track links and feedback among the different social-ecosystem components. Mapping tools and the proper representation of the temporal and spatial scales of the pressures and of the ecosystem state, reveals the properties and processes crucial for a Cumulative Effects Assessment.

## SCENARIO ANALYSIS

In describing the proposed or planned marine system, it is important to consider the development phase and future projections of surrounding boundary conditions and influences, including the climate scenario. For development projects, the operational or production phase and the decommissioning phase should also be considered. For each of these phases, key impacts should be identified, taking into account factors such as discharges (air, water, soil, seabed), activities, light, noise, and human presence. A CEA must be adaptive, i.e., able to add, reduce, or remove pressures/impacts in response to advances in knowledge and methods. The process must account for the fine-tuning of a project and include both operational and regulatory management decisions.

## COMMUNICATION AND STAKEHOLDER INVOLVEMENT

Overall, transparency and documentation are critical. All data sources, methods, and results should be clearly documented and made available to stakeholders and the public. Involvement of residents, experts, and stakeholders is also important to ensure that potential impacts are properly identified and addressed.

## CASE STUDY

### CUMULATIVE IMPACTS INDEX FOR THE ADRIATIC SEA

The Cumulative Impact Assessment for the Adriatic Sea evaluated cumulative impacts posed by climate and anthropogenic factors (Furlan et al., 2018). This assessment utilized the Cumulative Impact Index (CI-Index) to integrate multiple data sources and analytical methods, providing a holistic view of the environmental risks in the region.

The process incorporated spatial data characterizing the location and vulnerability of key marine targets such as seagrasses and coral beds, alongside the distribution of 17 human activities like trawling and maritime traffic. The assessment was conducted for a reference period (2000-2015) and projected into a future scenario (2035–2050) under the RCP8.5 climate change scenario. This projection included physical and biogeochemical parameters like temperature and chlorophyll 'a' concentration.

#### 5 key steps to a Cumulative Impacts Index

**1. Multi-hazard Interaction Assessment:** spatial modeling of pressures and their interactions, such as the combined effects of shipping traffic, aquaculture activities, and sea surface temperature variations using the Choquet integral to model interactive effects and non-linear behaviors in dynamic marine systems.

**2. Exposure Assessment:** identification and mapping of vulnerable receptors and environmental/socio-economic valuable hot spots that could be threatened by the hazards considered. The selection of relevant receptors is based on the purpose of the assessment, spatial scale of the analysis, and data availability.

**3. Vulnerability Assessment:** selection of the relevant physical and environmental factors, such as seabed typology and biodiversity indices, to characterize exposed marine targets (Furlan et al. 2018). These factors are classified and normalized into vulnerability classes based on expert judgment and literature into a single normalized score, ranging from 0 (no vulnerability) to 1 (highest vulnerability).

**4. Risk Assessment:** risk is evaluated using a function that aggregates hazard, exposure, and vulnerability scores. This function calculates a risk score for each cell that reflects both individual and interactive hazards. Values range from 0 (no risk) to 1 (highest risk). The output is an array of six risk layers linked to each hazard, identifying and ranking areas most affected by multiple risks.

**5. Cumulative Impact Assessment:** all previously gathered assessments are integrated into the CI-Index according to the approach of Halpern et al. (2008). Scores for each cell are computed for both reference and future scenario. The score incorporates the six risk layers from individual and interactive hazards, therefore ranging from 0 (no cumulative impact) to 6 (highest cumulative impact).

The application of the CI-Index in the Adriatic Sea revealed several critical insights. Higher cumulative impacts were predominantly observed in the Northern Adriatic Sea, largely due to the concentration of human activities and the presence of vulnerable benthic habitats. The future scenario under climate change conditions indicated an increase in cumulative impact scores, reflecting the potential exacerbation of existing pressures. The assessment produced GIS-based maps and statistics, enabling the visualization of multi-hazard interactions, exposure, vulnerability, and cumulative impacts across both the reference and future scenarios.

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# 5.0 CHOOSING A FRAMEWORK TO CONDUCT A CEA

**A Cumulative Effects Assessment can be conducted adopting different frameworks and using different types of methods, like analysis of single and multiple pressures and stressors, data integration, modelling and communication. The types of methods are listed and described in further detail in Table 1.**

**Table 1. Types of methods needed to conduct a Cumulative Effects Assessment.**

| Methods | Description |
|---|---|
| Analysis of single and multiple pressures and stressors | Laboratory assessment and/or field assessment of multiple stress effects. Literature review. Metanalysis and other statistical tools. Tools to relate drivers to pressures. |
| Data integration | Integration of data from multiple sources including physical, chemical and biological parameters, and social-economic data into a database or a Geographical Information System (GIS). This can be challenging, especially if data are collected at different spatial and temporal scales. |
| Modelling | Modelling tools are essential for predicting the cumulative effects of different pressures, stressors and their potential interactions. They can help identify areas of high vulnerability and guide management decisions. Tools can be conceptual, as the DAPSI(W)R(M) (to frame the system and its functionalities) or numerical (biogeochemical, oil spill, high trophic level) to quantitatively represent the system. Numerical models may be based on statistical methods, machine learning or deterministic models. |
| Communication | Communicating the results of cumulative effects assessments to stakeholders, policymakers, and the public is essential for raising awareness and promoting effective management. Visualization tools and other communication strategies can help to convey complex scientific information in an accessible and engaging way. |

## ANALYSIS OF SINGLE AND MULTIPLE STRESSORS AND PRESSURES

Cumulative effects assessments involve establishing and evaluating links between multiple activities with multiple effects on multiple ecosystem components.

For any given sea basin, there is potentially a mix of local human activities (shipping, fishing, etc.) that can create pressures (noise, alteration of seabed habitat, etc) that can potentially impact a species or habitat (disturbance of spawning, loss of habitats etc). In addition to local activities, species and habitats can also be impacted by pressures that are of a regional or even global scale. To assess the potential degree of impact from multiple sources in an area, it is necessary to identify all relevant human activities known to have an impact on ecosystem components or the physiochemical properties of the ecosystem.

### Source-pressure-pathway-receptor framework

The source-pressure-pathway-receptor framework is a useful tool for understanding the complex relationships between human activities and their potential impacts on the environment. Several applications, reviews and studies elaborate the framework adopting different terminologies, depending on the scope. As a general approach, the source-pressure-pathway-receptor framework defines the four key components of this relationship: the source of the pressure, the pressure itself, the pathway through which the pressure is transmitted, and the receptor that is affected by the pressure. Each of these components is critical for understanding the potential impacts of human activities on the environment, and for developing effective management strategies to address these impacts.

## 7 STEPS TO ANALYSE MULTIPLE PRESSURES

1. Define the system and the ecosystem components, including the ecological, social, and economic systems, that may be affected by the stressors.

2. Identify all the stressors that can affect the system, including natural stressors such as climate change, and anthropogenic stressors such as pollution, land-use change, and water extraction.

3. Evaluate the stressors by quantifying their magnitude, frequency, duration, and spatial extent. This helps in identifying the most significant stressors.

4. Characterize and separate the different pressures by assessing the individual and combined effects of the stressors. This can be done using modelling tools, field studies, or experiments.

5. Identify the dominant pressures by ranking the stressors based on their magnitude, frequency, and spatial extent. The most significant stressors should be given priority in the cumulative effects assessment.

6. Identify non-additive combined effects such as synergism and antagonism by assessing the interactive effects of different stressors. This can be done using models, experiments, or field studies.

7. Assess the consequences of omitting some stressors by modelling the impact of the dominant stressors on the system. This can help identify any gaps in the cumulative effects assessment and help prioritize future studies, data bases and GIS support.

The pressure is defined as the event or agent (biological, chemical, or physical) exerted by the source to elicit an effect that may lead to harm or cause adverse impacts. The effect is the outcome of the pressure, which may or may not lead to an impact on a receptor. The pathway is the mechanism by which a receptor is exposed to the pressure and effect, while the receptor is the physical, ecological, economic, or social/cultural entity that is sensitive to the hazards under investigation. Finally, the impact is a measurable, detrimental change to a species or habitat attributable to human activities.

By understanding the relationships between these components, it is possible to identify which receptors could be at risk from exposure to specific pressures and develop management strategies to reduce or prevent impacts. The source-pressure-pathway-receptor framework is particularly important in the context of cumulative effects, where a multitude of sectors and activities contribute to a complex array of different sources for different pressures that act via multiple pathways on the various receptors. In this context, the framework helps to reduce the complexity of the problem and focus on the most critical linkages between sources, pressures, pathways, and receptors.

The models DPSIR and DAPSI(W)R(M) (Elliot et al., 2017) adopt the concepts of Driving forces, Pressures, State, Impact, and Response, and of Drivers, Activities, Pressures, State, Impact, and (Wider) Responses, including Monitoring. Both frameworks are used in environmental management. Halpern et al. (2008) presents a framework for understanding and managing marine ecosystems at a wider scale. While DPSIR and DAPSI(W)R(M) emphasize the causal relationships between environmental factors and human activities, Halpern et al. (2008) emphasizes the complex interactions among various components in marine ecosystems and the need for a holistic approach to ecosystem management. DAPSI(W)R(M) includes monitoring as a key component, but DPSIR and Halpern et al. (2008) do not explicitly include it as a separate component.

### Varied data sources

In order to conduct a thorough marine cumulative effect assessment (CEA), several types of data are typically needed. These can include Baseline data, Spatial data, Environmental monitoring data, Data on human activities, Social and economic data, and Model simulation outputs. They provide information on the reference or present state of the marine environment, including physical, chemical, and biological characteristics. Data on human activities include information on the nature, location, and intensity of human activities in the marine environment, like touristic and port activities, shipping, fishing, oil and gas, mineral extraction, and renewable energy. Spatial data include geospatial data, such as bathymetry, shoreline features, and presence of human activities and marine protected areas. Environmental monitoring data report on changes in environmental conditions like water quality, sediment composition, geochemical conditions, and marine biodiversity, over time. Social and economic data include information on the social and economic impacts of human activities, including fisheries, aquaculture, and tourism, on local units.

### Missing or imperfect data

Any assessment of ecosystem condition faces the challenge of missing or imperfect data. This is a particular challenge for spatially explicit information about habitats, and a wide range of human uses and associated stressors (Halpern and Fujita, 2013). Halpern and Fujita identify three potential solutions to this challenge, each with its own shortcomings:

1. Find a proxy measure for which existing data is assumed to be sufficiently accurate,
2. fill gaps in the data through one of many statistical or geospatial modelling

techniques, given that missing data can be extrapolated from existing data, or

3. forego using any data, thereby assuming that overall assessment will be accurate enough despite excluding a key issue.

In each case one must be transparent about the assumptions made. Sensitivity analyses can be used to assess the potential importance of missing information. However, a review of CEAs showed that only 6 out of 46 studies tried to assess more than two sources of uncertainty (Stelzenmüller et al., 2018). In addition, there is likely a mismatch between the need for information on stressor intensity needed for cumulative impact assessments, and information on human activities needed for management purposes.

**Uncertainty**

The uncertainty in CEAs results from the required assumptions. Even when data uncertainty is known and communicated, one must decide how strictly or loosely to apply criteria for data inclusion. If high levels of certainty are required, little data will meet those standards, and the overall cumulative impact assessment will provide little new insight. If instead data with higher uncertainty are included, which is usually the case, then the overall assessment may be driven by the weakest data. It is imperative that these uncertainties are communicated clearly, especially when integrating cumulative impact mapping into decision making, to ensure results are interpreted correctly (Halpern and Fujita, 2013).

In a review of eleven recent case studies, Steltzenmüller et al. (2020) found that reconciling data of different geographic scales (local to regional), seasonal dimensions (spawning, secondary production) and temporal resolutions (past and current dynamics) seemed to be the main challenge for most case studies. Moreover, they highlight that the essential prerequisites for establishing cause-and-effect relationships involve having a comprehensive understanding of causality and having data to substantiate such conclusions.

Both of these aspects introduce uncertainties into the interpretation and communication of cumulative effects assessment results. Nevertheless, it's crucial to acknowledge that uncertainty is an inherent element of any decision-making process. Therefore, it necessitates a transparent and explicit approach to handling both knowledge and data.
To address this challenge, the authors propose a confidence matrix (Figure 3) as a tool for effectively communicating uncertainty concerning our understanding of causality and the quality of pressure data. The CEA-based scientific advice for policy-related processes can be based on low level of confidence, while the regulatory processes need the highest level of confidence.

Figure 3 shows a Confidence matrix highlighting the use of various CEAs based on the uncertainty of the data and assumptions. The different colours of the quadrants represent different levels of uncertainty and different confidence levels on the CEA, which therefore can be used for different purposes.

**1. Dark Blue Quadrant:** When giving advice for rules and regulations (like environmental standards), we should have a very good understanding of the science with very little uncertainty. In other words, we should be pretty confident in our scientific knowledge.

**2. Middle Blue Quadrant:** It's acceptable to have more uncertainty in the scientific evidence when we're making plans, like spatial planning for different activities. Some uncertainty is acceptable.

**3. Light Blue Quadrant:** Scientific results that are not very certain can still be useful when guiding the creation of environmental policies.

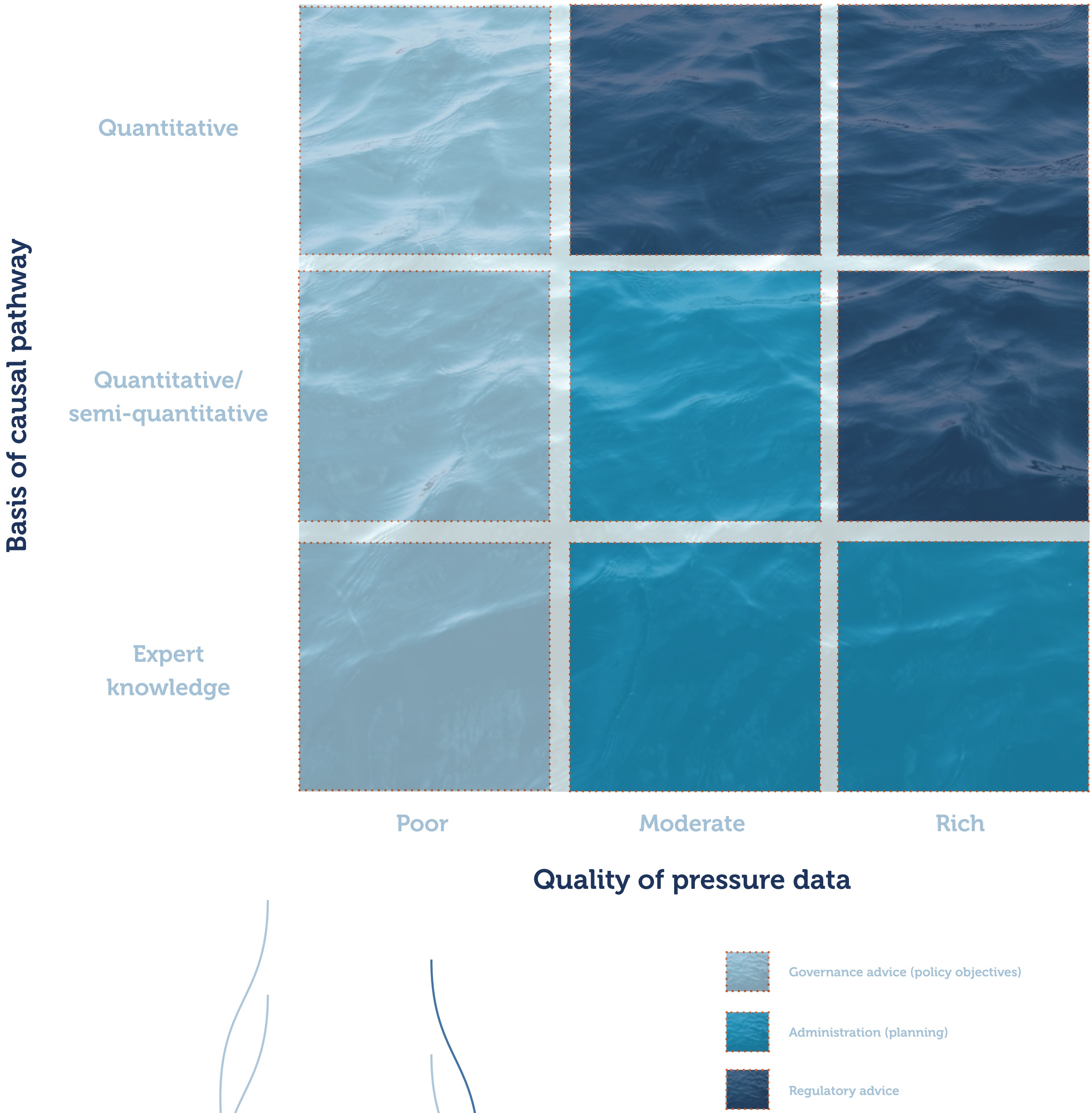


Figure 3. Confidence matrix which ranks the quality of the pressure data as: Poor (spatiotemporal resolution showing a mismatch with spatiotemporal data on ecosystem components), Moderate (spatiotemporal resolution showing a partial overlap with spatiotemporal data on ecosystem components), and Rich (spatiotemporal resolution showing a sufficient overlap with spatiotemporal data on ecosystem components). Causal pathways can be derived from expert knowledge, semi-quantitative, or quantitative assessments (Steltzenmüller et al., 2020).

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## COMMON AND CONSOLIDATED CEA FRAMEWORK

The ICES Working Group on Cumulative Effects Assessment Approaches in Management (WGCEAM) is working on the development of a common and consolidated CEA framework to implement such assessments in different planning and regulatory contexts, considering the different settings regarding data, knowledge, and decision-processes. This CEA framework is based on identifying and prioritizing the pressures that would need to be addressed by management measures, based on the vulnerability of the ecosystem components to those pressures.

The CEA framework is a flexible application where different data, evidence and knowledge availabilities can be accommodated, and that spans from qualitative, to semi-quantitative, to fully quantitative approaches, depending on the available data for each of the causal pathways in such assessments.

The qualitative approach relies on expert solicitation, which depends on the current knowledge of causal pathways and also considers evidence from similar situations. Semi-quantitative approaches use pre-established criteria and tabulation techniques, initially developed through expert solicitation that would be applicable to the specific areas or species. The quantitative approach is primarily a data driven process to generate the evidence of the effect-potential based on the spatial and temporal distribution of the pressures.

# 6.0 MODELS USED IN CEA

**Different models can be used in Cumulative Effects Assessment. Here we present a selection of models that are useful in marine and aquatic habitats.**

## OCEAN MODELS

Ocean models are used to simulate the behaviour and interactions of marine ecosystems, including the physical, biochemical, and ecosystem processes that occur in the ocean. Models can be used to study a wide range of marine systems, from individual species and populations to entire ocean basins. Ocean models are a powerful tool for understanding the complex dynamics of marine ecosystems and predicting how these ecosystems may respond to various environmental stressors such as climate change, pollution, and overfishing.

The use of models can help understand the combined effects of various stressors on marine ecosystems, including the effects of climate change, pollution, overfishing, and other human activities. Models can be used to simulate the behaviour of marine systems under different combinations of stressors and project how these systems might respond over time, using scenario analysis. Different types of models can also be used in combination, with offline and online coupling possible. They can be used to explore different management options, using ecosystem-based and risk-assessed approaches.

## ECOSYSTEM-BASED MANAGEMENT MODELS

Ecosystem-based management models can be used to evaluate the impacts of different management strategies on marine ecosystems, including the establishment of marine protected areas, the implementation of fishing quotas, and the reduction of nutrient pollution. By simulating the behaviour of marine systems under different scenarios, these models can help identify potential vulnerabilities and opportunities for conservation and management and inform decision-making for sustainable use of marine resources.

## SCENARIO ANALYSIS

Scenario analysis can be used to explore how marine ecosystems might respond to different future conditions. This approach uses ocean models to simulate ecosystem behaviour under different assumptions about future ecological and socioeconomic conditions, such as changes in sea temperature, sea level and ocean acidification, as well as land and sea use. By running simulations under different scenarios, scientists and policy makers can examine how marine ecosystems might respond to different environmental stressors and identify potential vulnerabilities and opportunities for conservation and management. One of the main strengths of scenario analyses is their ability to simulate ecosystem behaviour over long periods of time and at large spatial scales.

## OCEAN PHYSICS MODELS

Ocean physics models like MOM, MITGC, Nemo Ocean and SHYFEM, provide information about ocean circulation, sea currents, wave conditions, sea level and tides at various time periods, from hours to days or even weeks or decades. These model results are important for coastal planning and management, and for understanding the impacts of sea level rise and climate change on coastal communities.

## MARINE ECOSYSTEMS MODELS

Marine ecosystem models simulate the behaviour of marine ecosystems, including interactions between different species and the physical and chemical properties of the environment. The results of these models can be used to support fisheries management, marine conservation, and marine spatial planning. For example, OSMOSE (Shyn et al., 2001, Travers-Trolet 2014), Ecopath and Ecosim and Ecological Network Analysis (ENA) (Nogues et al., 2023) provide powerful tools for studying and understanding ecological systems. They have been used in everything from studying the effects of climate change on marine ecosystems to predicting the outcomes of different fisheries management strategies.

The ICZM platform provides practical guidance of the Marine Spatial Planning (MSP) process adopting the Ecosystem Approach. This approach includes the analysis of the pressures, cumulative impacts of human activities on the marine resources, the analysis of conflicts, and synergies between different uses. Both current conditions and future scenarios are recommended to be included in these analyses and a quantitative approach preferred.

## WATER QUALITY MODELS

Water quality models simulate the behaviour of pollutants and nutrients in marine systems and provide predictions of their concentration and distribution. These model outputs can be used to support environmental management and monitoring programs, including management of harmful algal blooms and assessment of pollution impacts on marine ecosystems.

Marine biogeochemical models like BFM Community and Darwin Project simulate the complex interactions between living organisms and the chemical and physical properties of the ocean, such as nutrient availability, phytoplankton growth and carbon cycling, to predict the distribution and abundance of marine life. Pollutant models like Medslik are important tools for managing marine pollution and assessing the impacts of human activities on coastal and marine ecosystems. They are used to predict the effects of oil spills from oil tankers, discharges of pollutants from wastewater treatment plants, and releases of pollutants from industrial activities. By predicting the fate and transport of pollutants, these models can help policy makers and environmental managers make informed decisions about how to mitigate the effects of pollution and protect marine ecosystems.

Models can be tailor-made or can be obtained from open access repositories like the Marine Copernicus repository* which provides open access to a wide range of marine data and products for the global ocean and for regional European marine areas, including model outputs. For specific coastal cases, however, the resolution of model products provided by the Marine Copernicus could not be sufficient and un purpose, high resolution models should be preferred.

* Marine Copernicus, the marine segment of Copernicus, the Earth observation division of the European Union's Space program. Its primary objective is to offer comprehensive, reliable, and consistent data on the condition of the world's oceans, encompassing the physical (Blue), sea ice (White), and biogeochemical (Green) aspects, both on a global and regional level. Access to this valuable information is freely available to the public on a regular and structured basis.

Photo credit: ©Oleksandr Sushko

# 7.0 COMMUNICATING RESULTS

**When communicating the results from a CEA it is important to be transparent on its purpose and scope. Was it done to provide planning or management options for activities, or to assess and predict total effects from all or a subset of multiple pressures?**

It is vital to describe the linkages between the human activities, pressures, and ecosystem components up to ecosystem services, and if simplifications are made for illustrative, scientific or policy reasons, these must also be described. There are multiple methods to communicate results of a CEA.

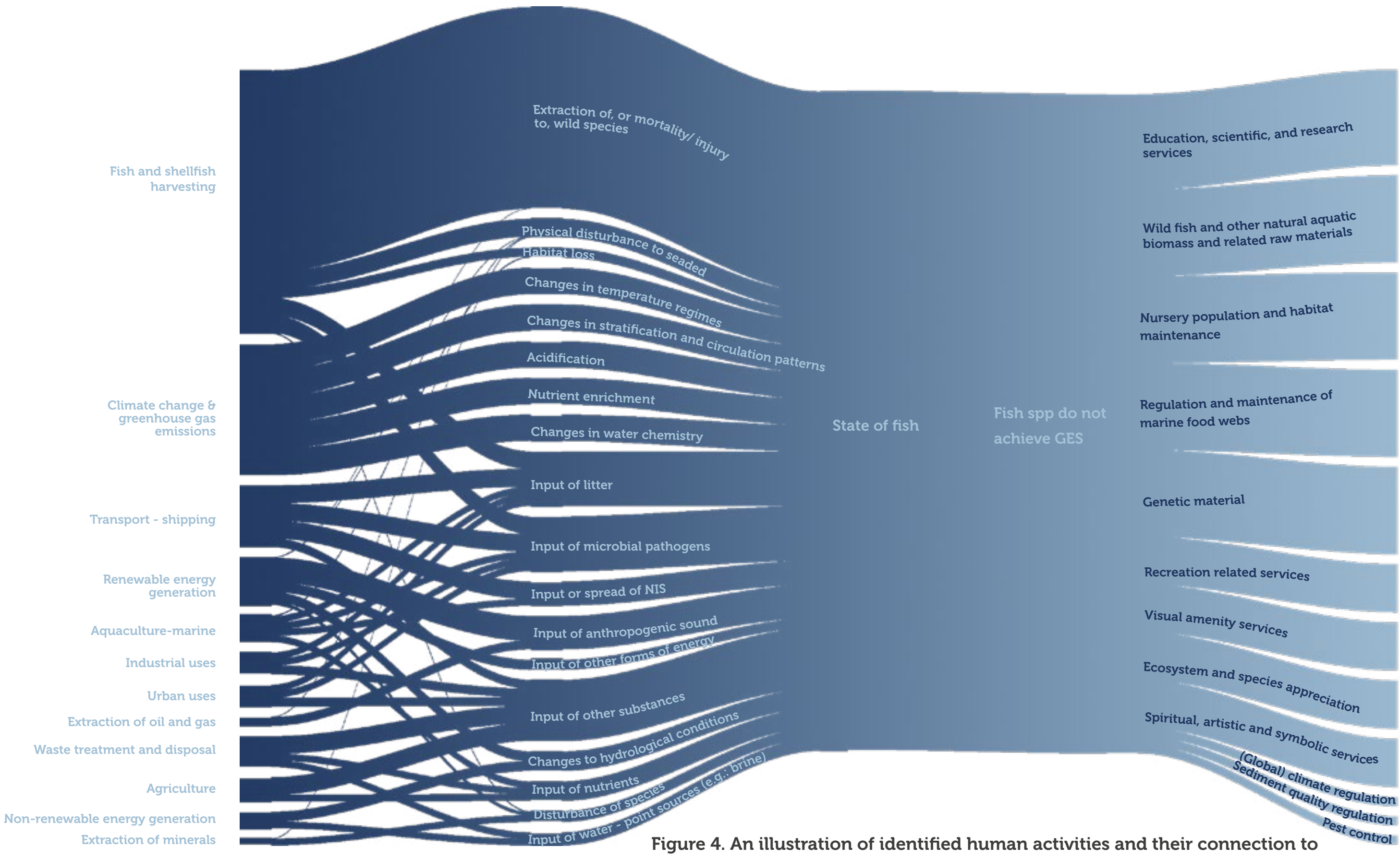


**Figure 4. An illustration of identified human activities and their connection to pressure types, Sankey diagram, from the OSPAR thematic assessment of the interactions between the Drivers, Activities, Pressures, States, Impacts, and Responses (DAPSIR) components in the Northeast Atlantic ecosystem. The diagram illustrates cumulative effects by showing how multiple human activities contribute to pressures that in turn affect fish condition and associated ecosystem services. Wider arrows represent stronger connections and give stakeholders a quick understanding of where the most important impacts or influences occur.**

The Sankey diagram (Figure 4) described in the OSPAR thematic assessment on Fish and shellfish harvesting in the Northeast Atlantic, shows the complexities of the interactions between the Drivers, Activities, Pressures, States, Impacts, and Responses (DAPSIR) components in the Northeast Atlantic ecosystem. The diagram visually depicts the flow of information and interactions between the different components of the system, providing an overview of the relationships between human activities, pressures, ecosystem states, impacts and responses. The diagram illustrates cumulative effects by showing how multiple human activities contribute to pressures that in turn affect fish condition and associated ecosystem services. This is important for stakeholders to understand the collective impact of different activities on the ecosystem.

By following the DAPSIR, the Sankey diagram facilitates a holistic understanding of ecosystem dynamics. It allows stakeholders to recognize the interplay of different elements and how they contribute to the overall health and functioning of the ecosystem and help stakeholders prioritize management efforts based on the most important factors.

The diagram should be interpreted along with the full report on cumulative pressures, to ensure a full understanding of the system. Confidence levels for the evidence and the degree of agreement in the analyses should be provided along with the diagram in the full report. This transparency helps stakeholders understand the reliability and the level of uncertainty of the information.

# 8.0 CONCERTED EFFORT NEEDED

Assessing cumulative effects of pressures in marine systems presents several challenges and uncertainties. Limited data, limited knowledge of the synergies and interactions among pressures and receptors, and lack of understanding of the complexity and interconnected nature of marine ecosystems contributes to this (Stock and Micheli 2016, Steltzenmüller et al., 2020) and are summarised in Table 2. Addressing these gaps and challenges requires a concerted effort from researchers, policymakers, and other stakeholders to improve data collection, enhance modelling techniques, and foster collaboration for a more comprehensive understanding and effective management of cumulative effects in marine systems.

Despite the challenges, conducting a Cumulative Effects Assessment remains an essential component of marine spatial planning. Researchers must work to overcome these challenges by collaborating across agencies and organize to share data, conduct targeted surveys to fill data gaps, and develop innovative modelling approaches to generate more comprehensive assessments of cumulative impacts. In their 2019 paper, Hodgson et al. argue that to address the complexities of cumulative effects research, interdisciplinary and transdisciplinary frameworks are needed. These frameworks should prioritize the formalization of cumulative effects research as a subdiscipline, which would help to create communities of researchers who are actively engaged in this area of study, and who can collaborate more effectively.

Another priority identified is the need to develop a shared framework and language for cumulative effects research. This would ensure that researchers from different disciplines can communicate effectively and work together towards common goals. In addition, the authors emphasize the importance of open access to data, as this would enable researchers to build on each other's work and facilitate the development of more robust and reliable models of cumulative effects.

Table 2 gives a more schematic and detailed overview of gaps and challenges in Cumulative Effects Assessment.

# DETAILED OVERVIEW OF GAPS AND CHALLENGES IN CUMULATIVE EFFECTS ASSESSMENT

**Table 2. Detailed overview of gaps and challenges in Cumulative Effects Assessment.**

| | |
|---|---|
| Data Gaps and Inconsistencies | Limited availability and quality of data on various pressures and ecological components can hinder accurate assessments. Poor or absent knowledge on some pressures may increase uncertainty on the assessment. |
| Tools to detect the Spatial and Temporal Variability | Marine systems exhibit considerable spatial and temporal variability, making it challenging to capture the full range of ecological responses and pressures. The analysis should be conducted at an appropriate spatial and temporal resolution, according to the resolution of the pressures and responses. |
| Interactions and Synergies | Cumulative effects assessments often assume additive pressure effects, but interactions and synergies between different pressures can lead to non-linear and unexpected outcomes. Most of the outcomes are poorly known, and ecological studies and more data are needed to assess them. |
| Lack of Baseline Data | Incomplete or missing baseline data for certain pressures and ecological components make it difficult to establish reference conditions for assessing changes. Data of pristine conditions are needed to assess the response to the alteration. |
| Sensitivity Weights and Expert Judgment | Reliance on sensitivity weights derived from expert judgment introduces subjectivity and uncertainty, especially when the understanding of ecosystem responses is incomplete. |
| Non-linear Ecological Responses | The assumption of linear ecological responses to pressure may not hold true, as ecosystems often exhibit non-linear responses that may include thresholds and irreversible changes. |
| Spatial and Temporal Scales Mismatch | Mismatches in the scales of pressure data and ecological response data can lead to inaccurate assessments, particularly when pressures and ecological features operate at different scales. |
| Cascading Effects | Cumulative effects assessments may struggle to capture cascading effects through trophic levels and ecosystem components, resulting in an underestimation of overall impacts. |
| Model Complexity and Uncertainty | Complex ecological models used in cumulative effects assessments introduce uncertainties, and the sensitivity of results to model parameters may be challenging to quantify. |
| Ecosystem Connectivity | Many marine ecosystems are interconnected, and pressures in one area may have far-reaching effects in distant areas, making it challenging to attribute impacts to specific sources. |
| Climate Change Interactions | The influence of climate change on marine systems introduces additional complexity, with changing ocean temperatures, acidification, and other climate-related factors interacting with existing pressures. |
| Management and Policy Integration | Integration of cumulative effects assessments into marine management and policy frameworks is often challenging due to the need for interdisciplinary collaboration and coordination among various stakeholders. |
| Public Engagement and Communication | Communicating complex cumulative effects assessments to the public and decision-makers can be challenging, requiring effective strategies to convey uncertainties and potential impacts. |

Photo credit: © Silas Baisch

# 9.0 ANNEX

## CONCEPTUAL FRAMEWORKS FOR CEA IN THE EUROPEAN SEAS

European regional sea conventions, such as the conventions for the Baltic Sea (HELCOM), the North-East Atlantic (OSPAR Convention) and the Mediterranean Sea (Barcelona Convention), have recognized the importance of considering cumulative effects, and have incorporated provisions related to Cumulative Effects Assessment (CEA) to some extent. However, the specific details and approaches may vary among these conventions.

### BALTIC - HELCOM

The latest published state assessment of the Baltic Sea was published in 2018 (HELCOM 2018). For the assessment on cumulative impacts, they used two different methods: the Baltic Sea Pressure Index and the Baltic Sea Impact Index. The Baltic Sea Pressure Index evaluates the distribution of pressures and assesses where their current cumulative distribution is highest. The Baltic Sea Impact Index estimates the cumulative impacts in the Baltic Sea, by using information on which species and habitats are likely to be present in an area. Both methods are using information on the spatial distribution of human activities and pressures in the Baltic Sea during 2011–2016. They are building on the use of area-based information on both pressures and species and habitats, similar to the approach of Halpern et al. (2008).

The Pan Baltic Scope focuses on cross-border collaborations and activities. The Pan Baltic Scope develops tools and approaches at pan-Baltic level, to contribute to coherent maritime spatial plans in the Baltic Sea Region, including:

- Implementation of an ecosystem-based approach;
- Cumulative impacts (http://www.panbalticscope.eu/wp-content/uploads/2019/11/PBS_Cumulative_Impacts_report.pdf)
- Green infrastructure;
- Economic and social analyses;
- Data sharing.

The Cumulative impact Assessment Toolbox (BSII CAT) that was developed to facilitate regionally coherent assessments of cumulative impacts, includes tools for calculating the Baltic Sea Impact Index and the Baltic Sea Pressure Index. It also supports the identification of areas with high ecological value or high potential provision of ecosystem services.

### NORTH-EAST ATLANTIC - OSPAR

OSPAR publish their Quality Status Report (QSR 2023) for the environmental state of the North-East Atlantic. OSPAR is using a Driver-Activity-Pressure-State-Impact-Response (DAPSIR) framework and a semi-quantitative weighted Bow Tie Analysis (Cormier et al., 2018, Cormier et al., 2019) as an indicative assessment of cumulative effects. This has been undertaken as a first step to describe potential pathways of cumulative causes and consequences of change in the ecosystem linking these to impacts on ecosystem services. The reason for choosing this approach is mainly because huge areas of the North-East Atlantic are lacking area-based information on pressures, species and habitats.

## THE MEDITERRANEAN - MAP

The Mediterranean Action Plan (MAP) was adopted in 1975 by 16 Mediterranean countries under the auspices of the United Nations Environment Programme (UNEP), and aims to protect the environment and promote sustainable development in the Mediterranean region. The legal framework of MAP includes the Barcelona Convention, adopted in 1976 and revised in 1995, and six protocols on specific aspects of environmental protection. In addition, a Mediterranean Commission for Sustainable Development was established in 1995 to facilitate the participation of all Mediterranean stakeholders. The MAP is a regional cooperation project involving 21 Mediterranean countries.

The ultimate goal of MAP is the achievement of good environmental status (GES) of the Mediterranean Sea and its coast. The Integrated Monitoring and Assessment Programme for the Mediterranean Sea and Coast (IMAP) operates under this approach, which shares many common elements with the EU Marine Strategy Framework Directive. The ecosystem approach (EcAP) is a key principle of the Barcelona Convention's ICZM Protocol to ensure that coastal planning and management enable sustainable coastal development. It applies to all related planning processes for land- and sea-based activities and thus underpins the implementation of MSP as a whole.

Several studies have quantified and mapped cumulative impacts across the Mediterranean and Black Seas (Micheli et al., 2013) to provide guidance, and support local and regional ecosystem-based management. A regional assessment of cumulative impacts has been conducted for coral reefs in the Mediterranean Sea along 1000 km of the Italian coast (Bevilacqua et al., 2018). The Mediterranean Action Plan (MAP) has also developed guidelines for conducting environmental impact assessments (EIAs) for the Mediterranean offshore area. The cumulative impact assessment is the main methodological tool used in ADRIPLAN to assess the potential impacts of maritime activities on the environment.

## TOOLS AND METHODS IN MORE DETAIL

There are many tools and methods that can be used for Cumulative Effects Assessment. In Table 3 there is a selection of useful tools and methods, further described below. The list is not exhaustive but is meant to give an overview, and we recommend following the references to learn more about them.

**Table 3. Tools and frameworks for Cumulative Effects Assessment (Depellegrin et al. 2021). DST= Decision Support Tools, CEA=Cumulative Effect Assessment, MUC= Maritime Use Conflict, C-S= Conflict and Synergy analysis.**

| DST Name | Application Domain | Method | Link | References |
|---|---|---|---|---|
| Tools4MSP | Adriatic ionian | CEA MUC | http://data.tools4msp.eu/ | Menegon et al. (2018b), Farella et al. (2020) |
| Mytilus | Baltic Sea | CEA C-S | https://bonusbasmati.eu/ | BONUS BASMATI (2000), Hansen (2019) |
| Symphony | North Sea<br>Baltic Sea | CEA | https://www.havochvatten.se/en/eu-and-international/marine-spatial-planning/swedish-marine-spatial-planning/the-marine-spatial-planning-process/development-of-plan-proposals/symphony---a-tool-for-ecosystem-based-marine-spatial-planning.html | Hammar et al. (2020) |
| Baltic Sea Impact Index Assessment Tool (BSII CAT) | Baltic Sea | CEA | https://github.com/helcomsecretariat/Cumulative-impact-Assessment-Toolbox<br><br>http://www.panbalticscope.eu/ | Bergström et al. (2019), PanBalticScope (2019) |
| PlanWise4Blue | Estonia | CEA | http://www.sea.ee/planwise4blue | PlanWise4Blue (2020), Kotta et al. (2020) |
| MSP Challenge | North Sea, Baltic Sea, Fith of Clyde | CEA | https://www.mspchallenge.info/ | MSP-Challenge, (2020), Steenbeek et al., (2020) |

| | | | | |
|---|---|---|---|---|
| DAPSI(W)R(M) | Marine environment | CEA | | Elliott, et al. (2017) |
| Ecological Network Analysis (ENA) | Bay of Seine | CEA | | Nogues et al. (2021) Nogues et al. (2023) |

## TOOLS4MSP

The Tools4MSP Geoplatform implements a Cumulative Effects Assessment (CEA) for the analysis of cumulative effects generated by anthropogenic activities on marine environmental components as described by Menegon et al. (2018b; 2018c). Its implementation is based on the CEA framework, defined as a systematic procedure for identifying and evaluating the significance of effects from multiple pressures and/or activities on single or multiple receptors (Judd et al., 2015).

Tools4MSP analyses the sources, pathways and interactions of pressures, assigns weights to pressures, assesses the vulnerability of receptors, and the consequences of the pressures on them. The inputs of the Tools4MSP CEA tool are: 1) the area of analysis; 2) the grid cell resolution; 3) layers representing intensity or presence/absence of human uses (e.g., intensity of fishery and maritime transport, presence of aquacultures and oil and gas platforms) and 4) environmental components (e.g., seabed habitats, probability of presence of nursery habitats, and probability of presence of marine mammals). In addition, the tool includes 5) use-specific relative pressure weights; 6) distances of pressure propagation; 7) environmental component sensitivities related to specific pressures or more general 8) ecological models that describe the response of the environmental components to a specific pressure.

The CEA model implemented in Tools4MSP considers 15 MSFD pressures out of 18 provided by the MSFD (EC, 2008), described according to MSFD amended version (EC, 2017, Annex 4, Table 3).

The model estimates the spatial distribution of each single pressure and computes the cumulative effects and impacts by combining together the (weighted) pressure layers and the environmental components (receptors) layers through a sensitivity score. The tool is available online to be applied to the user case studies, after registration.

## SYMPHONY

The SYMPHONY Cumulative Impact Assessment (CIA) framework, developed by the Swedish Agency for Marine and Water Management (SwAM), is a streamlined tool for ecosystem-based Marine Spatial Planning (MSP). The framework integrates CIA with MSP, enhancing decision-making through scenario analysis and a five-step methodology:

1. Mapping ecosystem components and human-induced environmental pressures.
2. Developing an expert-based sensitivity matrix to assess ecosystem reactions to these pressures.
3. Calculating baseline cumulative impacts using GIS-based maps following Halpern et al.(2008).
4. Analysing alternative MSP scenarios.
5. Generating visual MSP results with heat maps and sector analysis.

In its initial application in the Swedish North Sea and Baltic Sea, SYMPHONY demonstrated its effectiveness in mitigating cumulative environmental impacts (Hammar et al., 2020). The framework initially assessed 37 human pressures and 33 ecosystem components, selected specifically for their relevance to Swedish marine environment. The process involved expert assessment of the interaction between ecosystem components and pressures, ensuring the responses were both significant and reliable.

Two different scenarios were examined for the year 2030: 1) 'Negotiated Plans', collaboratively developed with stakeholders, and 2) 'Eco-Alternative Plans', which focus on ecological preservation and aim to achieve good environmental status in line with the MSFD requirements. These scenarios were benchmarked against a 'Business As Usual' scenario, projecting a future without MSP intervention, based on current industry trends.

## BSII CAT

The BSII CAT (Cumulative impact Assessment Toolbox), developed in the context of the Pan Baltic Scope project, is a sophisticated set of instruments that allows thorough and detailed assessments of cumulative impacts on the Baltic Sea ecosystem.

Components of the Toolbox:

1. Baltic Sea Impact Index (BSII) Tool: Calculate the BSII to measure the cumulative impact on the Baltic Sea. Inputs are ecosystem and pressure data to generate the BSII grid layer, along with a statistics matrix to understand individual contributions.
2. Baltic Sea Pressure Index (BSPI) Tool: Determine the Baltic Sea Pressure Index by including pressure data, resulting in a BSPI grid layer.
3. Ecological Value (EV) Tool: Identify areas of high ecological value using ecosystem component data. The tool assesses ecological value criteria and ecosystem components to create aggregated results and a total ecological value grid layer.
4. Ecosystem Service (ES) Tool: Pinpoint areas with potential ecosystem service provision. Inputs are ecosystem component data and ecosystem services criteria to generate grid layers for specific combinations and aggregated results.
5. BSII Batch Tool for Ecological Values or Ecosystem Services: Calculate the BSII for areas important for ecological values or ecosystem services. By choosing criteria and ecosystem components, the tool will create BSII grid layers, with optional statistics matrices.
6. Sensitivity Score Matrices for BSII Batch Tool: Create custom sensitivity score matrices for the BSII Batch Tool. It allows to combine existing matrices to assess ecological value criteria and ecosystem components or ecosystem services and sub-groups.

The toolbox is user-friendly, transparent and highly flexible: it empowers users to tailor assessment to their specific sectors and scenarios by allowing the implementation of new data and  methodologies. The software is specifically designed for ArcGIS users and available as free software on GitHub. The tools' description (chapter 4) and use cases (chapter 5) are presented in the "Cumulative Impact Assessment for Maritime Spatial Planning in the Baltic Sea Region" report (Bergström et al., 2019).

## MYTILUS

MYTILUS is a Cumulative Impact Assessment (CIA) tool which is inspired by the widely cited CIA method developed by Halpern et al. (2008). The CIA method includes three types of data categories; spatial pressures from human activities, spatial ecosystem components, and expert-derived sensitivity scores that evaluate each pressures' effect on each ecosystem component. The tool offers options to calculate statistics overall for a specific case area as well as for sub-areas. The statistics are shown in graphs with the relative distribution of pressures and ecosystem components in the chosen area. These graphs can be used to explore what pressures could potentially be interesting to target, and what ecosystem components could be interesting to protect, in a new planning scenario.

## PLANWISE4BLUE

PlanWise4Blue (PW4B) is a versatile web-based Maritime Spatial Planning Decision Support Tool (MSP-DST) developed by the Estonian Ministry of Finance, drawing upon insights from the Pan Baltic Scope project and the Adrienne project. This tool is instrumental in planning for sustainable marine growth by allowing users to analyse and explore various scenarios of marine use. PW4B operates by simulating initial conditions using current use-pressure maps and spatial data on species distribution, which are generated via machine learning approaches that correlates biotic and abiotic factors (Elith et al., 2008). Users can interactively plan new marine uses, with the system accounting for additive and synergistic pressures. These are then assessed against the spatial distribution of natural assets through an impact matrix, forecasting changes in ecosystem values measured by biomass or density (Kotta et al., 2020).

At the current development stage, PW4B accounts for few economic sectors (aquaculture, fishing, mining, offshore wind, shipping and ports) and it doesn't include exogenic pressures or cross-border aspects, but is a promising tool with a lot of room for improvement.

## DAPSI(W)R(M)

The DAPSI(W)R(M) framework was established in 2017 as an advanced iteration of the DPSIR framework. It offers a comprehensive and theoretical approach for integrated marine management (Elliot et al., 2017). This framework is grounded in a holistic, risk-based methodology and has been further developed through the adoption of the IEC/ISO 31010 bow-tie method (Cormier et al., 2019). This method is instrumental in identifying crucial drivers, activities, and response measures aimed at preventing, mitigating, or restoring state changes and impacts on human welfare. Central to the DAPSI(W)R(M) approach is the concept of 'footprint' which is applied to activities, pressures, and effects. This concept is essential for accurately estimating impacts during the planning phase. The bow-tie analysis elucidates essential control points and escalation factors within the management process flow.

The framework is characterized by its cyclical and nested structure, emphasizing both horizontal (encompassing stakeholders, definitions, objectives) and vertical (spanning national, regional, international levels) integration in assessment and management processes, aligning them with sustainability goals. This framework has gained wide recognition and support, with an array of tools developed to facilitate its workflow (Nygård et al., 2020).

## MSP CHALLENGE

The MSP Challenge is an interactive, multiplayer simulation platform developed collaboratively by Breda University of Applied Sciences and the Ecopath International Initiative (Keijser et al., 2018). This innovative tool is specifically designed for stakeholder engagement and training in Marine Spatial Planning (MSP) processes. It employs a game-based approach, providing an immersive experience where participants, through role-playing, navigate various stages of MSP. This includes 1) gathering and sharing information, 2) collaboratively designing and implementing MSP plans based on assigned objectives, and 3) evaluating outcomes using detailed heatmaps and indicators.

The platform operates on a turn-based system, allowing users to iteratively refine their strategies by learning from the environmental and social consequences of previous planning rounds. One of the key features of MSP Challenge is its ability to convert spatially explicit plans and activities into inputs for dynamic models reproducing spatial and temporal dynamics, including accumulation processes and various types of disturbances (Heymans et al., 2016).

Currently, MSP Challenge incorporates three dynamic models: Ecospace (a spatially explicit Ecopath with Ecosim module), a shipping simulator, and an energy simulator. These models collectively address ecological, social, and economic aspects of MSP, offering a holistic view of the potential impacts of different spatial planning strategies. The modularity and compatibility ensure straight-forward implementation of new study areas and dynamic models (Santos et al., 2020).

## ECOLOGICAL NETWORK ANALYSIS (ENA)

Tools like the ecological network analysis (ENA) indices, offer the opportunity to study interactions at the ecosystem level. ENA indices are OSPAR candidate indicators to assess food webs (FW9 indicator). A pilot study was conducted for the Quality Status Report 2023 (Schückel et al., 2022). These model-derived indicators consider: i) all ecosystem compartments starting from primary producers via plankton to top predators like fishes, birds and mammals, ii) all direct and indirect trophic interactions between ecosystem compartments within the food web and iii) non-feeding pathways such as respiration, export out of the systems and pathways to detritus pools.

ENA allows assessing the structure and functioning of food webs based on the analysis of the interactions among all compartments (like species, functional groups, trophic guilds). It identifies the most important trophodynamic links between compartments and analyses the effects of specific pressures on Ecological Network Analysis indices or biomass distribution of specific compartments.

ENA indices were successfully tested by combining the effects of the reef formed by the future offshore wind farm of Courseulles-sur-Mer, and climate change on species distribution (Nogues et al. 2021). ENA indices proved sensitive to this cumulative impact, displaying a wide variety of cumulative effects. They were also very powerful to characterize the role of the cumulative impact on ecosystem functioning. The study demonstrates the capacity of ENA indices to describe and understand cumulative effects at the ecosystem scale. Using a set-up of ENA indices will help to reach an overall picture of the ecosystem organization and function.

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