MaCoBioS' Conceptual Models

Conceptual tool to understand the risk that changes present to ecosystem services

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This project has received funding from the European Union's Horizon 2020 research and innovation Programme under grant agreement No 869710

Suggested citation:

Maréchal, J.-P., Trégarot, E., and Cornet, C.C. (2024). MaCoBioS' Conceptual Models: Conceptual tool to understand the risk that changes present to ecosystem services. A report prepared by Nova Blue Environment and the University of Portsmouth for MaCoBioS.

Ackowledgments:

The authors are grateful to the MaCoBioS Team for their support in developing MaCoBioS' Conceptual Models.

Editing: Cindy C. Cornet

Photo credits: Silvia de Juan (top left), Rémy Simide (bottom right), Ewan Trégarot (all others)

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MaCoBioS' Conceptual Models

MaCoBioS' Conceptual Models are interactive conceptual tools based on scientific data and expert knowledge that can help support decision-makers to understand the risks ecosystem changes present to ecosystem services and inform on the best management options. They describe ecosystem structure and connect components to possible drivers of change, while also looking at ecosystem services provision.

MaCoBioS' Conceptual Models have been developed as part of a collaborative programme through the EU funded MaCoBioS project (www.macobios.eu) under the lead of researchers from Nova Blue Environement and the University of Portsmouth.

Key information

- This document provides guidance on the main methodological steps to develop and/or use these conceptual models.
- MaCoBioS' Conceptual Models help simplify complexity in the marine and coastal ecosytems we studied, allowing practitioners to visualise the effect of changing conditions in the system to better understand whether they need to act to counter those changes.
- The output is a graphical visualisation of predicted positive, negative, and neutral changes to all model components as a result of altering one or multiple driver(s) of change using «*what if*» scenarios for the examined ecosystem in a specific place.
- To use MaCoBioS' Conceptual Models you will need:
    - This guidance;
    - MaCoBioS' Conceptual Model for the specific ecosystem and place of interest;
    - An account with the free online tool MentalModeler, *(or our own software)*;
    - A pool of experts for your specific ecosystem in a specific place who can provide knowledge on ecosystem function and interaction between components to adapt the model to your needs.
- Please be aware that MaCoBioS' Conceptual Models have been constructed for specific ecosystems and place, and as such are not directly transferable to other ecosystems or places. You therefore need to build on, adapt, and validate these models to your specific ecosystem and area of interest.

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Developing conceptual ecosystem models using Fuzzy Cognitive Mapping (FCM) involves a systematic approach to understanding and simulating the complex interactions within marine and coastal ecosystems. This methodology, particularly when implemented using the MentalModeler software (or similar), offers a dynamic and integrative way to model ecological complexities, accommodating both qualitative expert insights and quantitative data inputs and fostering discussion with a range of stakeholders. Below are detailed guidelines structured into four major methodological phases to facilitate the development of robust ecosystem models.

Conceptual models provide a foundational structure for understanding essential ecological mechanisms and elements that influence the robustness and adaptability of individual ecosystems. Their application involves analysing the connections between the state of ecosystems and the services they offer in response to human influence and climate variations. By comprehending the interrelationships among the physical elements of the environment, biological interactions, and human activities that shape the vitality and adaptability of ecosystems, we can uncover key drivers of change and formulate strategies to mitigate detrimental impacts.

Table 1. *General components framework of conceptual models for the MaCoBioS project.*

Component	Examples
Physical environment	Temperature, Salinity, Water quality, pH
Biological interactions	Trophic interactions, Competition, Predation
Human activities	Fishing, Coastal development, Pollution, Climate change (e.g. warming, acidification, sea level rise)
Ecosystem services	Provisioning (e.g. fisheries production, timber), Regulating (e.g. coastal protection, carbon sequestration, water purification), Cultural (e.g. recreation, tourism, spiritual and cultural values)
Coastal ecosystems	Coral reefs, Seagrass beds, Mangrove forests, Kelp forests, Maërl beds, Salt marshes

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Introduction to Fuzzy Cognitive Mapping

Fuzzy Cognitive Mapping (FCM) is a tool used to capture and analyse the complexity of systems where precise data may be scarce and uncertainty is inherent. This approach is particularly beneficial in ecological studies, where multiple variables interact in ways that are not entirely predictable. Understanding the principles of FCM, including the intergations of fuzzy logic and the iterative refinement process, is crucial for effectively modelling marine coastal ecosystems. As such, we provide a few definitions and clarifications on related terminology and concepts below.

Understanding FCM: the principles underlying FCM, include the integration of fuzzy logic to handle vagueness and the iterative process of model refinement. FCM involves creating a map where each element (or variable) of the ecosystem is represented as a node. These nodes are linked through edges that signify the relationships (causal or correlational) between them.

Fuzzy logic introduction: fuzzy logic used in FCM allows for varying degrees of truth. This means that relationships between nodes are not confined to true or false but can encompass degrees of influence, represented numerically (e.g., ranging from -1 to 1).

Degrees of association: fuzzy logic enables the model to handle vague, imprecise, or qualitative information by assigning degrees of association between nodes. This method allows for a more nuanced representation of ecological interactions than binary outcomes could provide.

Weighted relationships: each directed edge in the FCM is assigned weights that quantify the strength and direction (positive or negative) of one variable's impact on another, thus accommodating the subjective and uncertain nature of ecological data.

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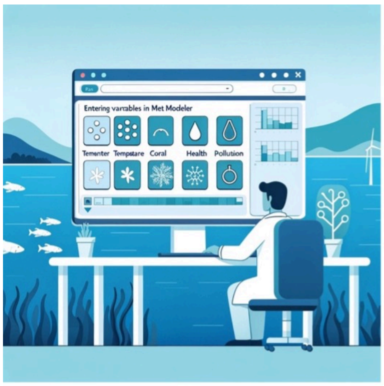
Methodological phases

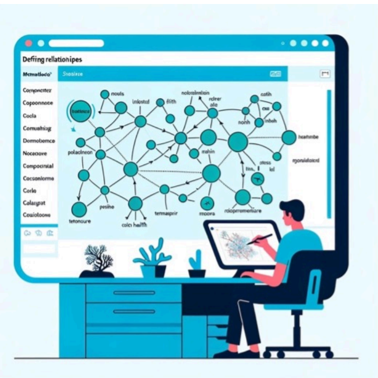
Phase 1 – Building the initial version of the model

The process of constructing FCM starts by following detailed steps from setting up the software to defining ecosystem components. This first phase is critical as it lays the foundation for accurate and functional models.

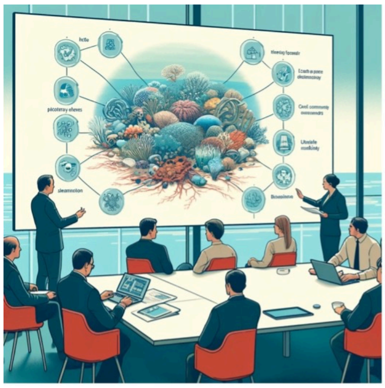
Step 1. Setting up your software (e.g., MentalModeler): open and get accustomed to the software interface and features.



Step 2. Defining the ecosystem components: identify and categorise the variables that will be included in the model, such as biological, physical, and human activity factors. These might include biotic factors like species, abiotic factors such as temperature or salinity, and anthropogenic factors like fishing pressure or pollution.



Step 3. Establishing relationships: define the causal links between the identified variables and assign initial weights based on available data or expert judgment. Determine the nature of these relationships (positive or negative) and their strength.



Step 4. Building the model: construct the initial FCM using MentalModeler or similar software, placing variables as nodes and connections as edges with directional and weighted links. This helps to visually map out the variables and their connections, creating a network that represents the ecosystem.

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Phase 2 – Model validation with experts' and other stakeholders' engagement

Model validation

Model validation involves challenging the initial model to additional experts' vision to validate the key components, relationships, and links' weight in the model.

Following validation, regular consultation with local communities, policymakers, and other stakeholders to gather insights also ensures the model reflects varied interests and knowledge. Stakeholder engagement helps incorporate diverse perspectives and local knowledge which is crucial for the model's practical application.

Stakeholder engagement

Phase 3 – Iterative refinement of the model

Iterative refinement

The iterative refinement of the model ensures its accuracy and relevance. This process follows two parallel and non-mutually exclusive pathways:

- Iterative refinement: continuously update and refine the model based on new data, research, and feedback from ecosystem experts and other stakeholders.

- Model validation: validate the model by comparing simulation results with observed data and adjust as necessary to improve its predictive accuracy.

Phase 4 – Documenting and reporting

Keep detailed records of all model development stages and decisions and prepare comprehensive reports to share findings with the broader community and stakeholders.

Documenting & reporting

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Application in marine and coastal ecology

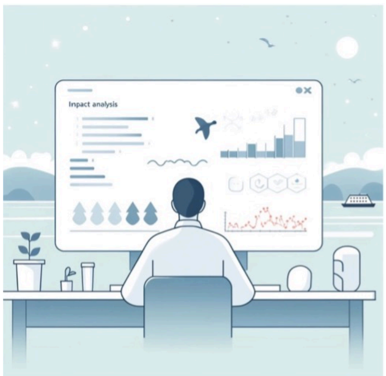
Applying the developed FCM model to real-world marine and coastal ecosystems allows researchers to simulate various scenarios and assess the impacts of different environmental and anthropogenic factors.

Model specific ecosystems:

Develop and customise models for different types of marine and coastal ecosystems such as coral reefs, mangrove forests, etc.

Scenario simulation:

Use the models to simulate effects of potential changes like climate variables, species interactions, or human interventions (e.g., reducing pollution).



Impact analysis:

Analyse the outcomes to understand how changes in one part of the ecosystem affect others and the overall system stability.

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Model co-construction using MentalModeler

MentalModeler is a user-friendly free software tool designed to facilitate the creation and analysis of FCMs. It provides an intuitive interface for constructing, visualising, and simulating FCMs, making it accessible for researchers, practitioners, and decision-makers to model complex systems.

MentalModeler simplifies the process of developing FCMs by allowing users to create nodes and edges through a graphical interface. It enables users to assign weights to these relationships, indicating the strength and direction of influence between nodes. Additionally, MentalModeler includes functionalities for:

1. **Modelling uncertainty:** allowing users to incorporate uncertainty or varying degrees of influence by using fuzzy logic principles.

2. **Simulation and scenario analysis:** enabling users to simulate different scenarios and assess the potential outcomes of changes within the modelled system. This feature aids in understanding how alterations in variables or relationships might impact the overall system behaviour.

3. **Visualisation:** providing visual representations of the FCMs to enhance comprehension and facilitate communication of complex systems to diverse stakeholders.

4. **Integration and export:** offering options to integrate data, import/export models, and potentially link with other analytical tools or data sources. For instance:

    Geographic information systems (GIS): linking FCMs with spatial data to analyse the geographic distribution of variables and their relationships.

    Statistical softwares (e.g., R, Python): exploring data for advanced statistical analysis, enabling deeper insights through multivariate analysis or time series analysis.

    Databases (e.g., SQL, Excel): importing/exporting data from various databases to ensure comprehensive and up-to-date information is utilised in FCMs.

    Environmental modelling tools (e.g., InVEST, SWAT): integrating FCMs with environmental models to assess ecosystem services or predict environmental changes.

    Decision support systems (DSS): linking with DSS platforms (e.g., TABLEAU, ArcGIS) to support decision-making processes by providing comprehensive scenario analysis and impact assessments.

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MentalModeler is a valuable platform for leveraging FCMs in various fields, including ecology, social sciences, decision-making, and policy analysis, due to its user-friendly interface and capabilities for modelling complex systems. This online tool has been used to co-construct marine coastal ecosystem conceptual models in the MaCoBioS project for coral reefs (Figure 4), seagrass beds, mangrove forests, maërl beds, kelp forests, and salt marshes.

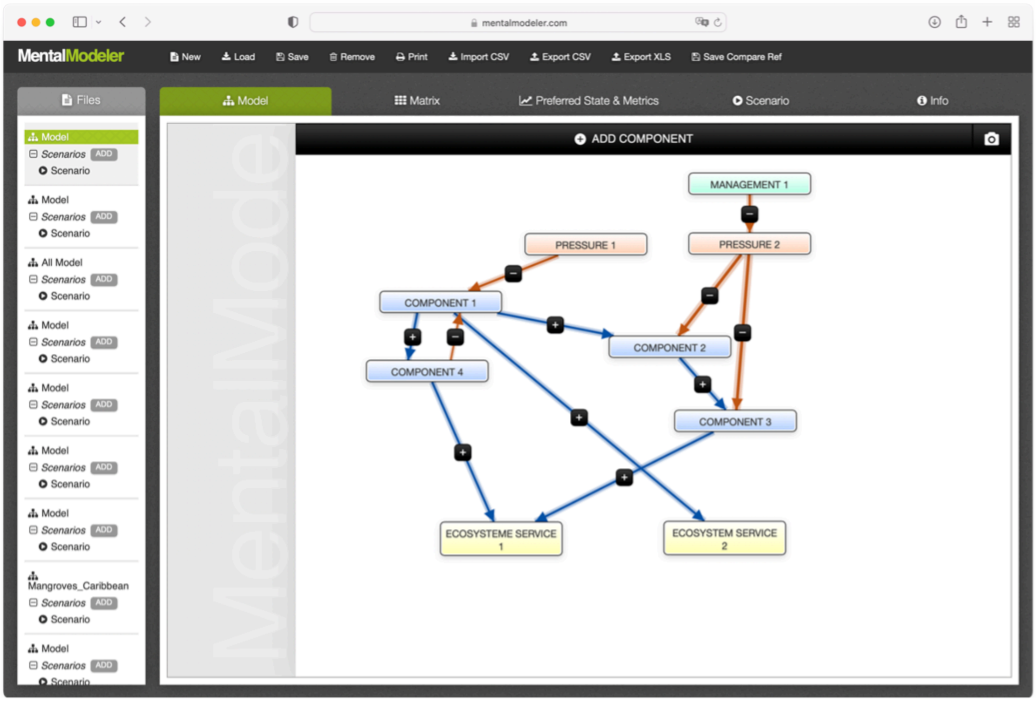

Figure 1. Theoretical example of conceptual model development under MentalModeler.

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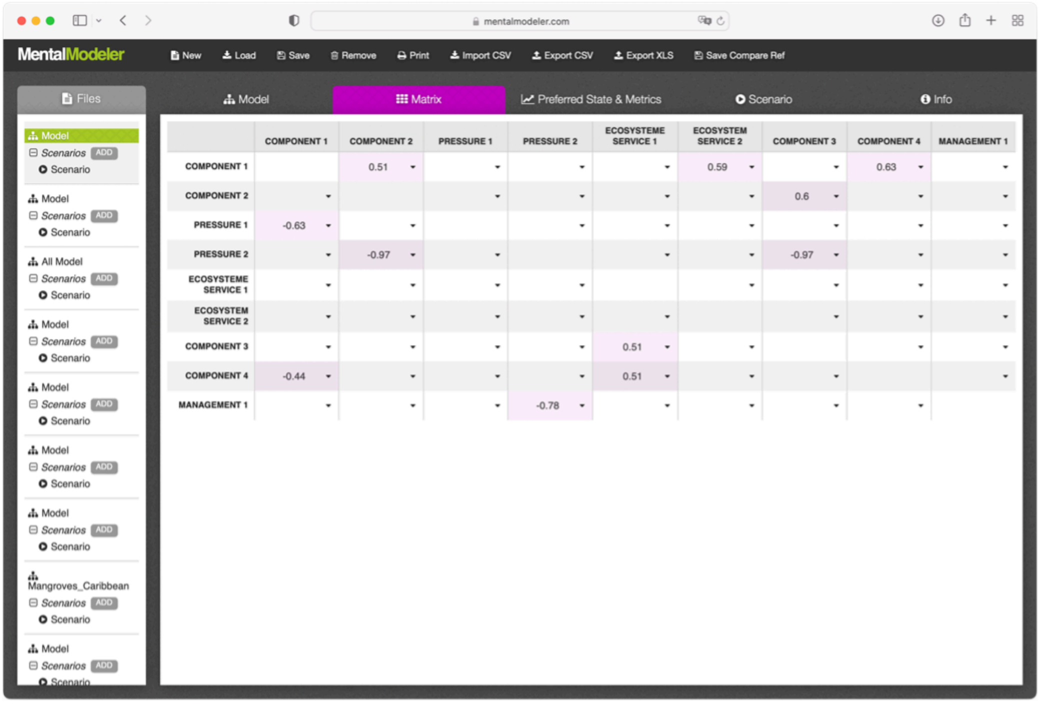

Figure 2. *Theoretical example of a matrix of interactions between components in MentalModeler, based on the conceptual model from Figure 1.*

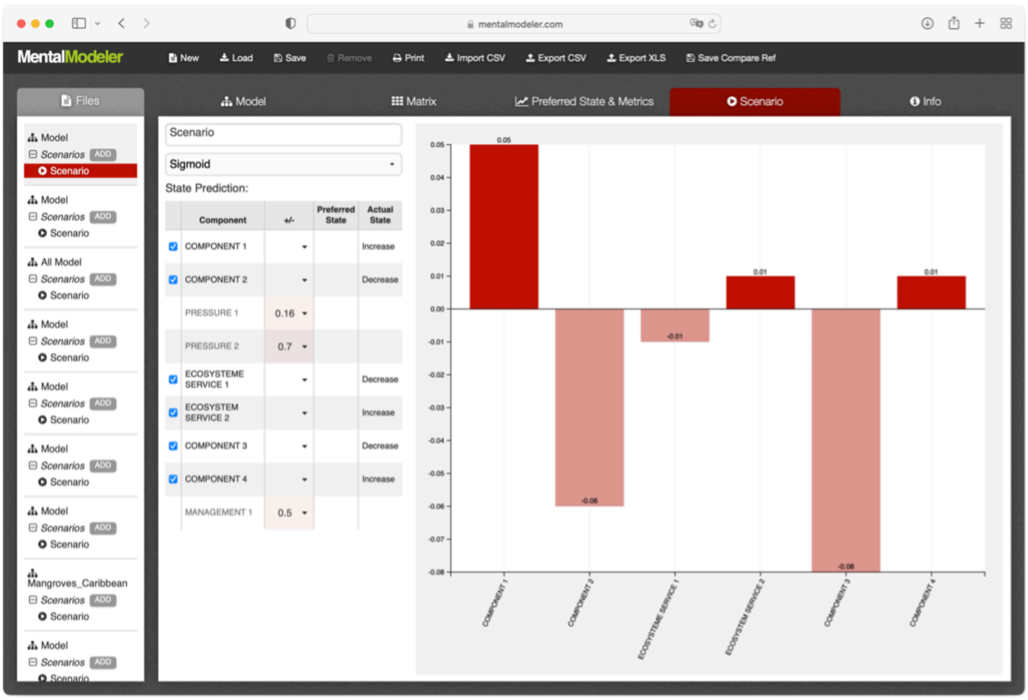

Figure 3. *Theoretical example of scenario analysis using MentalModeler, based on the conceptual model from Figure 1.*

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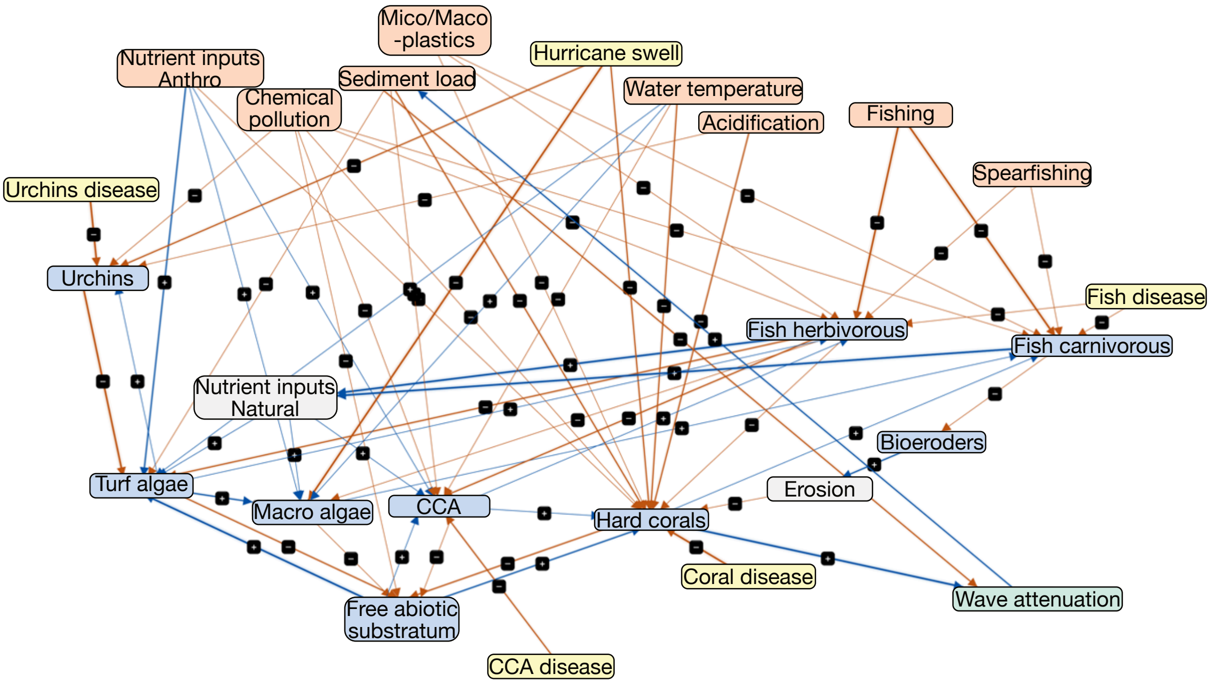

Figure 4. *Coral reef conceptual model developed in MaCoBioS under MentalModeler.*

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Conceptual Models' strenghts and caveats

Conceptual models, such as those created using FCM) in marine and coastal ecology, offer valuable tools for understanding and managing complex ecological systems. The following offers a detailed look at the strengths and caveats of using these models:

Strengths of conceptual models in marine and coastal ecology:

Simplification of Complexity: conceptual models help simplify complex interactions within ecosystems into understandable components and relationships. This helps researchers and stakeholders to visualise and discuss the system's dynamics.

Integration of qualitative and quantitative data: FCM allows for the integration of both qualitative expert knowledge and quantitative empirical data, integrating various sources of knowledge in a cost and time-effective manner. This is particularly useful in ecological studies where some data may not be easily quantifiable.

Identify knowledge gaps: conceptual models help identify knowledge gaps and highlight research needs and priorities.

Enhancement of communication: conceptual models provide a visual and intuitive means to communicate complex ecological interactions to a broad audience, including policymakers, stakeholders, and the public. This facilitates better-informed decision-making.

Support for scenario analysis: conceptual models are practical tools for conducting scenario analysis, allowing researchers to simulate the effects of various management decisions, environmental changes, or catastrophic events on ecosystem health and services.

Flexibility and adaptability: conceptual models can be easily updated or modified as new data become available or as system understanding improves, making them particularly useful in adaptive management strategies.

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Caveats of conceptual models in marine and coastal ecology:

Dependence on expert knowledge: the accuracy of a conceptual model heavily relies on the knowledge and assumptions of the experts who design it. Misinterpretations or incomplete knowledge can lead to less reliable models. Conceptual models do not replace quantitative models based on robust quantitative data.

Oversimplification: while simplification is a strength, it can also be a drawback if it leads to the omission of critical variables or interactions that influence ecosystem dynamics, potentially leading to misguided conclusions. Conceptual models are not predictive tools but more indicative tools.

Challenges in quantifying relationships: in FCM and other conceptual models, quantifying the strength and direction of relationships between components can be subjective and vary among experts, leading to variability in outcomes.

Limited predictive power: conceptual models, particularly those not integrated with quantitative analytical models, may have limited predictive capabilities. They are better suited for understanding potential trends and scenario outcomes rather than precise predictions. Although the FCM method is referred to as 'semi-quantitative' and not a simulation approach, there is always a temptation to over-interpret the model outputs. Always be cautious in the interpretation.

Risk of bias: the development of conceptual models can be influenced by the biases of the individuals or groups involved in the modelling process, affecting the objectivity of the model.

We emphasise that these models should be used as a **discussion and thinking tool** rather than a precise forecast of what might happen.

Conceptual models should be **tailored to fit local environmental contexts** (i.e., estuaries vs exposed coast, tropical vs temperate seagrass beds, specific local stressors, etc.) at a scale relevant to decision-makers. The models developed in the MaCoBioS project are 'generic' models that should be seen as a starting point for your local application.

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Conclusion

With today's information overload, analysing vast amounts of data and generating appropriate management decisions has become increasingly difficult. Furthermore, the data are often imprecise and incomplete, and often include quantitative and qualitative components. Fuzzy Cognitive Mapping is a practical tool for dealing with current uncertainties.

Despite a few caveats, those conceptual models can be very useful for scientists, decision-makers, and other relevant stakeholders. They help us understand the potential synergistic and antagonistic effects of multiple pressures and how they affect, through cascading effects, ecosystem services. They also reveal knowledge gaps where future research efforts are needed.

Finally, by interacting directly with decision- and policy-makers, opening the discussion on ecosystem services, this participative approach paves the way to bridging the science-policy gap.

Marine Coastal Ecosystems Biodiversity and Services in a Changing World (MaCoBioS) was a four year research project running between 2020 and 2024 funded by the European Union's Horizon 2020 research and innovation programme. Its objective was to inform efficient and integrated management and conservation strategies for European marine and coastal ecosystems to face climate change by: (a) advancing the scientific evidence base on ecosystem functioning, and (b) developing tools to assess vulnerability and advancing understanding of potential management options.

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