Deliverable 3.3 Guidance for building climate change scenarios for protection strategies

Guidance for building climate change scenarios for protection strategies

This project has received funding from the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

Grant Agreement number	101060707
Project title	MSP4BIO: IMPROVED SCIENCE-BASED MARITIME SPATIAL PLANNING TO SAFEGUARD AND RESTORE BIODIVERSITY IN A COHERENT EUROPEAN MPA NETWORK
Deliverable title	Guidance for including climate change scenarios in protection and prioritization strategies for Marine Protected Areas development
Deliverable number	3.3
Deliverable version	1
Contractual date of delivery	31/01/2024
Actual date of delivery	31/01/2024
Document status	Final
Document version	1
Online access	No
Diffusion	Public
Nature of deliverable	Document/Report
Work Package	3
Partner responsible	CNR
Contributing Partners	VLIZ, UTARTU, UAC, CCMS, HELCOM, UN, WWF-MMI, CORPI, NIMRD, s.Pro
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Abstract	Marine Protected Areas (MPAs) are designated zones aimed at conserving marine ecosystems, safeguarding biodiversity, and sustaining yields of nearby artisanal fisheries, with potential benefits on provisions of jobs and marine economies. However, the increasing impacts of climate change now pose additional significant challenges to MPA effectiveness. Climate change (CC) will in fact affect all aspects of marine life, via warming (including extreme phenomena such as heat waves), acidification, deoxygenation, salinity changes, circulation changes (and associated transport of marine organisms), sea level rise, and more, hence it is imperative that MPA management nowadays takes CC into account. The purpose of the guidance is to provide an original framework for MPA managers and modelers to assess the vulnerability of marine species and ecosystems to climate stressors. The vulnerability assessment is a key element in climate-smart management, since the responses of marine organisms and ecosystems to climate-induced changes are neither straightforward nor linear, as they depend on the species' sensitivity, resistance and adaptivity to the (single or combined) stressors. In other words, some species may survive, while others may disappear or invade; depending on the trophic role of the species, the ecosystem may undergo an abrupt shift to a different state (with consequent modification of ecosystem services) or exhibit resilience. The guidance is made to be used by everyone and is designed to be comprehensive, versatile and easy to apply. It is also meant to be bottom-up, starting from the management concerns, then assessing the vulnerabilities related to the species and areas of interests, followed by providing prioritization criteria, for use by managers and modelers.

	This guidance constitutes **Deliverable D3.3** of the Horizon Europe project **MSP4BIO**.
Keywords	Climate change; Marine Spatial Planning; MSP; Marine Protected Area; MPA; Vulnerability assessment; Conservation; Prioritization; Scenario; Driver of change; Mangement; Policy; Marine Ecology
Suggested citation	Cambra et al (2024). Guidance for including climate change scenarios in protection and prioritization strategies for Marine Protected Areas development. Deliverable D3.3, under the WP3 of MSP4BIO project (GA n° 101060707)

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Glossary

Adaptivity: capacity to *adjust in response to actual or expected climatic stimuli and their effects*. *It refers to changes in processes, practices and structures to moderate potential damage or to benefit from opportunities associated with climate change* (United Nations Framework Convention on Climate Change (UNFCCC), 2023).

Area-based Management Tools (ABMTs): ABMTs are instruments that entail "*the implementation of a system of rights and duties in a particular management area, under the responsibility of a designated authority, and ABMTs tend to afford high levels of protection*" (definition from Gissi et al. 2022, based on UNGA 2007; Prior et al. 2010). ABMTs include Marine Protected Areas (MPAs) and Other Effective area-based Conservation Measures (OECMs).

Biological organizational levels: biological organization levels refers to the classification of biological systems in a hierarchical manner according to their level of complexity (e.g. from molecules to single organisms, from species to communities and ecosystems). The level of biological organization has been defined by several studies, such as for example in Scheffers et al. (2016), to address climate change (CC) impacts and responses on different biological systems.

Climate Change Mitigation: Action to limit climate change, avoiding and reducing emissions of heat-trapping greenhouse gases into the atmosphere to prevent the planet from warming to more extreme.

Climate proofing: analysis of current mitigation and adaptation development strategies and programs through a climate lens (Climate Policy Info Hub, 2023). In the framework of MSP4BIO, this climate proofing could be extended to MPA management strategies and scenarios.

Conservation scenario: vision of long-term ecosystem health through investment in conservation and restrictions to coastal development.

Criterion/criteria: in the context of the present document, a criterion is defined as a standard or principle for prioritizing and managing conservation areas and designing and evaluating the effectiveness of conservation measures. Some examples of criteria can be the protection of feeding grounds for endangered predators, areas/habitats essential for the development of the life cycle of keystone species, or the maintenance of gene.

Desirability Matrix: can be found in the literature as *Adaptivity Matrix*. The *Desirability Matrix* will compile the traits linked to stressor Resistance, Resilience, Adaptivity and will be particularly of interest to escape the area under stress.

Development scenario: vision of rapid economic development and urban expansion.

Exposure: selection of, at least, a climatic stressor or a list of stressors (including climatic and non-climatic stressors) that will be used as drivers of changes regarding the chosen management target.

Indicator: an indicator is a direct measurement or a proxy of relevant biotic or abiotic components/processes used to implement and assess criteria.

Imputing: using alternative values in place of missing data following a certain number of rules.

Informed Management scenario: blends strong conservation goals with current and future needs for coastal development and marine uses. This scenario was refined over time through iterations of ecosystem-service modeling and stakeholder review.

OECM: *Other Effective area-based Conservation Measures*. The OECM englobe all “geographically defined area other than a Protected Area, which is governed and managed in ways that achieve positive and sustained long-term outcomes for the in situ conservation of biodiversity, with associated ecosystem functions and services and, where applicable, cultural, spiritual, socioeconomic, and other locally relevant values” (CBD, 2024).

Resilience (or recovery): ability of a receptor to recover from disturbance or stress (Holling, 1973).

Resistance: the capacity of an organism to absorb disturbance or stress without changing character (Holling, 1973).

Sensitivity: the degree to which a species is influenced by one or more aspects of climate (Dawson et al., 2011). The sensitivity is directly linked to the species' inner traits.

Sensitivity matrix: spreadsheet tool that will assess the degree of sensitivity of a given species/habitats to a chosen climatic stressor. The sensitivity is evaluated based on a selection of traits from 6 categories (e.g. morphological) that will confer advantages or disadvantages to the species considering a chosen stressor. The sensitivity matrix is compiled and filled based on Traditional and Expert Knowledge. The Sensitivity matrix makes the link between the chosen stressor and the species inside Trait-based Vulnerability models.

Species’ environmental envelopes: set of environments within which it is believed that the species can persist (where its environmental requirements can be satisfied). Many large-scale vegetation or species models are based on environmental envelope techniques (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), 2022).

Time of emergence: *the point in time (past or future) when the signal of climate change emerges from the noise of background variability* (John et al., 2023).

Traits: the measurable biological characteristics of organisms, such as morphology, physiology, behavior and phenology, which shape their ecological performance (Cadotte et al., 2011).

Trait-based approaches: trait-based approaches are defined in ecological research as any method that focuses on individual traits rather than species, could provide this common framework (McGill et al. 2006, Kremer et al. 2017). These approaches emerged from terrestrial ecology when attributes at the individual level, initially used to describe ecosystem function based on elements common to multiple species, were considered to gather individuals into functional groups (i.e., “plant functional types”) based on their physical, phylogenetic, and phenological characteristics, rather than on their taxonomy (e.g., species).

VME: Vulnerable Marine Ecosystems. A marine Ecosystem should be classified as vulnerable as vulnerable based on the characteristics that it possesses. This criteria englobes their *uniqueness or rarity*, the *functional significance of the habitat*, the *fragility of the Ecosystem*, the *Life-history traits of component species that make recovery difficult* and the *structural complexity* (adapted from FAO, 2024).

Vulnerability assessment: function *of both intrinsic and extrinsic factors and assessments often considering exposure, sensitivity and adaptability in combination* (Pacifici et al., 2015). In fact, the vulnerability function will make the link between the Exposure score, the Sensitivity matrix and, eventually, the Adaptivity/Desirability matrix.

Acronyms

ACCOBAMS: Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and contiguous atlantic area

CC: Climate Change

DST: Decision Support Tool

EC: Ecological Corridor

EK: Expert Knowledge

ESA: European Space Agency

ESE: Economical-Sociological-Ecological model

FAO: Food and Agriculture Organization of the United Nations

GA: General Assembly

GBIF: Global Biodiversity Information Facility

GHG: Greenhouse Gas

ICES: International Council for the Exploration of the Sea

IPCC: Intergovernmental Panel on Climate Change

IUCN: International Union for Conservation of Nature

LEK: Local Ecological Knowledge

LOESS: LOcally Estimated Scatterplot Smoothing or local regression

LSMPA: Large-Scale Marine Protected Areas

MSP: Marine Spatial Planning

MPA: Marine Protected Area

NTZ: No-Take Zone

OBIS: Ocean Biodiversity Information System

OECM: Other Effective area-based Conservation Measure

PPA: Partially Protected Area

RCP: Representative Concentration Pathway

RMSE: Root Mean Squared Error

SLR: Sea Level Rise

SSS: Sea Surface Salinity

SSP: Shared Socioeconomic Pathway

SST: Sea Surface Temperature

SST: Seasonal Trend Decomposition Procedure Based on LOESS

ToE: Time of Emergence

TVA: Trait-based Vulnerability Analysis

VME: Vulnerable Marine Ecosystem

WoRMS: World Register of Marine Species

WP: Work Package

Executive Summary

Marine Protected Areas (MPAs) are designated zones aimed at conserving marine ecosystems, safeguarding biodiversity, and sustaining yields of nearby artisanal fisheries, with potential benefits on provisions of jobs and marine economies. However, the increasing impacts of climate change now pose additional significant challenges to MPA effectiveness. Climate change (CC) will in fact affect all aspects of marine life, via warming (including extreme phenomena such as heat waves), acidification, deoxygenation, salinity changes, circulation changes (and associated transport of marine organisms), sea level rise, and more, hence it is imperative that MPA management nowadays takes CC into account.

The purpose of the guidance is to provide an original framework for MPA managers and modelers to assess the vulnerability of marine species and ecosystems to climate stressors. The vulnerability assessment is a key element in climate-smart management, since the responses of marine organisms and ecosystems to climate-induced changes are neither straightforward nor linear, as they depend on the species' sensitivity, resistance and adaptivity to the (single or combined) stressors. In other words, some species may survive, while others may disappear or invade; depending on the trophic role of the species, the ecosystem may undergo an abrupt shift to a different state (with consequent modification of ecosystem services) or exhibit resilience.

The guidance is made to be used by everyone and is designed to be comprehensive, versatile and easy to apply. It is also meant to be bottom-up, starting from the management concerns, then assessing the vulnerabilities related to the species and areas of interests, followed by providing prioritization criteria, for use by managers and modelers.

This guidance constitutes **Deliverable D3.3** of the Horizon Europe project **MSP4BIO**.

1 Introduction

1.1 Guidance and MSP4BIO project

Marine Spatial Planning (MSP) is emerging as a vital tool for sustainable ocean management, aiming to balance ecological conservation, economic activities, and societal interests. MSP is an evolving approach that seeks to optimize the use of marine space while minimizing conflicts among various users (Ehler, 2021; Frazão Santos et al., 2019, p. 30; Reimer et al., 2023). As this approach expands, its significance in the designation and establishment of Marine Protected Areas (MPAs) is becoming increasingly apparent (European Commission, 2024).

MPAs are designated zones aimed at conserving marine ecosystems, safeguarding biodiversity, and sustaining yields of nearby artisanal fisheries, with potential benefits on provisions of jobs and marine economies (Balmford et al., 2004). About 8 % of the world ocean are currently protected (https://www.protectedplanet.net/en/thematic-areas/marine-protected-areas) and the EU Biodiversity Strategy for 2030 establishes the goal of safeguarding 30% of both EU land and sea by the year 2030 (https://environment.ec.europa.eu/strategy/biodiversity-strategy-2030_en; Hermoso et al., 2022). Not all MPAs offer the same level of benefits, and several studies indicate that the effectiveness of MPAs relies on factors such as their legal status, strictness and enforcement of regulations, and their size and age (Claudet et al., 2008; Costello and Ballantine, 2015; Edgar et al., 2014; Grorud-Colvert et al., 2021).

However, the increasing impacts of climate change now pose additional significant challenges to MPA effectiveness (Simard, 2016), yet the inclusion of climate change in MPA planning is still at an early stage (O'Regan et al., 2021). The project **MSP4BIO** (*Improved Science-Based Maritime Spatial Planning to Safeguard and Restore Biodiversity in a coherent European MPA network*), financed by Horizon Europe, intends to address this gap.

Within MSP4BIO, WP3 (*Systemic approach to biodiversity consideration*) has the goal to build the ecological module ESE1 of the Ecological-Socio-Economic (ESE) framework, which is the central focus of MSP4BIO. WP3 is subdivided into 3 tasks: *Task 3.1* has identified, through a systematic review of the scientific literature (Deliverable D3.1), a portfolio of improved functional ecological criteria to be applied in biodiversity protection (D3.2). *Task 3.2's* focus is to build from T 3.1 results to explore and assess species and ecosystems ecological vulnerability, resistance, mitigation, and adaptation to climatic drivers (and their interaction with human impacts) for MPA prioritization. To achieve this, T3.2 has built a framework to assess the vulnerability of marine species and ecosystems to climate stressors, which is detailed in this **guidance (D3.3)**. *Task 3.3* will include the findings of 3.1 and 3.2 into operational tools to build the ESE-1 ecological framework (D3.4).

1.2 Purpose of the guidance

Climate change will affect all aspects of marine life, via warming (including extreme phenomena such as heat waves), acidification, deoxygenation, salinity changes, circulation changes (and associated transport of marine organisms), sea level rise, and more. However, the responses of marine organisms to these changes are neither straightforward nor linear, as they depend on the species' sensitivity, resistance and adaptivity to the (single or combined) stressors. In other words, some species may survive, while others may disappear; depending on the trophic role of the species that have disappeared, the ecosystem may undergo a shift to a different state or exhibit resilience (Conversi et al., 2015). Thus, understanding species and ecosystem vulnerability is crucial for the prioritization of conservation measures.

The purpose of the guidance is to provide a framework for managers and modelers to assess ecological vulnerability, resistance, mitigation, and adaptation of species and ecosystems included in marine conservation areas to climatic drivers (and their interaction with human impacts), considering a portfolio of climate change (CC) scenarios at multiple spatial and temporal scales. The guidance builds on the ecological criteria distilled in T3.1 and guides through the vulnerability assessment steps necessary to managers and scientists for the prioritization of conservation measures in MPAs. The suggested methodologies will provide interested stakeholders with the elements to make climate-proof scenarios.

1.3 Methodology

The approach for building the guidance included:

- A literature screening of CC incidence on MPA, MPA management, marine biota and on ecological traits, which included 424 articles, ~250 of which are the basis of the guidance. The integration of CC assessment in the management of MPAs is very recent and of most articles have been published post 2018, with many just off the press (2023).
- Identifying gaps for some key topics. For example, the sensitivity to deoxygenation and connectivity emerged as research areas needing more development, especially regarding impacts on traits.
- Identifying databases for traits and for species projections
- Identifying approaches for areas with limited data
- Designing a framework for assessing the vulnerability of marine protected areas to climate change.
- Writing this guidance and subdividing it in easy-to-follow steps.

The guidance encapsulates the cutting-edge findings and latest research on the impacts of climate change on marine species, considering the sensitivity of species traits. It then reinterprets this information, tailoring it for practical application in MPA management that is specifically designed to address the challenges posed by climate change.

1.4 Constraints of the guidance

The main constraint of the guidance is dealing with data availability issues. Therefore, the guidance also proposes methods that include the knowledge of local experts.

The guidance is made to be used by everyone and is designed to be comprehensive, versatile and easy to apply. It is also meant to be bottom-up, starting from the management concerns, then assessing the vulnerabilities related to the species and areas of interests, followed by providing prioritization criteria to be embedded in the ESE-1. Thus, it constitutes a building block of the ESE-1. The ESE-1 will then provide the final ecological prioritization.

1.5 Guidance Structure

The guidance flow is divided into five major steps summarized in the following flowchart (*Fig. 1*). This flowchart aims to highlight all steps covered in this guidance, spanning from management questions to the risk assessment, needed to generate insights for climate-informed decision-making in MPA contexts.

The first step is the Management question aims to help Managers, Planners and Expert to the framework of analysis including clear management questions and targets. The second step *Risk Identification* aims to select one or several stressors (climatic and non climatic) relevant in the framework previously defined. Another tool, the sensitivity matrix will be created based on traits to assess the potential sensitivity of the target of conservation under the influence of the chosen stressors. Exposure and Sensitivity Matrix will be the key elements necessary to perform the Trait-based Vulnerability Assessment (TVA) (step 3 *Risk Analysis*). TVA scores are used in the following step *Risk Assessment* (step 4) to identify the incidence of climate on species and areas and propose future evolutive pathways, creating a portofolio of climate-scenarios usefull for management. This portofolio of scenario are used in step 5 *Informed Management and Monitoring* to propose spatial climate management measures.

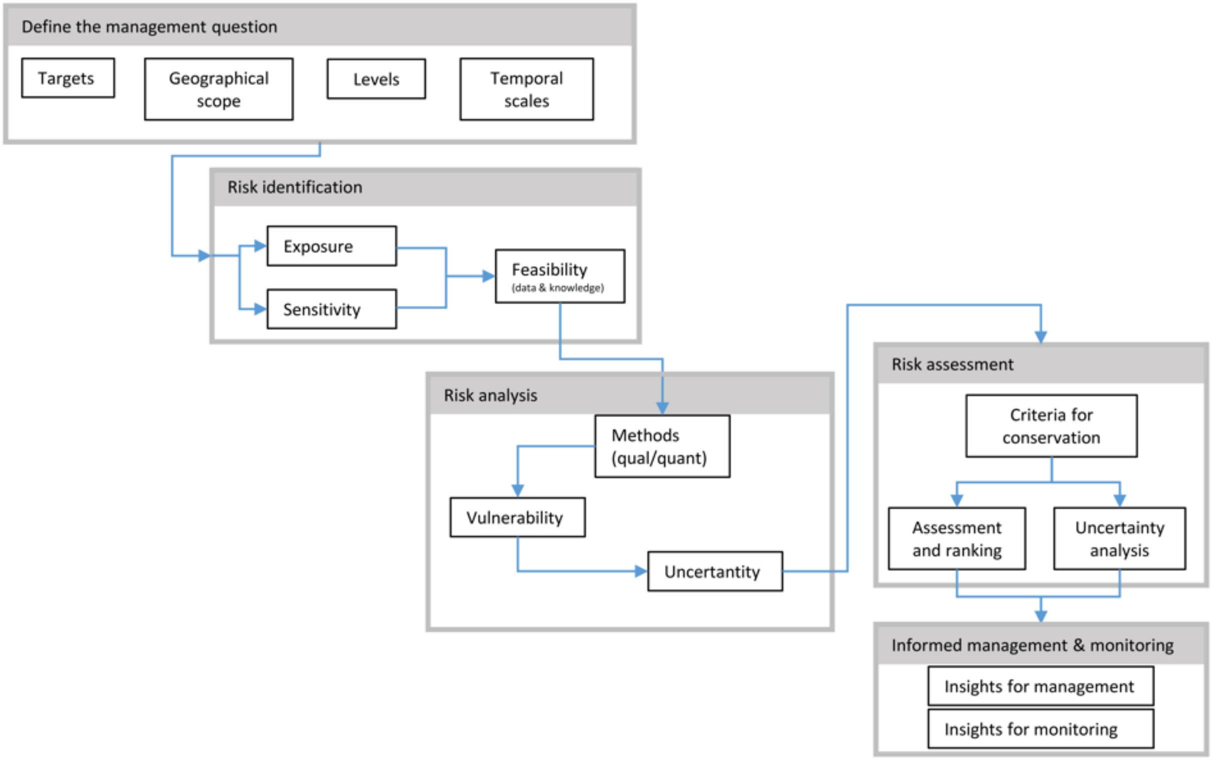


Figure 1 – General Flowchart of the guidance

The structure of the guidance was presented in the MSP4BIO General Assembly (GA) in Oostende in March 2023 and approved by the partners. Following the GA meeting, T3.2 requested feedback from all partners, and held additional meetings with representatives of T3.3 to identify their needs for the ESE-1 framework. It was clarified that T3.2 should focus on the vulnerability assessment because it provides an essential block to build a reliable ESE-1 framework. Additional meetings were held with representatives of WP5 to identify management concerns that could be addressed by the Guidance. Some of these management questions were chosen as examples of how to apply the guidance. The steps in building the vulnerability assessment, and examples of their applications were shown to the partners in the GA held in Split in November 2023.Thus, the vulnerability assessment is the core of the guidance.

The structuring of this guidance has considered the ongoing conceptualization of the ESE framework within Task 4.4-part II (a preliminary version of the ESE was presented at the Oostende meeting). This ensures alignment with the development of WP4, promoting compatibility and facilitating the seamless integration of the guidance into the elements of the ESE framework.

1.6 Guidance Chapters

Chapter 1 is this introduction to the guidance and the presentation of its structure. Each of the steps are presented in the next chapters.

Chapters 2 to 6 present the Guidance structure. Five main steps are involved:

Chapter 2 presents Step 1) Setting the assessment, i.e., identifying management goals and the boundaries of the assessment.

Chapter 3 shows Step 2) Risk identification for the area/species identified in Step 1, i.e., how to identify the exposure to climate stressors and the sensitivity of the selected species (or ecosystems) to these stressors (or combinations thereof).

Chapter 4 explains Step 3) How to perform the vulnerability analysis based on the exposure of the area and the sensitivity of the species.

Chapter 5 describes Step 4) Risk analysis, based on the management goals, the areas' exposure, and target ecological vulnerabilities. This chapter provides the methodologies to prioritize management actions.

Chapter 6 presents Step 5) Informed management and monitoring, returning to the management and focusing on choosing the final scenario for managing a complete MPA network.

Finally, **Chapter 7** provides the conclusions and final remarks.

The chapters are structured according to the following flowchart (*Fig. 2*).

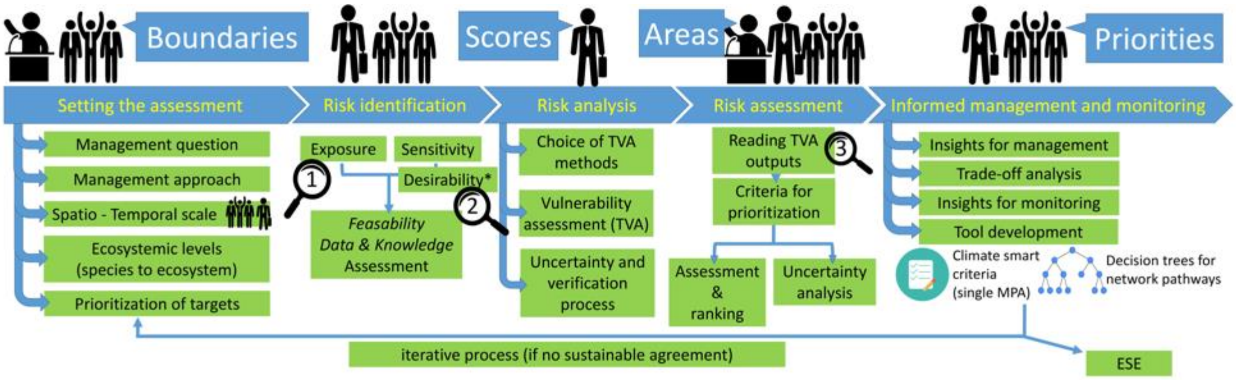


Figure 2 – Detailed flowchart of the guidance

2 Setting the assessment (Step 1)

The guidance framework adopts a bottom-up approach, commencing with the identification of the management questions, ecological goals and priorities unique to each distinct area, considering climate change. Defining clear management question(s) and analysis boundaries represent a crucial first step toward the choice of the most relevant and comprehensive vulnerability assessment of the targeted species or ecosystem.

The definition of an adapted analysis framework requires the cooperation of all the local actors or representatives of a territory (at each scale from local to international) and involve at least Managers, Planners and chosen Experts. Involving local representatives and/or stakeholders in the decision process is a key component toward management success (Cormier-salem, 2014; Giglio et al., 2019; Gomei and Di Carlo, 2012).

This first step is based on 5 fundamental components (*Fig. 3*). These components define the scope and the boundaries of the assessment.

They include:

- Define the management questions or conservation goals for Marine Protected Areas (MPAs)
- Choose the management approach (e.g., conservative or selective)
- Define the spatial and temporal scales of concern
- Define the ecological level of analysis (from species to ecosystem)
- Define and prioritize among the targets of conservation

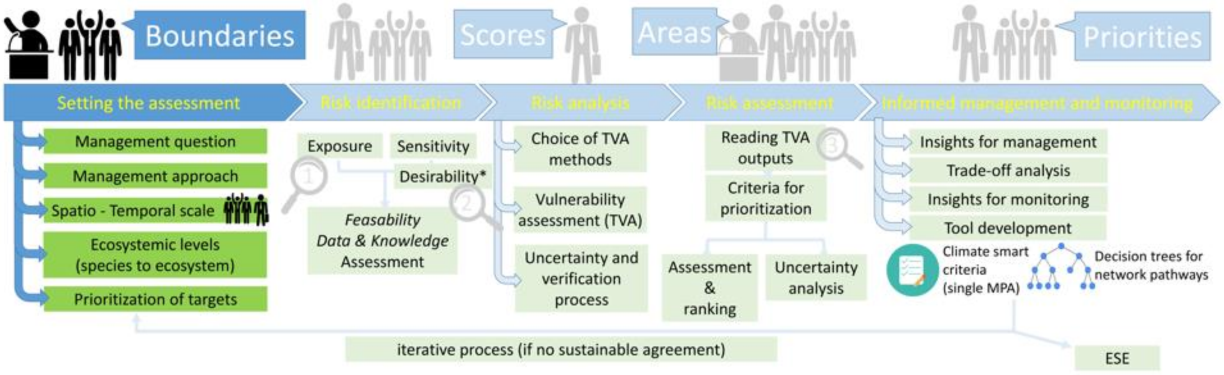
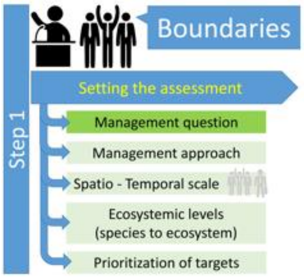


Figure 3 – Content of the first step of the Guidance

2.1 Select a management question



The selection of the management question(s) is clearly the most important part of the analysis as it defines and clarifies the objective (or a list of objectives) to which the analysis can provide an answer. Questions may include a spatial or temporal dimension and could call for a quantitative or descriptive response. The questions can target single species or habitats, or targets of protection (e.g., 30% of protection, 10% of strictly protection). The type of question will determine the methodology and complexity of the analysis.

The definition of the management questions aims to highlight the subject of the analysis. In general, the overall management issue can be formulated as follows:

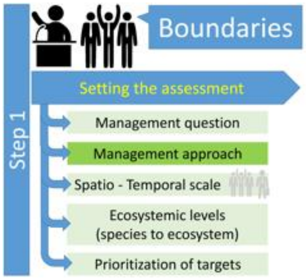
- *Which areas to protect in order to achieve the 30-by-30 target?*
- *How to protect habitats and species of priority for conservation in the context of a changing climate?*
- *What do I want to achieve?*

While more specific questions can be similar to the following (profided by test sites):

- Does warming influence the reef-former *Lanice conchilega* in the Belgian coastal area?
- How to predict the future of cod and sprat nurseries in the Bay of Gdansk regarding Climate Change?

All management questions need to be specified in the course of the Step 1 in order to achieve realist objectives from a specific, spatial and temporal point of view.

2.2 Choose the management approach: conservative or selective



Example of questions whose 2.2 aims to answer: What area the conservative features that I need to consider?

The next point is to choose a management approach. In general, there are two main approaches: ***conservative*** and ***selective***. Thus, the managers need to choose one to direct the analyses.

The ***conservative*** approach is cautious and considers the most pessimistic hypotheses. It encompasses as much of the entire ecosystem as possible to tend toward holistic protection based on current scientific and empiric knowledge and limiting the impacts of uncertainties on protection efficiency (modified from Beaugelin and Simon-Cornu, 2021). Historically dominant, the conservative approach is generally highly promoted by the international conventions, especially for MPAs whose role is to primarily combat the erosion of biodiversity. The current MPA conservative approach is currently facing criticism for perceiving the system as “static” (Cashion et al., 2020). It encounters challenges in adapting to persistent drivers of change, notably climate change. Since most species are foreseen to be impacted by climate change, the only management lever will be the mitigation of direct pressures such as fisheries to avert cumulative impacts (Grorud-Colvert et al., 2021; Roberts et al., 2017).

Conversely, the ***selective*** approach is a more pragmatic, anthropocentric approach, which considers the limitation of means that ensure ecological protection and the difficulty of management trade-offs between conservation and human activities, particularly for heavily frequented coastal areas. The principle of selective approaches is to narrow the scope of management to certain species and/or conservation priorities because of their disproportionate contribution to human societies or environment (modified from Swan et al., 2017). Generally, this approach will prioritize species or areas that directly provide high value ecosystem functions and services (e.g. mitigating climate change, sustaining fisheries, protecting engineer species), or have a certain cultural or representative value, or species whose conservation will benefit less visible species (e.g. the so-called umbrella or flagship species) (Branton and Richardson, 2011). It promotes a binary approach of the environment by promoting the fact that there will be winners and losers (Kayal et al., 2020; O’Brien and Leichenko, 2003; Venegas et al., 2023) and by encouraging the more efficient conservation of ecological key processes which sustain human activities. This strategy aims to enhance the species' resilience and recovery potential in response to evolving environmental conditions.

Both approaches present their own advantages and limitations. Far from being anecdotal, the choice of conservative or selective approach can arise from a difficult choice between socio-economic and ecological needs. Regarding climate change, ideal protection would rely on a balanced mixed approach to geared to minimizing the impacts of human pressures and increasing the capacity of ecosystems to provide goods and services. Climate-smart management will so beneficiate considering a focus on key species, especially those presenting desirable adaptive or resilient traits, from selective approaches while promoting a broad study and protection of the ecosystem as a whole from conservative approaches (see section 6.1 - *Designing climate-smart MPA*). In both cases, the chosen approach needs to be reevaluated regularly.

Examples of conservative approach:

- Promote the conservation of the list of Vulnerable species (e.g., from IUCN red list)

Examples of selective approach (SMART-approach):

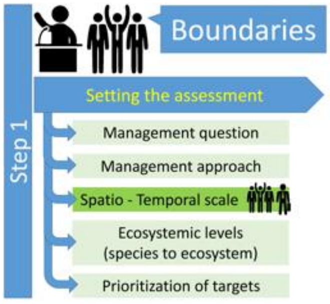
- Conserve 75% of the species in the area that are most likely to survive (thus excluding the most vulnerable species)
- Focus on foraging species (e.g. small-pelagic) to sustain the trophic network
- Focus on Flagship species including in the management plan of the area of interest (e.g. Marine mammals for the Pelagos sanctuary)
- Focus on the main fished species
- Focus on species representing desirable adaptive traits

While the choice is up to the decisions makers, the following warning should be considered:

> When it comes to setting priorities, there is still a lack of valuable information to support decision-making, which is partly why a "conservative" approach is favored. For example, to date, there is no hierarchy of ecosystem services and functions to help identify key ecosystem species. In this case, managers are strongly advised to maintain this "conservative" approach, or to take decisions only with the assistance of a committee of experts. In any case, it's important to recognize that there's still a great lack of knowledge about how marine ecosystems function, and that this calls for caution. In practice, decision makers ground the identification of conservation priorities and conservation features in MSP on the existing policies identifying conservation features, such as the Habitat and Species Directive, or the Marine Strategy Framework Directive.

Once the decision makers have chosen whether to use a more generalistic, ***conservative*** approach, or a more limited and anthropocentric ***selective*** approach, they can move to the identification of space and time boundaries.

2.3 Define the spatio-temporal scales of concerns

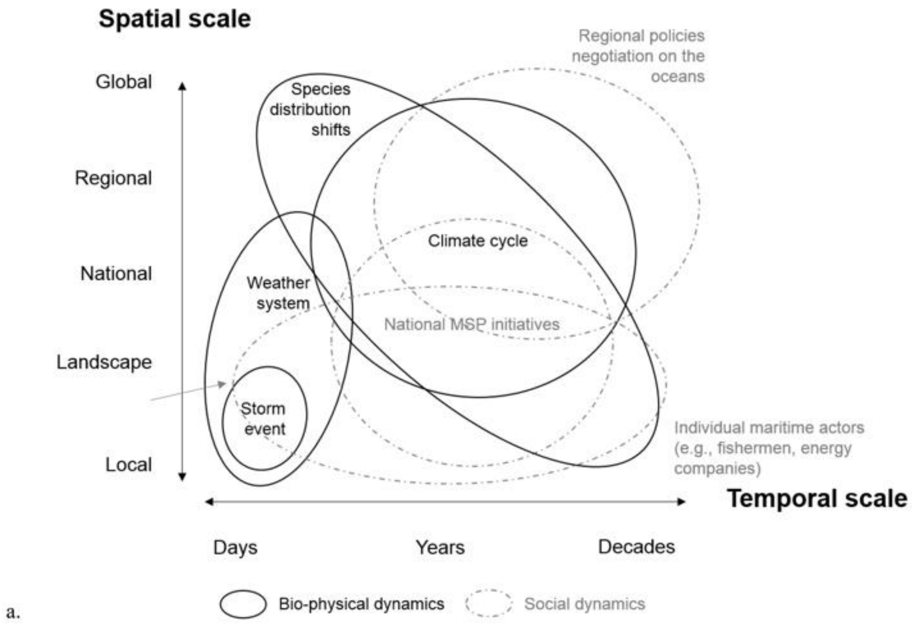


Example of questions that 2.3 aims to answer:

- *What is the spatial scale I am interested in? Does it include multiple jurisdictions? Am I interested in a single MPA, several MPAs, or MPA network(s)?*
- *What is my temporal horizon regarding climate change and my management questions? Which projection should I consider or build on?*

The next major point is to define the spatial (from local to international) and temporal (from decades to centuries) scales of the assessment. This step will (i) verify that all the actors of the chosen territories are identified and involved in the decision process and (ii) define a common vocabulary, considering that timescales and territories could be used differently between the fields of research and considering different goals.

A scale is defined as "*the spatial, temporal, quantitative or analytical dimensions used to measure and study any phenomenon*" whereas the 'levels' are defined as "*the unit of analysis that are located at different positions on this scale*" (Cash et al., 2006; Gibson et al., 2000 and references therein). Defining the spatio-temporality of management concerns will set the boundaries for analysis. It is an important factor as management priorities and reliable indicators will change from one scale to another (Trifonova et al., 2022), especially as the studies tend to consider different compartments of the water column or highly mobile species. Climate change impacts vary significantly across regions, necessitating an understanding of diverse climatic phenomena and physical processes within a vast dynamic range. The range can span spatial scales from 10^{-3} to 10^{7} meters and temporal scales from seconds to millions of years (Williams et al., 2017), such as those necessary for the identification of climate anomalies, for example (Franzke et al., 2020). The selection of spatio-temporal boundaries depends on the study's objectives (*Fig. 4*), acknowledging that uncertainties escalate with future projections and that the spatial resolution of the projection will generally decrease when we consider broader areas. Consequently, defining observation frequencies becomes integral to effective exposure analysis.



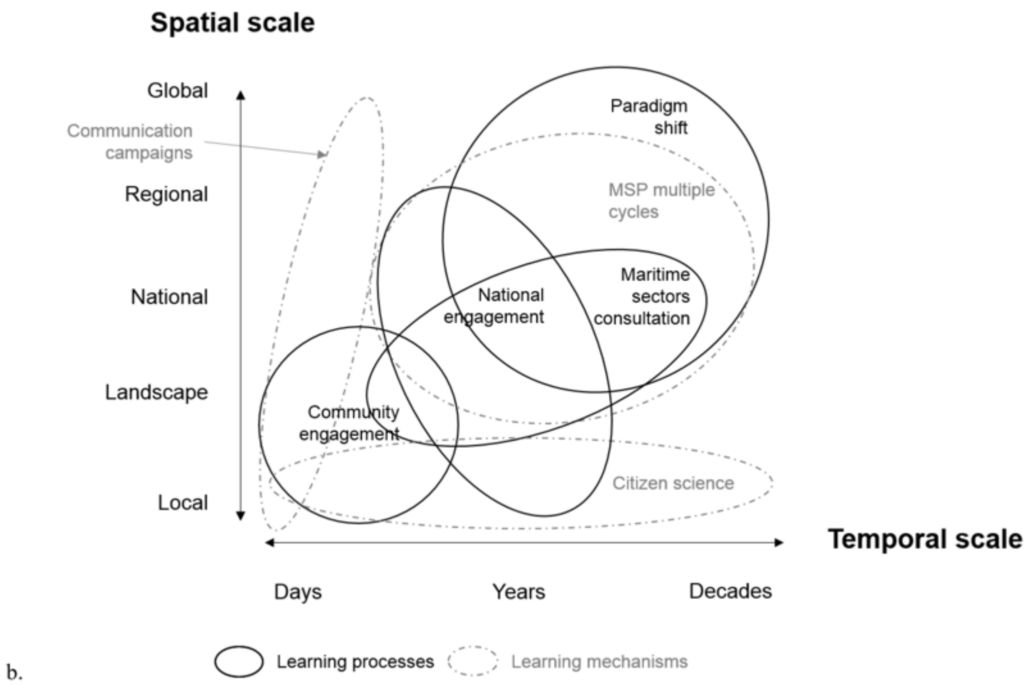


Figure 4 – Example from Gissi et al., 2019 of marine social and bio-physical dynamics inducing change at multiple spatial and temporal scales within MSP; panel a) reports examples of spatial-temporal dynamics as the “object” of the MSP processes; panel b) reports examples of spatial-temporal dynamics in relation to MSP processes, with specific attention to learning processes and mechanisms (elaborated considering the loopbased learning process proposed by Hargrove, 2008 in Pahl-Wostl, 2009).

The questions of scale and scale interactions are central in most of the research fields such as ecology, sociology, economy and policy sciences, in essence every component of the Ecological Socio-Economic (ESE) framework. They are nevertheless understudied (Gibson et al., 2000). The definition of scale must be agreed on by all parties, as consideration of what could be considered large- or small-scale is highly dependent on the research field and management issues and could lead to mismatch in the interpretation of results.

2.3.1 Spatial scale

- *What is the spatial scale I am interested in? Does it include multiple jurisdictions or boundaries? Will it focus on a single MPA, several MPAs, or MPA network(s)?*

The choice of the spatial scale will depend mainly on the management scope in ideal conditions (data-rich areas or when the data can be supplemented by complementary observation networks or dedicated funds). Pragmatically as data availability depends on the chosen scale, it will depend on a balance of two parameters: the management scope and the data availability. Indeed high-resolution data could be lacking for some climatic stressors or on the region of interest.

Large-scale or Macro-scale (global to supranational):

- Advantages: Identifies global trends and highlights the most vulnerable or resilient regions by comparing across regions, in order to maximize ecological and conservation benefits, while better distributing efforts and costs. Absolutely necessary in the context of mitigating global change, which calls for rapid and concerted action on a planetary scale due to the globalization of human pressures and shared resources.
- Disadvantages: Working on a large scale presents two major limitations. The first is the degradation of data accuracy compared to the local scale. The second is the growing complexity of decision-making procedures, due to the multiplication of the number of actors involved (Landauer et al., 2019). The centralization of issues can lead to disagreements between the states involved with regards to the strategies to be employed, depending on their respective internal policies. Enlarging the scale will uproot from the local actors network and can lead to blockages in the implementation of regulations or a drop in public compliance.

Small scale (from national to subnational scales)

- Advantages: better at capturing the local realities and heterogeneity. Working at small-scale generally favors a better inclusion of key local actors and local knowledge benefits (Pinsky et al., 2021) and provides a more flexible framework to implement and test iterative processes such as adaptative management. Arguably, the impacts of climate changes are most acutely felt at a local scale (Li et al., 2023). That is why small-scales are particularly relevant to study adaptivity and the efficiency of adaptation actions when management questions require specificity on particular areas. The local scale will also give the possibility to compare and better fit the models using both global and local monitoring networks, where available.
- Disadvantages: A downscaling process is necessary both for data and the research paradigm (Wilbanks and Kates, 1999), there is a limitation of forecast qualities of regional (if not local) impact, the monitoring data is difficult to access, and supplementary steps are necessary to distinguish between local and broader trends (*see section 3.2.4.1 – Methods, Downscaling*).

2.3.2 Temporal scale

- *What is my temporal horizon regarding climate change and my management aims? Which scenario should I use?*

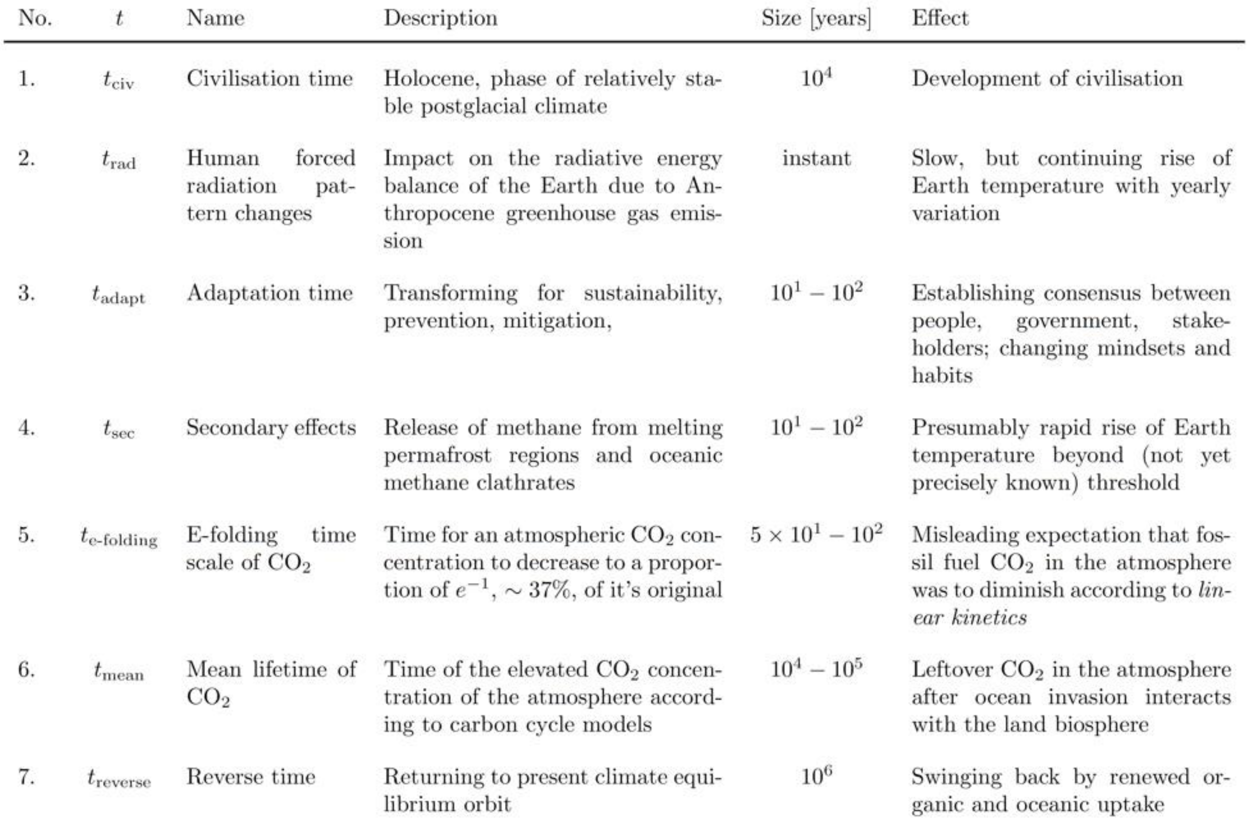
Regarding climate, the temporal scale is more challenging to choose than the geographic scale since long-term monitoring data are rarely available (Rilov et al., 2020). In any case, geographical and temporal scales are in part correlated. For example, century-scale phenomena cover large geographical areas and vice versa (Williams et al., 2017).

Basically, three primary time scales are commonly considered for forecasts:

- Early Century/Near Term: ~ 2015-2044
- Mid-Century/Medium Term: ~ 2035 - 2064
- Late Century/Long Term: ~ 2070-2099/2100

Most of the studies use 2100 since this represents the acceptable limit of the prevision of IPCC scenario (as the uncertainty of the prediction will be too large afterwards) (see section 3.2.3 - *Climate scenario and Timescales*). This time frame incorporates most of the different expected effects of climate change on the environment including the human-forced radiation pattern changes (resulting from Anthropocene greenhouse gases emissions) on which the climatic scenarios are based. Indeed, greenhouse gas emissions have a long residence time in the atmosphere and the benefits of mitigation will be evidenced after several decades. On a social or policy scale, the time step of 100 years is also considered to be the scale of a human lifetime (memory time), while allowing reasoning on an average of three generations, which is a sufficient time step to observe behavioural or societal adaptations (*Table 1*) (Hesselbjerg Christensen et al., 2023). For the biological component, this time-scale also includes most of species' complete life cycles and generation times (Jackson et al., 2021) except for some longeval species which have been relatively little studied to date (e.g. the Greenland Shark, *Somniosus microcephalus*) (Edwards et al., 2019), but that will become a priority as mineral and hydrocarbon exploitation, marine spatial planning policies and MPAs are currently expanding to the open sea and higher latitudes.

Table 1 – Time scales from climate change. Figure source: (Hesselbjerg Christensen et al., 2023).



No.	t	Name	Description	Size [years]	Effect
1.	t_{civ}	Civilisation time	Holocene, phase of relatively stable postglacial climate	10^4	Development of civilisation
2.	t_{rad}	Human forced radiation pattern changes	Impact on the radiative energy balance of the Earth due to Anthropocene greenhouse gas emission	instant	Slow, but continuing rise of Earth temperature with yearly variation
3.	t_{adapt}	Adaptation time	Transforming for sustainability, prevention, mitigation,	$10^1 - 10^2$	Establishing consensus between people, government, stakeholders; changing mindsets and habits
4.	t_{sec}	Secondary effects	Release of methane from melting permafrost regions and oceanic methane clathrates	$10^1 - 10^2$	Presumably rapid rise of Earth temperature beyond (not yet precisely known) threshold
5.	$t_{\text{e-folding}}$	E-folding time scale of CO_2	Time for an atmospheric CO_2 concentration to decrease to a proportion of e^{-1}, $\sim 37\%$, of it's original	$5 \times 10^1 - 10^2$	Misleading expectation that fossil fuel CO_2 in the atmosphere was to diminish according to *linear kinetics*
6.	t_{mean}	Mean lifetime of CO_2	Time of the elevated CO_2 concentration of the atmosphere according to carbon cycle models	$10^4 - 10^5$	Leftover CO_2 in the atmosphere after ocean invasion interacts with the land biosphere
7.	t_{reverse}	Reverse time	Returning to present climate equilibrium orbit	10^6	Swinging back by renewed organic and oceanic uptake

The choice of temporal scale will depend on the management question, the acceptable uncertainty, and the policy limitation.

Early-Term: The early term includes most of the actual convention goals such as the 30% spatial conservation target by 2030 (Target 3 of the Kunming–Montreal Global Biodiversity Framework, adopted during the 15th Conference of the Parties to the Convention on Biological Diversity). It is considered an appropriate timescale to see the first sign of migration, recovery or adaptivity of environmental, biological and societal components such as the co-benefits of gas emission reduction (e.g. air pollution reduction) or the efficiency of a marine reserve (e.g. spill-over effects) especially for the local scale. The interest of this time scale is mainly to evaluate the near effect of management lever and is used as an early warning of the climate trajectory taken by our society following the current management choice. For example, this timescale is suitable to evaluate the effect of the transformation of a local fishing fleet, or the effect of acute events such as heat waves, or bleaching events on marine organisms. Local/regional monitoring programs and policies are appropriate for this time scale. This time scale also presents the most reliable forecasts (Coro et al., 2020), although it does not allow for concerted long-term political action on a wider scale.

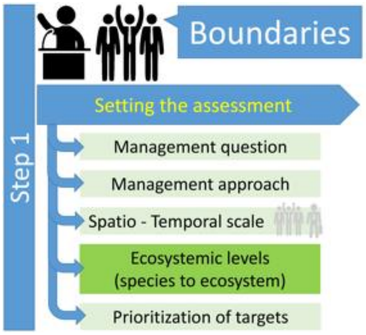
Mid-Term: The mid-term is a satisfactory compromise between early and long-term as it allows us to evaluate change over a longer term with an intermediate uncertainty, whilst also allowing us to deal with reasonable policy timing.

Long-Term: Long-term assessments are generally uncommon as they require high-performance computing and introduce more uncertainty in the predictions at small scale as the prediction are generally based on coarse hydrodynamic approximations such as general circulation models (Otto et al., 2016; Uhe et al., 2016). It also leads to more uncertainty regarding behavioural change, the potential spread of adaptivity traits, or the reaction of trophic networks regarding climate change (Petrik et al., 2020). The long-term assessment can be very useful to reveal global trends of ecological change, habitat shifts, impact on fisheries and on food provisioning due to climate change and is of primary interest for testing management trajectories (e.g. simulating broad scale connectivity networks considering migration capacities of species). This is especially true concerning the evaluation of the adaptability or transformation trends of human societies in response to climate change, since changing habits or developing new practices takes time. It is also true for the implementation of management bodies (such as MPA) as the MPA are not planned to be moved and should remain efficient.

To evaluate a MPA network and deal with climate uncertainty, we recommend considering at least two temporal scales (generally mid-term, long-term) as it is the best way to identify management options that meet the different objectives and to establish an efficient action plan over time (e.g. Hoegh-Guldberg et al., 2018).

Once the management temporal and geographical aims are defined, the next focus is the choice of the ecological level of interest.

2.4 Define the ecological levels (targets and criteria)



- *Shall I focus on species, or on areas/habitat, or on the ecosystem?*

After choosing the conservative or selective approach, the next level of the analysis is choosing from single species to ecosystem level. This depends on the management question that needs to be answered

2.4.1 Species Level

The species level is generally the most used in the trait-based analysis (Butt et al., 2022). This is primarily attributed to the availability of comprehensive databases containing biological and ecological traits at the species level, particularly for commercially important or flagship species.

Limiting management to the species level includes drawbacks, as not all species are thoroughly described, nor is their distribution. This level of analysis may provide decision-makers with only a partial perspective, as it overlooks the complexity of ecosystem interactions, including ecosystem function, trophic networks, and ecological services. This partly explains why MPA management tends towards a more holistic ecosystem-based management (Andradi-Brown et al., 2023; Marcos et al., 2021). This drawback is partially mitigated by incorporating trophic levels and descriptions of function or services as species traits in the analysis process. This helps with assessing trade-offs and making decisions by considering overlaps or mismatches in prey-predator distributions. It also allows us to evaluate which functions, services, or trophic networks are most threatened by comparing the vulnerability of species in different categories. In any case, these analyses are particularly suited for simulating species movement under climate change and identifying potential corridors. Thus, this level can be treated as a dynamic tool particularly suited to answer broad management questions such as defining the position of future MPAs for species of interest, or defining the minimum distance between two MPAs.

The second limit of trait-based assessment at single or multiple species level is that it does also overlook the intraspecific variability, assuming that all the individuals of a species presents the same reaction under climate change. If intraspecific variability is a reality, the evaluation of its importance in the success of management strategies seems difficult to achieve in Europe for numerous species at date. This could maybe be tested for some well-studied species or habitats, such as coral reefs for which dedicated surveys exist. Taking into account of intra-specific variability is a promising research theme which must be the subject of dedicated research, as it may be influenced by local factors and will instead derive from ensuring the functionality of MPAs. This dedicated reasearch is out of the scope of this guidance, as it mains purpose is to develop a framework applicable to many management questions and sites based on the current best available knowledge for the purpose of MSP.

2.4.2 Habitat/Grid cell Level (called Area level)

The area level is an intermediate level particularly relevant for simulating evolutionary trajectories of already implemented areas or potential areas of implementation of new MPA following species-level analysis. The area level will fix the geographical dimension of the analysis (e.g. MPA boundaries) and will focus on the temporal dimension. This level could be useful to determine the potential duration of management measures.

From a climate point of view, using climate-analogs will help managers to predict the potential evolution of the chosen area (see section 3.2 - *Exposure*). For areas vulnerability analysis, there is a short list of desirable areas-traits under climate change in marine ecosystems (e.g., Habitat redundancy inside the area of concern) that still need to be developed but that could be used to perform the analysis or support the selection decision process. Moreover, one of the possible proxies to analyze the evolutionary trajectory under climate change is to focus on species-traits for habitat-forming species. It is recommended to consider both the state of species and potential climate-induce presence or introduction of invasive species to perform vulnerability analysis on an Area-level as invasive species could greatly influence the state of areas that might be considered as part of MPA networks.

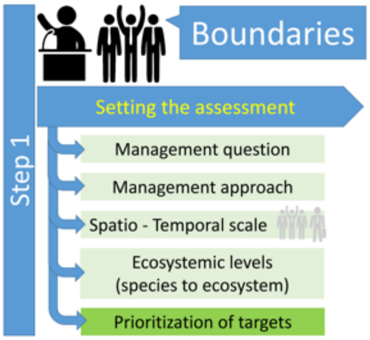
2.4.3 Community – ecosystem level

In general, in the trait-based analysis, the species level is considered as the unit of the ecosystem and the vulnerability of the ecosystem as the sum of the vulnerability of species within it. In fact, this view is supported by 5 reasons:

- The definition of the ecosystem by itself as an ensemble of organisms and their interaction both with the biotic and abiotic component.
- The possibility to simplify the analysis by selecting a subset of key species, ideally presenting various functions, services and trophic levels including habitat-forming species in the chosen area of concern
- The possibility to deal with uncertainty of presence or lack of data for certain species generally less of economic interest.
- The possibility to deal with the lack of data on desirable areas-traits
- The possibility to deal in the same analysis with the expectation of various actors or management concerns.

This approach presents nevertheless two main limitations: the impossibility of being exhaustive leading to the selection of a certain number of species and the need to develop a methodology to consider the uncertainty surrounding the selection of species (i.e. representativeness). It could be recommended at least to select enough species to represent as much as possible the variability of conservation issues, function, services and trophic levels. One of the possible guidelines is to select several species/habitat for each key element to simulate possible deferrals and to better understand the possible resistance or resilience of the studied ecosystems. Indeed, focusing on one species (especially flagship species) has shortcomings (Andelman and Fagan, 2000; Ricca and Coates, 2020) whereas the conservation of replicats is a key element to sustain environmental conservation under climate change (Green et al., 2007; McLeod et al., 2009).

2.5 Define and prioritize the targets of conservation including social concerns



What are the species/areas of key importance from ecological point of view? How to set priorities?

Once the level of analysis is defined regarding the general framework, the selection process of species of interest begins. This step is fundamental for selective approaches but also at ecosystem scale (to select key species used as proxy). It is strongly advised to rank species by ecological and socio-economical interest also for conservation approaches as this step allows the identification of the management targets for which trade-offs will need to be found with local actors if they are climate-sensitive. This list of species or areas is of great importance for the risk assessment (*see section 5 – Risk Assessment*) and the informed management steps (*see section 6 – Informed management and monitoring*).

The conservation target is defined based on a consultation between the different actors and considering both the ecological and the social inputs. There are several ways to prioritize targets of conservation both in terms of ecosystem and species. In general, the targets of conservation are already described in the management plans for the MPAs or listed in the indices of international conventions (e.g. Barcelona Conventions) and will remain so for most of them the same as they are mandatory. Nevertheless, it is important to keep in mind that the selection of that species or areas is often based on an analysis of stakeholders' perceptions, due to a lack of overall knowledge of the ecosystem, and therefore remains anthropocentric (Custodio et al., 2022). At any rate and considering climate change, some elements such as the potential of resistance, recovery or adaptation of species or areas are new elements that should be taken into account in the selection of species or areas of interest to tend towards the development of climate-smart management measures, MPAs and MPA networks. For example, for areas or ecosystems, the selection of areas with replicates of the same function, services, or habitat type inside the protected perimeter is one of the measures promoted to favorize the area’s climate resilience. Another measure is the inclusion in MPA networks of areas where we can already observe a diffuse incidence of climate change or episodic stress as it could theoretically promote the development and the spread of adaptivity traits. In each case, the trait-based sensitivity analysis could help to identify good candidates. The mobilization of expert knowledge and a in-depth analysis of the bibliography is still necessary to better define a list of relevant species for that purpose, at least to identify the knowledge gaps. Moreover, it could be interesting to redefine and adapt the concept of Vulnerable Marine Ecosystems (VMEs) developed by the FAO and ICES (ICES, 2021) to include other pressures, especially climatic pressures.

To identify the possibility of implementing a selective approach and ***setting priorities among species/areas regarding a given management goal***, **six questions** can be answered (*Table 2*, modified from Swan et al., 2017): (i) Can most of the benefits/function be ascribed to few areas/species/individuals? (ii) Is it possible to accurately identify and target these areas/species/individuals? (iii) Does targeting these species promote resistance/recovery/mitigation regarding climate change? (iv) Can indirect effects on the ecosystem be observed by conserving these areas/species/individuals? (v) On which scale can these effects be observed? (vi) Can targeting areas/species/individuals help to achieve social objectives (such as promoting stability or adaptivity)?

Table 2 – Step by step process to identify key species (modified from Swan et al., 2017)

Ecological evidence ➡	Targeting feasibility ➡	Impact evaluation ➡	Refinement ➡	Social assessment
1. Can most of the benefits/function be ascribed to few areas/species/ individuals?	2. Is it possible to accurately identify and target these areas/species/ individuals?	3.Does targeting these species promote resistance/recovery/mitigation regarding climate change?	4.Can indirect effects be observed on the ecosystem by conserving these areas/species/ individuals? 5.On which scale can these effects be observed?	5.Can targeting areas/species /individuals help to achieve social objectives (such as promoting stability or adaptivity)?

Setting priorities concludes the first step of the guidance as the framework and the management questions are detailed and clear enough to go further. The following step is the *Risk identification*.

3 Risk identification (Step 2)

Risk is defined by the IPCC as *the potential for adverse consequences for human or ecological systems, recognizing the diversity of values and objectives associated with such systems. In the context of climate change, risks can arise from potential impacts of climate change as well as human responses to climate change. Relevant adverse consequences include those on lives, livelihoods, health and wellbeing, economic, social and cultural assets and investments, infrastructure, services (including ecosystem services), ecosystems and species* (Reisinger et al., 2020). In the guidance, the *Risk identification* step (*Fig. 5*) aims to define ***Exposure*** and management target ***Sensitivity*** to be included in the adapted ***Vulnerability assessment*** if the ***Feasibility*** criteria are filled.The Exposure definition means the selection of, at least, a climatic stressor or a list of stressors (including climatic and non-climatic stressors) that will be used as drivers of changes regarding the chosen management target. *Sensitivity* is defined as the degree to which a system is affected positively and negatively by the stressors selected in the *Exposure* parts (Marshall et al., 2010; Tuler et al., 2008). In this guidance Sensitivity is assessed using management-target traits. Once *Exposure* and *Sensitivity* traits are defined using the analysis framework, the Feasibility step aims to define the vulnerability assessment methodology adapted to the management framework and according to data availability.

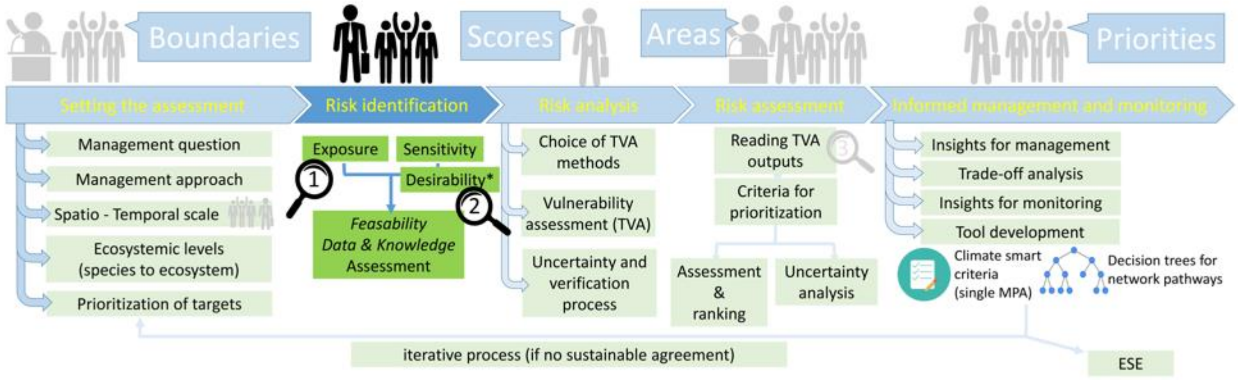


Figure 5 – Advancement in the guidance flowchart and key component of the second step "Risk Identification"

3.1 Background analysis about current species/communities/areas

The first step of risk identification is to provide an initial description of the current state of knowledge about the selected species/communities/areas, according to the level of analysis selected in Step 1 (*Fig. 5*). Data, information, and background knowledge are collected with respect to the ecological features targeted in the analysis. Specifically, available spatial data – such as spatial distribution of the species or habitats, habitat suitability information, maps about benthic ecosystems, or sightings of species – are collected to inform the spatial analysis performed in the following steps.

Sources of data can be manifold and depend on the conservation features targeted by the analysis, the capacity of the planning team and the data availability for the specific feature and geographical area. Presence/absence or occurrence data for many species can be obtained from geoportals such as the Global Biodiversity Information Facility (GBIF; http://www.gbif.org) or the Ocean Biogeographic Information System (OBIS; http://www.iobis.org). It could also be implemented with published datasets from scientific literature where available.

Systematic information on habitat suitability for many species or for all the priority species for conservation is unlikely to be available. Habitat suitability is defined as the habitat potential to support a species (Kellner et al., 1992) and represents a key component for presuming the distribution of a species when unknown. Habitat suitability models predict indeed the likelihood of occurrence of species based on environmental variables (Hirzel and Le Lay, 2008). Examples of datasets that provide projections of species distributions are provided in *Box 1*.

Box 1. Examples of available datasets and data platforms for species and habitat distribution

AquaMaps (Kashner et al. 2019, Kathleen-Reyes et al. 2019). AquaMaps is a tool for generating model-based, large-scale predictions of natural occurrences of marine species based on the description of species' natural envelopes (i.e. species environmental preferences) in terms of depth, water temperature, salinity, primary productivity, dissolved oxygen and association with sea ice and coastal areas from the actual main available dataset (e.g. Fishbase, SeaLifeBase). The outputs, a grid of half-degree (0.5°) latitude and longitude cell dimension of the models, are then verified by experts and exported to the platform. Some maps are not yet verified but could be used with caution.

The actual version available for AquaMaps (2019) includes 33,518 maps for all the marine species including 12,939 marine fishes, 123 marine mammals, 20,056 other marine metazoan, 299 macroalgae and marine vascular plants, 66 biodiversity maps, 66 checklists by Large Marine Ecosystem (LME, e.g. Baltic Sea, Kuroshio Current, Red Sea). The maps represent probability of occurrence at the baseline conditions and for future scenarios at year 2050 for Representative Concentration Pathways at 4.5 (intermediate emission scenarios) and 8.5 (high emission scenarios).

Link to AQUAMAPS *dataset*: https://www.aquamaps.org/

About data Processing:
https://aquamaps.org/main/FB_Book_MarineAquaMaps_062023.pdf#page=1

Access and use: The data could be accessible in csv format

Access the data with R: the aquamapsdata package
https://raquamaps.github.io/aquamapsdata/articles/intro.html

Fine-tuned global distribution dataset of marine forest (Assis et al., 2021): The dataset covers 682 accepted taxa (at the species level) belonging to the orders Fucales, Laminariales and Tilopteridales (i.e., brown macroalgae), and the families Cymodoceaceae, Hydrocharitaceae, Posidoniaceae and Zosteraceae (i.e., seagrass).

The dataset is publicly accessible for download in a permanent Figshare41 repository (https://doi.org/10.6084/m9.figshare.7854767). A version containing only pruned records is also accessible at https://www.dataone.org and https://www.marineforests.com.

OBIS (OBIS, 2023). The Ocean Biodiversity Information System (OBIS) provides access to over 45 million observations of nearly 120 000 marine species in a standardised format, with global coverage of the oceans. It integrates biogeographic, physical, and chemical environmental data and derives its taxonomic, geospatial, and conservation data from the World Register of Marine Species (WoRMS, https://marinespecies.org/), Marine Regions (https://marineregions.org/), and the IUCN Red List (https://www.iucnredlist.org/) respectively. EurOBIS (https://www.eurobis.org/) is the European node of OBIS

Link to OBIS dataset search: https://obis.org/datasets

Link to OBIS Mapper: https://mapper.obis.org/

Access the data with R via the robis package: https://github.com/iobis/robis

GBIF (GBIF, 2023). The Global Biodiversity Information Facility (GBIF) provides an index of hundreds of millions of species occurrence records, including non-marine species.

Link to GBIF occurrence search:
https://www.gbif.org/occurrence/searchhttps://obis.org/datasets

*Link to GBIF species search: https://www.gbif.org/species/search*https://mapper.obis.org/

Link to GBIF dataset search: https://www.gbif.org/dataset/searchhttps://obis.org/datasets

EMODnet Biology. EMODnet Biology provides open access to data and data products on the temporal and spatial distributions of marine species from European regional seas. The data can be accessed via the catalogue or the map viewer, both of which also include data products from EMODnet's other thematic lots.

Link to EMODnet product catalogue:
https://emodnet.ec.europa.eu/geonetwork/srv/eng/catalog.search#/searchhttps://www.gbif.org/occurrence/search

https://obis.org/datasets*Link to EMODnet map viewer:*
https://emodnet.ec.europa.eu/geoviewer/

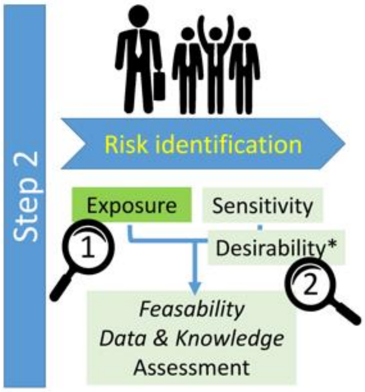
Local Species Databases:

Helcom species Database: https://maps.helcom.fi/website/biodiversity/

Considering the MSP principle of the best available knowledge (EC, 2014), planners are invited to take note of the type of data and information available for the analysis. For marine species, distribution boundaries on oceanic scales are often associated with gradients in temperature and depth, while regional to local-scale distributions are also limited by factors such as salinity, nutrient supply, topographic complexity and sediments (Sbrocco and Barber, 2013). If habitat suitability data and related maps are not available, statistical methods can be used to model species or habitat distributions (e.g., Foster et al., 2024; Melo-Merino et al., 2020), but this is not the focus of this guidance.

Of note, data, information and knowledge for the case study area are collected from literature review, grey literature, and often from local ecological knowledge.

3.2 Assessing exposure using climate scenarios



Objective. The exposure analysis is meant to guide the identification and selection of one or several stressors (climatic and human) for the risk analysis process. The description of stressor is generic and is redefined regarding the selected species and the scale of work.

This section should help to answer the following questions:

- Question 1: What are the most relevant climatic stressor(s) in the case study area?
- Question 2: What are the spatio-temporal scales and the timing of this/these stressor(s)? Do they match with the framework defined by the management objectives?

Pre-requisite. Regarding stressors, a third question arises:

- Question 3: Do the stressors interact? Is it relevant and possible regarding the state of knowledge and the management question to take the interactions into consideration?

In the case of this guidance, we chose to consider only additive stressors to reduce uncertainties on climate interaction without simplifying too much the incidence of CC.

Expected outputs.

- Current Climate conditions Layer serves as reference, generally from satellite data alone, observed data or a combination of both methods.
- Future Exposure Layers (see section 3.2.3 - *Climate Scenarios and Timescales*): as we consider additive methods, one layer per chosen stressor (climatic, climate change-induced invasive species and anthropic), climate scenario (IPCC scenario) and chosen timescale is produced (i.e. up to 9 layers per chosen stressor). These layers will represent a portfolio of potential futures conditions.
- Anomalies Layers (see section 3.2.4.1 – Methods, *Anomalies*): anomalies layer are synthesis layers revealing the disparities in exposure between current conditions to a potential Future Exposure Layers. Anomalies layers help to rank areas regarding the intensity of their exposure.
- Climate Velocities Layers (see section 3.2.4.1 – Methods, *Climate velocities*): velocities layers represent a set of similar areas in time and space regarding their climatic conditions. Velocities layers are defined regarding climatic data only or considering a management target.

Regarding the packages used to produce the data or the need from the ESE model, the layers could be produced in different formats.

The section *Assessing exposure using climate scenarios* is decomposed in three main components: (i) the definition of climate-related exposure criteria including the selection of stressors, the analysis of the Time of Emergence ToE, the selection of climate scenarios and the choice of climate-related methods of analysis; (ii) the selection of exposure non-climatic data; (iii) the calculation of the final Exposure score (additive method) (*Fig. 6*).

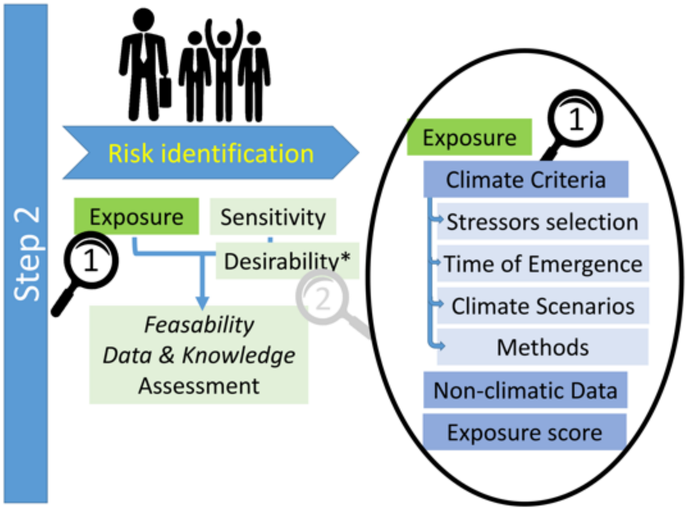
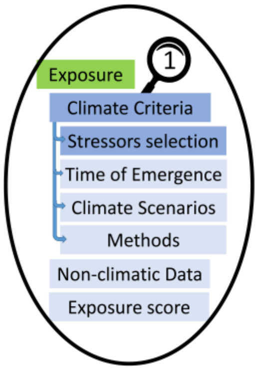


Figure 6 – Flowchart of the Exposure section (step 2 Risk Identification of the guidance)

3.2.1 Selection of climatic stressors (Question 1)



This step aims to select the climate-related stressors regarding both the species of interest and data availability in the area defined in the framework.

3.2.1.1 Climatic stressors presentation and stressors interactions

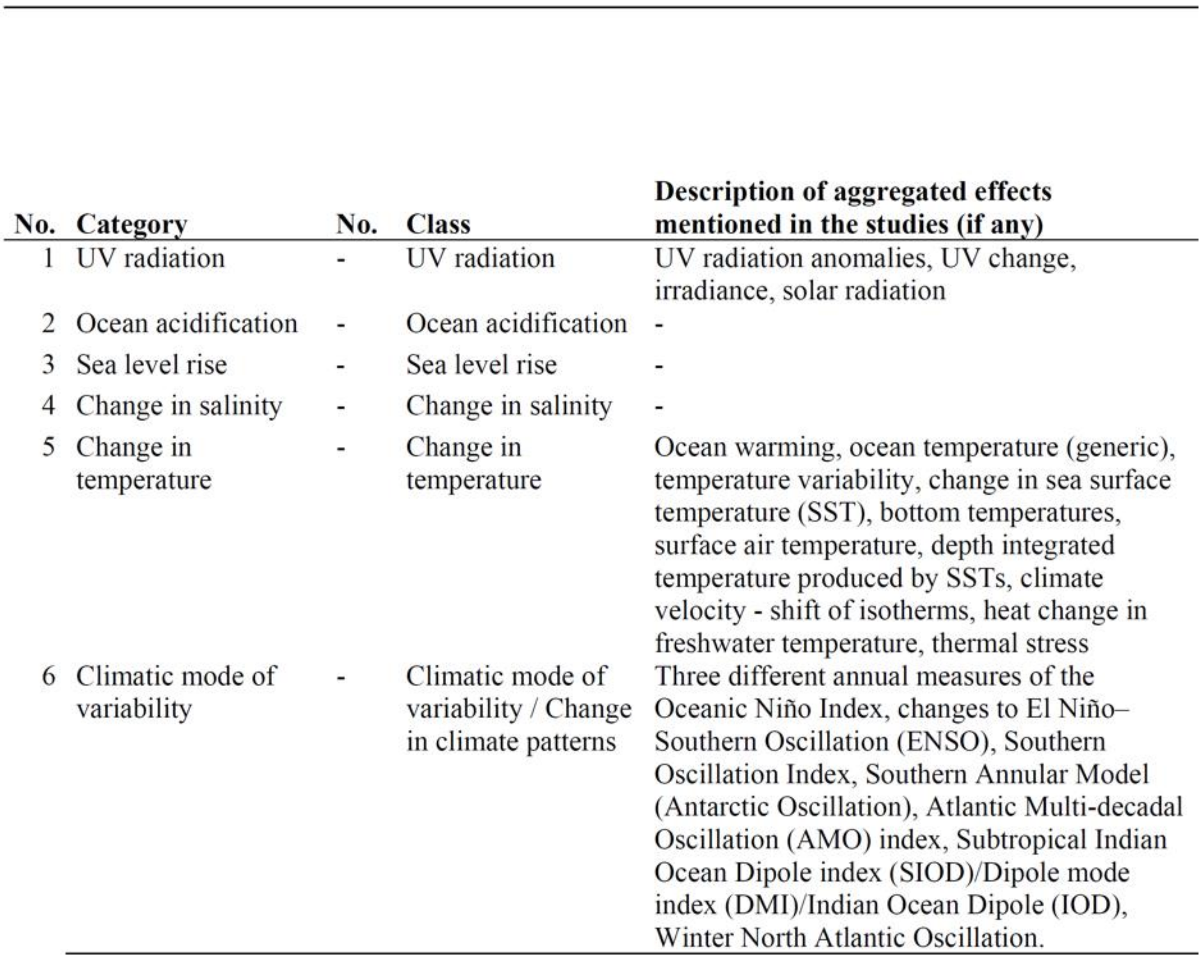
Regarding climate change, a list of ten major climatic stressors were established including water temperature change (and especially Sea Surface Temperature SST), changes in salinity, ocean acidification, deoxygenation, increases in storm disturbance, oceanographic processes, increased ultraviolet radiation, sea-level rise, increased air temperature and invasive species spread that represents an indirect but highly associated stressor (e.g. Villero et al., 2022).

In this guidance, we recommend using several climatic stressors (when available) and consider their effects as additive pressures (as stressors act in isolation) per grid cell using basic cumulative impacts models (Korpinen et al., 2021; Wahlstrom et al., 2022) as the interaction between the stressors is not well studied in the literature. Indeed, using a single stressor (often SST) could lead to significant underestimations of the climate incidence whereas considering the interaction(s) between stressors is complex and can often lead to a high level of uncertainty. The stressors could interact (i.e. synergize or act as antagonists) or dominance relationships can be observed (Nogues et al., 2023) which depend on the area and the species in question. Considering climatic pressures as additives is an acceptable compromise. For test sites where climatic pressures are better characterized, methods exist to discriminate the type of interactions (e.g. Nogues et al., 2023).

3.2.1.2 Choice of climatic stressors

When data are scarce or when the computation power is limited, it may be necessary to select or prioritize the inclusion of specific stressors. Indeed, climatic stressors are unevenly studied with a higher focus on change in temperature and ocean acidification (Gissi et al., 2021) (*Table 3*). Other stressors, such as deoxygenation (Morée et al., 2023), are much less studied. The choice of stressor will depend on three different components: the time of projection, the chosen area and the species considered. Ideally, data availability should not influence the choice of stressors inside the analysis but in reality, it will, particularly in data-poor countries. To partially address the lack of data, we recommend to consider proxies (e.g. SST for climate-induced ocean warming) as much as possible and suggest the implementation of dedicated survey when data is lacking.

Table 3 – Classification of the categories and classes on which climate change (CC) effects were grouped, and frequency of the CC effects with which they have been studied in combination to local human stressors at different levels of biological diversity in the 107 studies from the literature review (table from Gissi et al., 2021).



No.	Category	No.	Class	Description of aggregated effects mentioned in the studies (if any)
1	UV radiation	-	UV radiation	UV radiation anomalies, UV change, irradiance, solar radiation
2	Ocean acidification	-	Ocean acidification	-
3	Sea level rise	-	Sea level rise	-
4	Change in salinity	-	Change in salinity	-
5	Change in temperature	-	Change in temperature	Ocean warming, ocean temperature (generic), temperature variability, change in sea surface temperature (SST), bottom temperatures, surface air temperature, depth integrated temperature produced by SSTs, climate velocity - shift of isotherms, heat change in freshwater temperature, thermal stress
6	Climatic mode of variability	-	Climatic mode of variability / Change in climate patterns	Three different annual measures of the Oceanic Niño Index, changes to El Niño–Southern Oscillation (ENSO), Southern Oscillation Index, Southern Annular Model (Antarctic Oscillation), Atlantic Multi-decadal Oscillation (AMO) index, Subtropical Indian Ocean Dipole index (SIOD)/Dipole mode index (DMI)/Indian Ocean Dipole (IOD), Winter North Atlantic Oscillation.

7	Other atmospheric and weather effects	7.1	Winds change	Meridional wind speed anomaly (MWSA), wind direction, wind changes
		7.2	Increase in storm	Increase in storm frequency - cyclone frequency - rare storm events - Severe Tropical Cyclone
		7.3	Extreme weather events	Extreme weather events, hot weather events, change in weather
		7.4	Change to currents	Change to currents, currents
		7.5	Change in precipitations	Change in precipitations amounts and patterns, extreme rainfall events, decreased annual rainfall, precipitation records
		7.6	River inflow altered	River inflow, altered low and peak flows from climate change, change in freshwater hydrology
		7.7	Sea ice extent	Sea Ice Extent - sea ice decrease, sea ice concentration, loss of Artic sea ice
		7.8	Climatic models scenarios	Changing/dynamic carrying capacity of the climate change scenarios, regional climate models
		7.9	Atm. Sea level pressure	Atmospheric sea level pressure
		7.10	Oxygen conditions	Hypoxic areas, oxygen conditions
		7.11	Change in upwellings	-
		7.12	Change in pCO2	-
		7.13	Air-sea heat fluxes	Air-sea heat fluxes
		7.14	Evaporation	Evaporation
8	CC-induced biological drivers of change	8.1	Mass mortality effects	-
		8.2	Coral bleaching derived	Coral bleaching (derived from climate driven increase in temperatures).
		8.3	CC driven alga blooms	Climate driven alga blooms - specific events
		8.4	Disease	Disease - Temperature anomalies relevant to disease
		8.5	Invasive species	CC-induced invasive species increase
		8.6	Native species change	Native species changes in distribution and abundance induced by CC
		8.7	Q10 parameter	Magnitude of the Q10 parameter controlling temperature dependence

Selection considering the spatio-temporality of management concern

The shortlist of climatic stressors to be included in the analysis process depends on the spatio-temporality of interest (projected timescale, depth and geographic range) and the selection of stressors that are known to be relevant within the literature. In *Table 4*, as example, we present a proposition of stressors' selection for each test site that needs to be verified and actualized by deeper literature screening as part of it is based on scientific grey literature. The further into the future the climate projections are made, the greater the number of stressors to be considered (see section 3.2.2 - *Time of Emergence*) as climate change could be considered as a complex sequence of events that has yet to be described and understood.

Table 4 - Examples of climatic drivers that have been considered as major sources of change in the marine environment in the case studies at different scales. These drivers are examples that need to be further explored based on evidence in literature, and data, information, and knowledge on climate change in the different case study areas.

Case study	Primary climatic drivers	References
Mediterranean Sea	SST, pH, pCO2, * Add Invasive Species at Near-Term for Adriatic Sea *** SSS (Sea Surface Salinity) for long term	(Carrier-Belleau et al., 2021; Heip et al., 2011; Parras-Berrocal et al., 2020)
Baltic Sea	SST*, Ice Cover Reduction, Sea surface salinity (SSS)** Theoretically, Deoxygenation should be added for mid- and long-term projection, Acidification for long-term projection as eutrophication mitigates the effect at short-term) * mainly in Bothnian Bay and Bothnian Sea during summer ** In Danish straits region mainly and Belt Sea	(Andersson et al., 2015; Borges et al., 2022; Conley et al., 2002; Lin et al., 2006)
Belgium	SST, SLR, Flooding	(Heip et al., 2011)
Açores	SST, Precipitations	(Santos et al., 2004)
Black Sea	SST * Add Invasive Species at Near-Term for Adriatic Sea	(Borges et al., 2022; Conley et al., 2002; Heip et al., 2011; Lin et al., 2006)

Selection considering species of interest

The relevance of climatic stressors may also vary according to the taxa of interest. We propose in *Fig. 7* a global ranking of the main climatic stressors per taxon (adapted from Butt et al., 2022). The classification is based on a vulnerability assessment of taxa already performed at global scale, but the incidence of stressors could change from one area to another or from one species to another within the same taxa. Nevertheless, we consider that this ranking could be a great support to the decision-process as the ranking is less likely to change completely. All the vulnerability scores of the taxa (including human pressures) could be found in Annex 1.

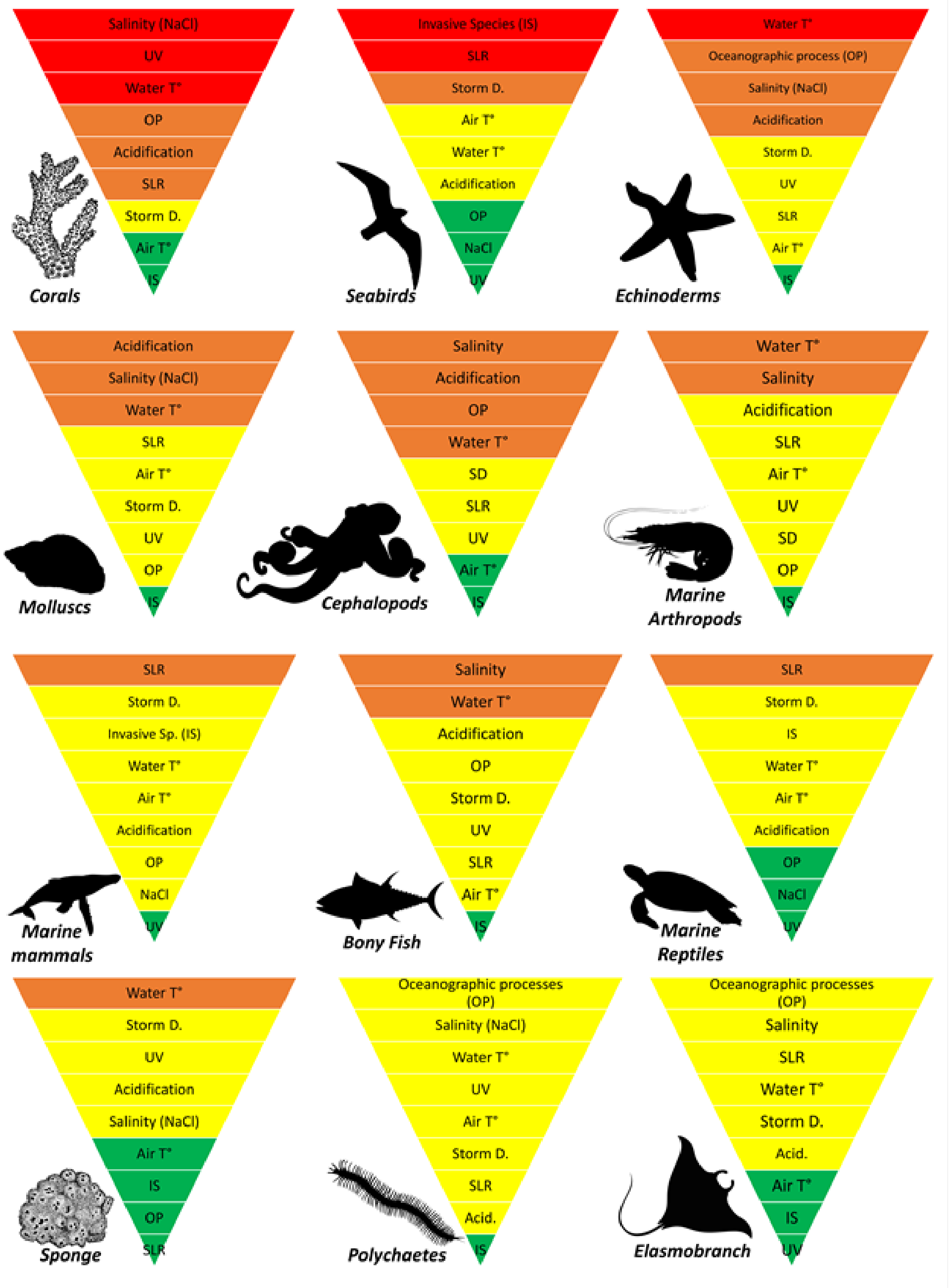
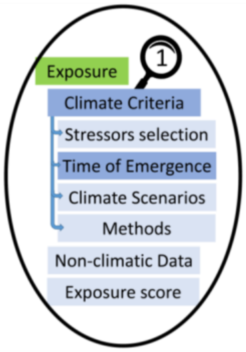


Figure 7 -– Relevance of climatic stressors by main marine taxa as emerging from the analysis by Butt et al. (2022). Red = high vulnerability (Vulnerability Score (VS) > 0.5), orange = medium vulnerability (0.5 ≥ VS > 0.3), yellow = Low vulnerability (0.3 ≥ VS > 0), green = No vulnerability (VS = 0). Figure adapted from Butt et al., (2022).

3.2.2 Time of emergence (Question 2)

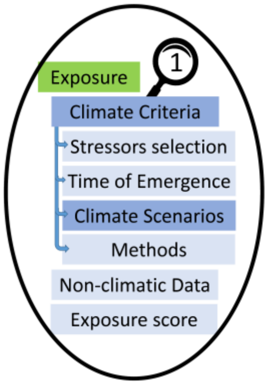


When the stressors are selected regarding data availability, areas and/or species of interest, the second step is to verify the *Time of emergence* (ToE) of each selected stressor in the areas to validate the stressor selection. The time of emergence is defined as *the point in time (past or future) when the signal of climate change emerges from the noise of background variability* (John et al., 2023). After selecting the stressors, the timescales of the analysis framework and the stressors' ToEs should be compared to ensure that they correspond. If this is not the case, the stressors can be removed from the analysis, as their effect is undetectable within the framework defined in step 1. Calculating the ToE for each of the stressors for which data are available is also a means to select relevant stressors inside the defined framework. If the management question focuses on the effect of a particular stressor, calculating the ToE would assess if the period considered in the analysis framework needs to be enlarged.

Several methods exist to calculate stressors' ToE generally based on the decomposition of climatic data sequences (see section 3.2.4.1 Method, *Time series decomposition based on LOESS* section) which discriminate the climate change signal from the noise of a detrending temporal series (e.g. Gaetani et al., 2020; Hawkins and Sutton, 2012).

Regarding Climate change, the ToE needs to be calculated based on different climate scenarios to provide a potential range of ToEs under different futures. This panel of ToEs will provide a probability that each of the stressors will influence the management target in the future within the boundaries defined in step 1.

3.2.3 Climate Scenarios



As future conditions are uncertain, it is necessary to consider a variety of future projections to define a range of possible future and deal with this uncertainty. This range of future projections will correspond to the creation of a range of layers, each one representing one of the potential futures.

3.2.3.1 IPCC scenarios presentation

The potential futures are synthetized by the Intergovernmental Panel on Climate Change (IPCC) through five main scenarios (*Box 2*). Each of these scenarios are linked to different radiative forcing and will lead to different level of changes. These levels of change need to be considered when projecting the future climate conditions.

Box 2. IPCC SCENARIOS (from IPCC, 2021)

The different IPCC Scenarios

In 2021, the Intergovernmental Panel on Climate Change (IPCC) published its latest report presenting 5 new scenarios covering a wide range of possible futures depending on our ability to reduce Carbon Dioxide (CO_2) and other greenhouse gas emissions. These scenarios are based on five *Shared Socioeconomic Pathways* (SSPs) linked to different radiative forcings by 2100 (O'Neill et al., 2017; Riahi et al., 2017).

The **SSP1**, also known as the *Sustainable Development Pathway*, is based on our ability to establish *strong international cooperation* to prioritize sustainable development. It aims at an overall improvement in living conditions and a shift in consumption patterns towards environmentally friendly and resource and energy efficient goods and services. Under this scenario, two trajectories emerge according to the probable increase in radiative forcing estimated between 1.9 (**SSP1-1.9)** and 2.6 W/m^2 (**SSP1-2.6**). This increase is linked to the estimated rate of greenhouse gas reduction, with future CO2 emissions expected to become zero between 2055 (SSP1-1.9) and 2075 (SSP1-2.6) followed by a progressive consumption of atmospheric CO_2. These trajectories result in an average temperature increase of between 1.5 (SSP1-1.9, closest to the Paris Agreement targets) and 1.8°C (SSP1-2.6), leading to global mitigation and adaptation challenges that are considered low under this paradigm.

The **SSP2**, based on a *continuation of current development and growth trends with strong geographical heterogeneity,* is considered an intermediate scenario. Sustainable development is difficult to achieve despite the support of national and international institutions and a decrease in resource and energy dependency. This scenario does not lead to neutrality by 2100 despite an observed decrease in CO2 emissions after 2050. SSP2 is currently considered the most plausible scenario given the current socio-political context and would lead to a radiative forcing of 4.5 W/m^2 (**SSP2-4.5)** or a global average temperature increase of 2.7°C by 2100. The SSP2 presents a challenge for mitigation and adaptation that is considered to be medium.

The **SSP3** is a scenario based on the emergence and maintenance of *regional rivalries and rising nationalism.* Economic development is slow with persistent inequality and conflict. Countries are in competition with each other, focusing on internal issues of energy and food security. The environment is not a priority and is deteriorating. Projections for this scenario suggest a steady increase in carbon dioxide emissions, which would double by 2100, as well as aerosols, methane and nitrous oxide. SSP3 would lead to a forcing of 7 W/m^2 (**SSP3-7.0**) or a temperature increase of 3.6°C by 2100 and would present high mitigation and adaptation challenges

SSP4 is the scenario of *inequalities both within and between states*. The gap between the globalized elite responsible for most greenhouse gas emissions and low-income populations vulnerable to climate change is widening, leading to increased conflict and a lack of social cohesion. Energy sources are multiple and environmental policies are locally focused. This scenario does not lead to a greenhouse gas projection in the IPCC report because its radiative forcing varies between 3.4 and 6 W/m^2 (rarely below 2°C) in the absence of additional climate policy and thus represents a range of trajectories that are difficult to predict. It is considered to present a low challenge for mitigation but a high challenge for adaptation.

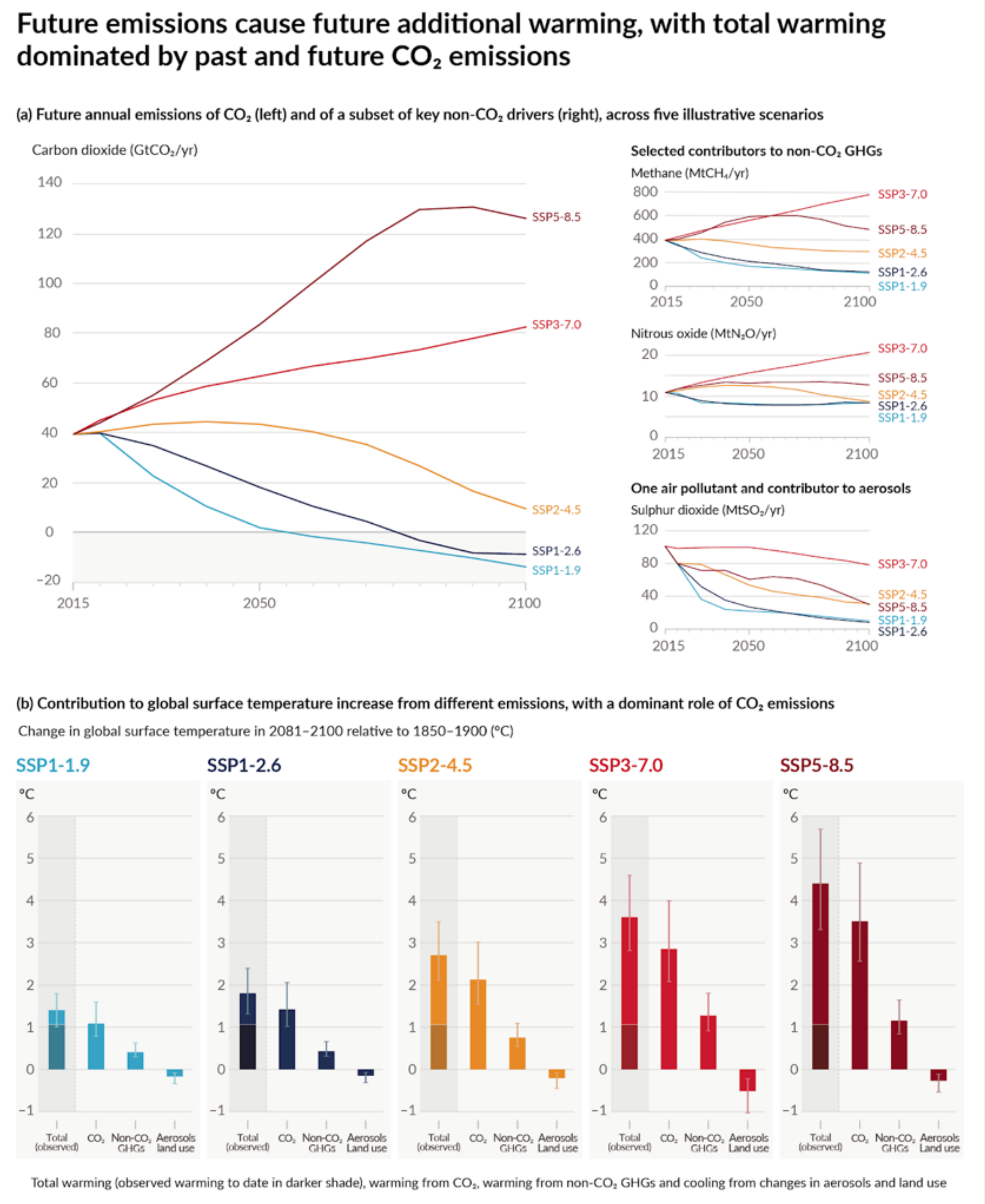


Figure 1 – Presentation of different climatic scenario trends according to greenhouse emission (IPCC, 2021: Summary for Policymakers p°13).

Finally, **SPP5** is the conventional development scenario. This scenario is based on *high economic growth and technological progress through strong exploitation of fossil fuels and high investment in health, education and new technologies that are resource and energy intensive*. Local pollution is well managed, and poverty is reduced. It results in an average radiative forcing of **8.5** W/m^2 (**SSP1-8.5**) or 4.4°C and a doubling of CO2 emissions by 2050. It represents a strong challenge for mitigation but a weak one for adaptation.

Overall, the SSP1 and SPP5 scenarios present positive trends for the development of human societies, but the SSP1 scenario presents a society that turns towards sustainable development and takes into account climate concerns, whereas the SSP5 scenario is based mainly on the exploitation of fossil fuels.

In contrast, SSP3 and SSP4 are rather pessimistic and assume rapid population growth and increasing inequalities in all sectors leading to high climate vulnerability. SSP3 focuses on inward-looking policy and inter-state inequalities, while in SSP4 inequalities are both within and between states.

Finally, SSP2 represents the intermediate trend.

The SSP scenarios represent an upgrade of the RCP (Representative Concentration Pathway) scenarios previously used by the IPCC. Here is a correspondence between the different scenarios as the two classifications are still used in literature (Pielke and Ritchie, 2021).

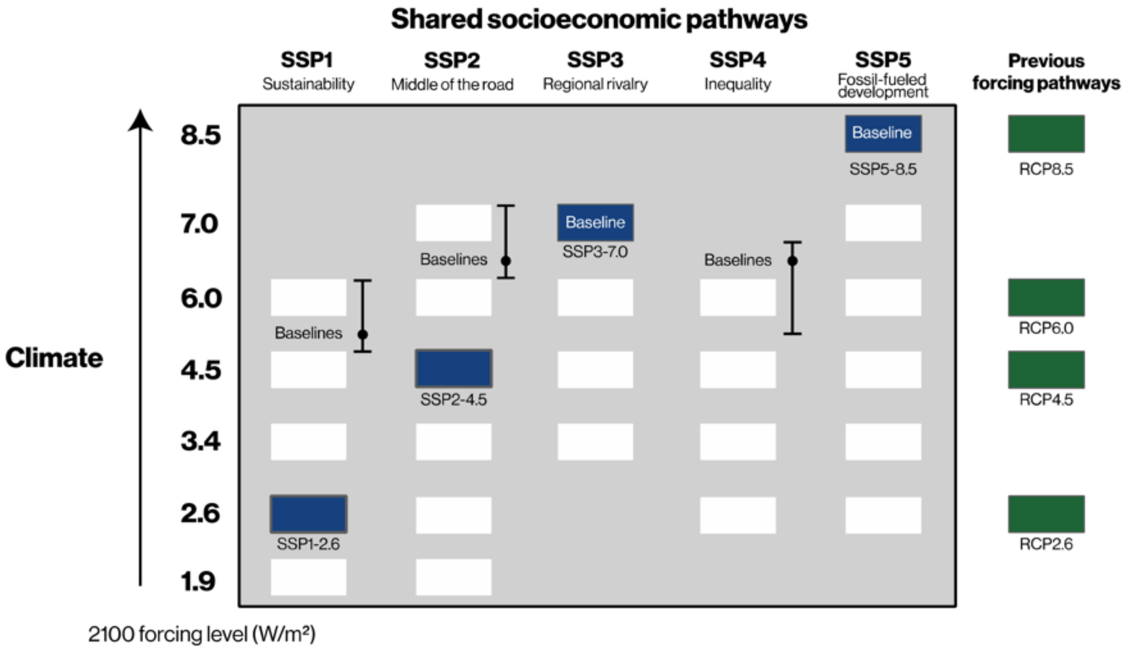


Figure 2 – SSP-RCP Matrix of scenarios for climate model experiment to inform the IPCC 6th Assessment. Source (Pielke and Ritchie, 2021)

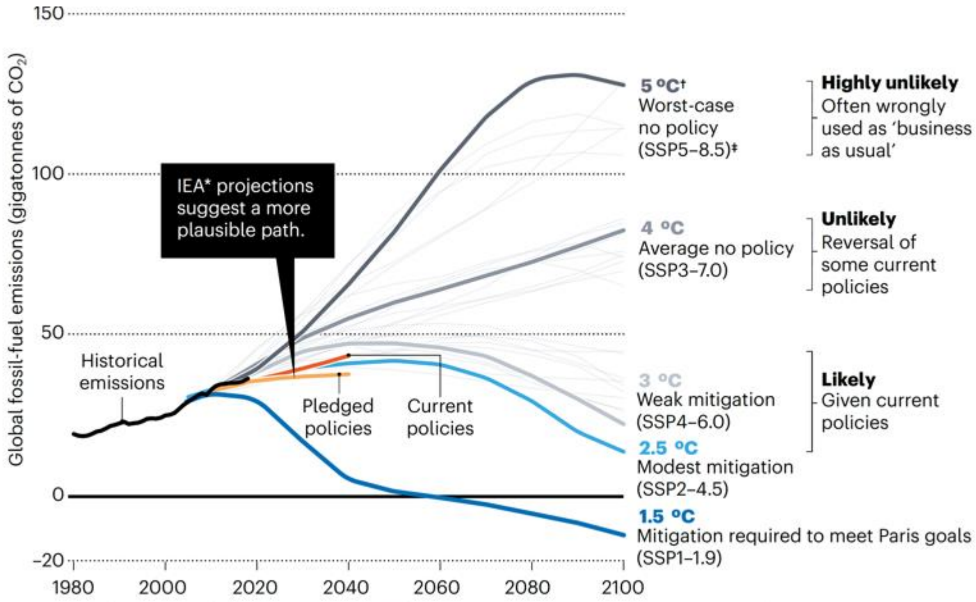
3.2.3.2 Scenario plausibility and selection of futures

If there are several climate scenarios, not all have the same probability of occurring. This reduces the number of layers to be produced to reach an acceptable consideration of possible futures and brings the tree structure and analysis time down to a more reasonable level.

Although the IPCC has never officially given a ranking of the scenarios in terms of plausibility, several studies (*Fig. 8*) and agencies such as the International Energy Agency (IEA) have expressed themselves on the subject (Hausfather and Peters, 2020).

Here is a summary of the elements to be retained (from IEA, 2019):

- The SSP1 scenarios appear to be unattainable or difficult to achieve
- The most likely scenario today is SSP2-4.5, with a temperature increase for 2100 of between 2 and 3°C (Pielke et al., 2022).
- Deep decarbonization remains an enormous challenge and emissions by 2050 remains outside the envelope of plausible scenario trajectories
- Impact studies generally focus on the most pessimistic scenario (SSP5-8.5 or RCP8.5) (*Fig 9*) especially since the U.S. National Climate Assessment published that the RCP8.5 likelihood scenario was very high (IEA, 2019) and confirm it in its fourth report (USGCRP, 2018). Nevertheless, this scenario appears less realistic today regarding the last evolution of gas emissions, but it is still necessary to quantify physical climate risk (Schwalm et al., 2020).

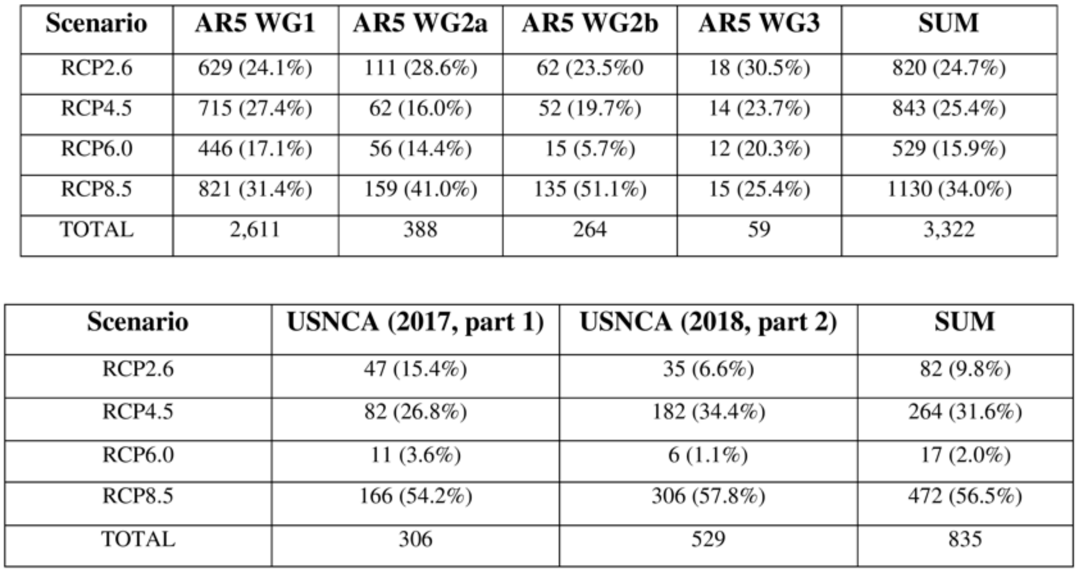


*The International Energy Agency (IEA) maps out different energy-policy and investment choices. Estimated emissions are shown for its Current Policies Scenario and for its Stated Policies Scenario (includes countries' current policy pledges and targets). To be comparable with scenarios for the Shared Socioeconomic Pathways (SSPs), IEA scenarios were modified to include constant non-fossil-fuel emissions from industry in 2018.
†Approximate global mean temperature rise by 2100 relative to pre-industrial levels.
‡SSP5–8.5 replaces Representative Concentration Pathway (RCP) 8.5.

Figure 8 – SSP pathways and supposed probability of occurrence (Hausfather and Peters, 2020)

Ideally, all scenarios should be tested, which is generally done in studies of the same type (e.g. Chollett et al., 2022). Nevertheless, if an order of priority were to be given, the SSP2 scenario would appear to be the first to be tested since it represents the most likely scenario today (Pielke et al., 2022). Regarding MSP, it is also the one that would be reasonably the least restrictive in terms of the number of sites identified, bearing in mind a target of 30% MPAs by 2030. However, this scenario may underestimate the climate risks and should not be analyzed without putting it into perspective with more pessimistic scenarios. In the second phase, it is important to run more extreme scenarios such as SSP3-7.0 or even better SSP5-8.5 (*Fig. 9*). Indeed, these scenarios would make it possible to highlight a robust network in the face of extreme degradations which, although less likely today, particularly for SSP5-8.5, should not be ruled out, especially for short- or medium-term projections (Schwalm et al., 2020). Not long ago, the U.S. National Climate Assessment published a report stating that RCP8.5 (a scenario very close to SSP5 and SSP3) had a very high probability of being the future scenario. Thus, it is the comparative analysis between the most likely scenario (SSP2) and the most extreme (SSP5) that should highlight the conservation priorities and the secondary areas that will become desirable as a secondary network if the current trajectory continues.

On the other hand, the SSP1 scenario appears to be too optimistic in the current framework of progress and do not appear to have priority. However, this theoretical prioritisation must be reviewed according to the input chosen, as the example of corals shows that sites supporting the maintenance of corals could simply no longer exist for a generic increase in temperature beyond 2°C (Dixon et al., 2022), with the most extreme or even the medium scenarios no longer being relevant for these species.



Scenario	AR5 WG1	AR5 WG2a	AR5 WG2b	AR5 WG3	SUM
RCP2.6	629 (24.1%)	111 (28.6%)	62 (23.5%0	18 (30.5%)	820 (24.7%)
RCP4.5	715 (27.4%)	62 (16.0%)	52 (19.7%)	14 (23.7%)	843 (25.4%)
RCP6.0	446 (17.1%)	56 (14.4%)	15 (5.7%)	12 (20.3%)	529 (15.9%)
RCP8.5	821 (31.4%)	159 (41.0%)	135 (51.1%)	15 (25.4%)	1130 (34.0%)
TOTAL	2,611	388	264	59	3,322

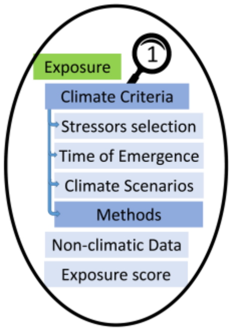
Scenario	USNCA (2017, part 1)	USNCA (2018, part 2)	SUM
RCP2.6	47 (15.4%)	35 (6.6%)	82 (9.8%)
RCP4.5	82 (26.8%)	182 (34.4%)	264 (31.6%)
RCP6.0	11 (3.6%)	6 (1.1%)	17 (2.0%)
RCP8.5	166 (54.2%)	306 (57.8%)	472 (56.5%)
TOTAL	306	529	835

Figure 9 – Prevalence of mentions of the RCP in the IPCC Fifth Assessment Report and the U.S. National Climate Assessment. RCP8.5 is highly prevalent in the reports that are

translated into literature as 16.800 articles (35.5%) of the screened literature refers ti RCP8.5 to the analysis from Pielke and Ritchie (Pielke and Ritchie, 2021).

To conclude, we recommend considering at least two climate scenarios in the analysis process: the bordering scenarios SSP2-4.5 and SSP5-8.5 to give a broad range of potential future conditions under which the response to the management issues needs to remain robust.

3.2.4 Climate exposure assessment (methods, datasets and limits)



Now that the stressors and the scenarios under which exposure need to be evaluated are defined, the data need to be gathered and the maps could be produced (one per condition, per stressor) to create the portfolio of Exposure layers using GIS or R packages.

3.2.4.1 Methods for climate exposure assessment

The creation of layer of exposure will repose on two main analysis types:

- *Time series analysis and anomalies maps based on LOESS method*
- *Climate-analogs velocity*

Each of them will assess a facet of exposure. The time series decomposition based on LOESS will lead to the identification, localization and quantification of the change by analyzing climate anomalies by cell of the Exposure grid under different climate scenarios. The Climate-analogs velocity, for its part, will provide a dynamic assessment of climate change by tracking climate evolution within the whole boundaries (spatial and temporal) defined in the framework. Its aims to better identify climate-refugia, highlight similar climate-analog areas and potential migration corridors. The two methods are therefore complementary.

Time series decomposition based on LOESS

The first method aims to identify the climate anomalies (intensity and frequency) from the “natural climate cycle” (climate normal) for a chosen stressor to identify the areas under climate exposure and assess the intensity of the exposure. A Climate Anomaly could be defined as a deviation of a chosen climatic value in a given period (e.g. temperature for a specific month) from the average climatic value (e.g. monthly value) estimated from a long-term dataset (Spies, 2007). The long-term data set is called *Climate Normal* and is calculated from meteorological data from a 30-year average period which is updated every 10 years as advised by the World Meteorological Organization (Arguez and Vose, 2011; WMO, 2017). The core of the methodology is the creation of spatialized climatic series on the chosen climatic stressor from monitoring data, satellite data (e.g Landsat 8 and Sentinel 3) or from existent datasets (Tuzcu Kokal et al., 2023) and the identification of the anomalies in these time series using the Seasonal Trend Decomposition Procedure Based on LOESS (Locally Estimated Scatterplot Smoothing or local regression) also called STL (Cleveland et al., 1990). The principle of the STL is to decompose the observation dataset (e.g. temperature value) into three components: the trend, the seasonal component and the remainder component. The trend component represents the low frequency variation in the dataset, the seasonal component the variation in the dataset at or near the seasonal frequency and the remainder represents the variations in the data when trend and seasonal trends are removed from the total variation and includes the anomalies (Cleveland et al., 1990). Anomalies can be identified from the noise using a threshold value that can be defined from different statistical methods (e.g. Grubb test or Generalized ESD Test for Outliers). For example, *Tuzcu-Kokal et al* fixed at 3 times the standard deviation from the mean value of the retrieved remainder component (Tuzcu Kokal et al., 2023). Copernicus propose a step-by-step methodology to identify and evaluate the anomalies with associated codes (Copernicus, 2023b) while there are some dedicated R packages such as *stlplus* (Hafen, 2016) or *anomaly* (Fish et al., 2023) and *AnomalyDetection* (Github depository) that will also help to evaluate the thresholds. When the anomalies are detected in the time series on each grid, their frequency and intensity can provide two metrics to evaluate the exposure. The interest of this method is that it could also be applied at a small-scale (e.g. MPA scale) to observatory data without having to obtain new data from surrounding sites. Some maps of anomalies could also be collected directly from satellite data. STL is also a well-known methodology in climatic science so there are numerous dedicated tutorials to help the analysis and to support the assessment of results and decision-making.

Climate velocities

Initially developed by Loarie et al. (Hamann et al., 2015; Loarie et al., 2009) the notion of velocities of climate change (or climate-velocity) can be apprehended based on two different metrics, the climate-analogs velocities for areas and the bioclimatic velocities that can be used to assess species potential pathways. A climate-analog could be defined as two locations with similar climates across current conditions and future scenarios (Veloz et al., 2012). The climate-analog velocity is a metric of distance (spatial, temporal or both) between the climatic conditions in an area of interest and the nearest area presenting similar climate conditions (Carroll et al., 2015). The climate-analogs could be identified on three timescales: on the past, present and future and will provide different key elements to sustain the decision-making process. Finding the climate-analogs of an area of interest (e.g. a given MPA) in the past (backward velocities) and analyzing the current trends observed in the backward climate-analogs identified will permit to create a portfolio of potential future climatic and eco-socio-ecological conditions for this area of interest. In addition to this portfolio, analyzing the proportion of the different patterns (current trend) observed in the pool of backward climate-analogs identified will provide a probability for each of the scenario of the portfolio. The probability can be directly evaluated by counting the number of climate-analogs that present each of the patterns of the portfolio and can be used to rank the scenarios as some are more likely to happen in the area of interest. This could be used as a ponderation system inside the climatic models. Moreover, the identification of backward climate-analogs will also permit to promote exchanges between the managers of the area of interest and those from the backward-analogs. It can maximise the benefit from experience feedbacks by promoting exchanges and the creation of dedicated networks of professionals, partially replacing the BACI (Before-After-Control-Impact) (Underwood, 1992) analysis in areas where there is no survey dedicated to climate change before the observation of climate change incidence. This could be an very important asset for MPA as the mutualization of knowledge and experience is a key element to promote the success of management measures (Friedlander et al., 2016; Wells et al., 2016). Finding the climate analogs in the present will be of interest to identify other areas that are experiencing similar climate issues and eventually to implement different management levers to compare the results with common and robust methodologies of comparison. Then, identifying future climate-analogs (forward velocities) would provide fundamental information for estimating the potential ecological corridors that the species could follow (Keeley et al., 2018) as assisting their range shift is a goal of prior importance to protect biodiversity under climate change (Nuñez et al., 2013).

A similar metric, “biotic diversity”, will evaluate the distance between a site and the nearest site where the climate conditions will be suitable in the future (Carroll et al., 2015). This metric could also help to identify possible corridors for migratory species but will also allow theoretically to calculate the probability of migratory success by analyzing in parallel the migratory capacities of the species of interest (its traits) and the distance from the current species distribution and the nearest area it will need to reach to find sustainable conditions. This could represent a fundamental tool for the design of MPA networks by identifying corridors and fixing a minimum distance between two MPA to ensure connectivity, at least for the rare species whose mobility capacities have been evaluated since it is still lacking for most of adult species (Allan et al., 2005). The combined analysis of climate-analogs and invasive species’ bioclimatic velocities is also a good way to evaluate invasive risk and identify potential invasive routes (Azzurro and D’Amen, 2022) to be taken into consideration in the MSP decision process or to promote attenuation measures. A detailed methodology about how to assess biotic and climate-analog velocities using multivariate Euclidian climate distance based on PCA score from the analysis of the 37 bioclimatic variables identified by Loarie et al. (Loarie et al., 2009) is presented in Caroll et al., 2015 (Carroll et al., 2015) whereas a detailed algorithm can be found in the paper of Hamann et al., 2015 (Hamann et al., 2015).

3.2.4.2 Data on CC scenario

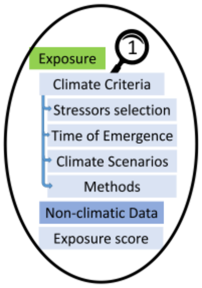
The actual projected climatic conditions came from the CMIP6 (Coupled Model Intercomparison Project 6) model. The CMIP models result from an international collaboration within the World Climate Research Program of the United Nations

Organization. A climatic projection could be defined as a future meteorological simulation based on about a hundred Global Circulation Models (GCM). It is therefore a representation of one possible future among many and must not be confused with prevision. The IPCC scenarios are based on CMIP model data. The Data from the CMIP6 model can be found on the Earth System Grid Federation (ESGF) website (https://esgf.llnl.gov/) and are made easier to access directly from Jupyter (https://www.climate4impact.eu/c4i-frontend). A catalog of climatic variables (https://pcmdi.llnl.gov/mips/cmip3/variableList.html) and of CMIP6 abbreviations (https://clipc-services.ceda.ac.uk/dreq/mipVars.html) can be found following the given link to help in the selection of layers. Generally, the same terminology is found in the websites using the CMIP data. It is nevertheless highly recommended not to use raw data from the CMIP6 as the rescaling and the process of data could be tricky (see section 3.2.4.1- Methods, *Downscaling*). If necessary, we advise calling on climate professionals to help you create the maps you need if they are not available online. Most of the climatic data from the CMIP6 (or previous CMIP5 model) and forecast gridded data are freely available online. The most famous website in Europe is the Copernicus Portal (https://climate.copernicus.eu/climate-datasets). Copernicus is the European Union program for Earth Observation and concentrates in situ and satellite data about climate from different Agencies such as the European Spatial Agency (ESA), the European Organisation for the Exploitation of Meteorological Satellite (EUMETSAT), the European Centre for Medium-Range Weather Forecasts (ECWF) and Mercator Ocean. Copernicus also provides access to data products derived from climate projections, such as projections of eutrophication (https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-fisheries-eutrophication?tab=overview) and fish abundance (https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-fisheries-abundance?tab=overview), and an MSP explorer map tool (https://cds.climate.copernicus.eu/cdsapp#!/software/app-marine-spatial-planning-explorer?tab=app). Other portals could also be of interest to access already transformed climatic and projected data such as Bio-oracle (https://www.bio-oracle.org/), Worldclim (*https://www.worldclim.org/data/index.html or* www.worldclim.com/), Marspec (http://www.marspec.org/), the Earth System Grid Federation portal (https://esgf-index1.ceda.ac.uk/projects/esgf-ceda/), the Essential Climate Variable inventory (https://climatemonitoring.info/ecvinventory/), or directly the IPCC atlas portal (https://github.com/IPCC-WG1/Atlas). For IPCC data, a dedicated R package exists integrating all the tools needed to directly produce and manipulate maps. One of these packages is called climate4R (Iturbide et al., 2019) and could be found at this address https://github.com/SantanderMetGroup/climate4R or https://github.com/SantanderMetGroup/ATLAS as it was recently updated. Regional IPCC data is also available from the IPCC WGI Interactive Atlas. The datasets and data platforms mentioned in this section are listed in the data inventory compiled by T2.1.

3.2.4.3 Limits: the problem of downscaling

The scale of General Circulation Models (GCM) at which the potential impacts of climate change are projected are too broad for most of the management issues (Tabari et al., 2021). Downscaling describes the processes used to reduce the spatio-temporal (less than monthly, less than 100x100km^2) resolution of predictions from the GCM to a more relevant scale to address policy or biological issues (Trzaska and Schnarr, 2014). The downscaling methods are divided into two branches: dynamical downscaling and statistical downscaling. Dynamical downscaling incorporates physical processes and additional data from higher resolution models called Regional Climate Models (RCM) to reproduce local climates. The RCM are available in a relatively small number of areas and use often a 0.44° grid (approximately 0.45x0.45 km^2 at the equator) (Copernicus Climate Change Service, 2023) considered as an acceptable regional scale. The statistical downscaling aims to develop a statistical relationship between historic observed climate data and climate models for the same period and applied to the projected data. Then uncertainty and bias should be assessed and corrected to validate the downscaled results (Trzaska and Schnarr, 2014). Downscaling processes require computing power and are time-consuming. They also require a good command of climatic data. That is why we recommend using available already downscaled projection data when possible.

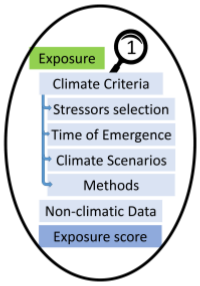
3.2.5 Inclusion of non-climatic stressor layers



In addition to climatic stressors, layers representing exposure to anthropogenic activities (distribution and intensity) should be added to the general GIS to support risk assessment (see section 5 – *Risk assessment*) and trade-off analysis (see section 6 – *Informed Management and Monitoring*) and as Climate and Human stressors should not be considered isolated in risk analysis (Alvarez-Romero et al., 2018).

In general, fine datasets of human pressure, especially for fisheries, are available on each site of interest. For example, several local-scale human pressure datasets covering each of MSP4BIO's six test sites were compiled during task 2.1, and the availability of such datasets was discussed in D2.1. In contrast, Halpern et al. provide a list of global databases of pressure (Halpern et al., 2008) but their update must be checked. The EMODnet Human Activities platform also compiles existing data on 18 differents themes related to human activities (from exploitation to cultural heritage) including cables, aquaculture, fisheries and shipping routes (https://emodnet.ec.europa.eu/en/human-activities). Free software dedicated to the evaluation of additive pressure *EcoImpactMapper* also exists and can be found at the following address https://figshare.com/articles/software/ImpactMapper/1519342 (Source code: https://github.com/anstoc/EcoImpactMapper) (Korpinen et al., 2021). Additional software tools for the evaluation of additive pressure analysis and cumulative Effects Assessment (e.g. Tools4MSP, PlanWise4Blue) will be presented in deliverable D3.4.

3.2.6 Calculation of Exposure score (cumulative approach)



At the end of the process, the compilation of maps and pressures will be used to create a synthetized map assigning a cumulated pressure intensity range score calculated under the different IPCC scenarios per grid cell. Different methodologies exist to calculate that score (Halpern et al., 2015; O’Hara et al., 2021; Wahlstrom et al., 2022) but in the case of exposure we recommend to keep it simple for a first assessment, considering a cumulated score of presence/absence of stressors per cell and, then, adding different weight regarding projected conditions and considered species in the analysis framework (O’Hara et al., 2021). We recommend favoring the inclusion of range rather than average, because averaging potential futures makes little sense. We strongly advise while making these synthetized layers to distinguish, in addition to this cumulated score, the human exposure score from the climate exposure score as each of them will lead to the favor of different management levers in the risk assessment step (see section 5 - *Risk Assessment*). The attribute table needs also to include maximum projected conditions, minimum projected conditions and the range of conditions for each of the climatic stressors considered in the analysis. The bathymetry should also be added by cell. Bathymetric data at global scale can be found in the General Bathymetric Chart of the Oceans (GEBCO) website (https://www.gebco.net/), and are available at European scale from EMODnet Bathymetry (https://emodnet.ec.europa.eu/en/bathymetry). These future conditions per cell will help to determine the potential survival rate of a species regarding their safety margin (*Fig. 10*) (*see section 3.3 - Sensitivity*) along their distributional range (e.g. Chatzimentor et al., 2022).

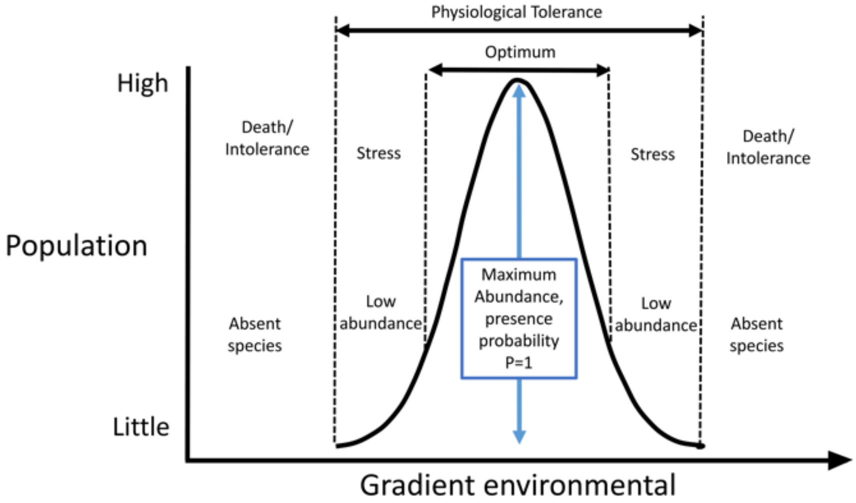


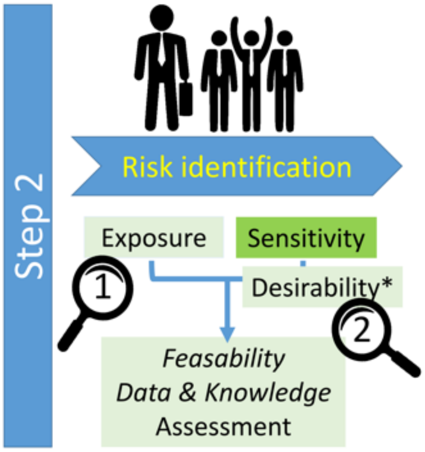
Figure 10 – Species response to a climatic gradient (from C. Bellard, Paris Sud University)

This synthesis layer could be unique or multiple if the management framework considered evaluating climate change conditions at near-term, mid-term and long-term, which is strongly recommended.

3.2.7 Conclusion of *Exposure* phase

At the end of the Exposure phase, a portfolio of spatialized future conditions under different climate scenarios is available as well as synthetized maps. These maps are useful to rank areas regarding exposure level and to assess potential species distributional range loss, setting theoretical priorities of concern among area and species that need to be validated by analyzing their sensitivity to the chosen stressors. Dynamic climate velocities maps are also available to assess the future potential evolutionary trajectories of areas of interest under selected stressor influence and identify future species migratory corridors.

3.3 Sensitivity



Objective. The Sensitivity analysis is meant to create a *Sensitivity Matrix* per stressor based on life traits. The Sensitivity matrix is a spreadsheet tool that will assess the degree of sensitivity of a given species/habitats to a chosen climatic stressor. The sensitivity is evaluated based on a selection of traits from 6 categories (e.g. morphological) that will confer advantages or disadvantages to the species considering a chosen stressor. The sensitivity matrix is compiled and filled based on Traditional and Expert Knowledge. The Sensitivity matrix makes the link between the chosen stressor and the species inside Trait-based Vulnerability models. This step aims to develop *Sensitivity matrices* for each of the previously chosen stressor (Exposure) that will be used to perform the Vulnerability Analysis.

Pre-requisite. Sensitivity is one of the three basic elements necessary to perform a climatic vulnerability assessment. It can be defined as “the degree to which a species is influenced by one or more aspects of climate” (Dawson et al., 2011). Sensitivity is directly linked to species' inner traits. Traits are defined as “the measurable biological characteristics of organisms, such as morphology, physiology, behavior and phenology, which shape their ecological performance” (Cadotte et al., 2011). Life traits (approach) was identified as one of the broad functional criteria categories reported in the scientific literature to prioritize and design area-based conservation measures (for additional information refer to D3.2). The sensitivity analysis will give a first answer to the 4th priority of the IUCN by helping to assess how the different stressors will influence marine life.

The objective of the sensitivity analysis is to identify, for the species or areas previously selected as target of conservation, the traits that confer them sensitivity to one or several chosen climatic stressor(s) (see section 3.2 - *Exposure*) and create an analytical tool called *Sensitivity Matrix*. The sensitivity matrix is generally used in a multispecific context (e.g. Doxa et al., 2022) but could also be used at a single species scale as a synthetical tool considering multiple stressors (*Fig. 11*).

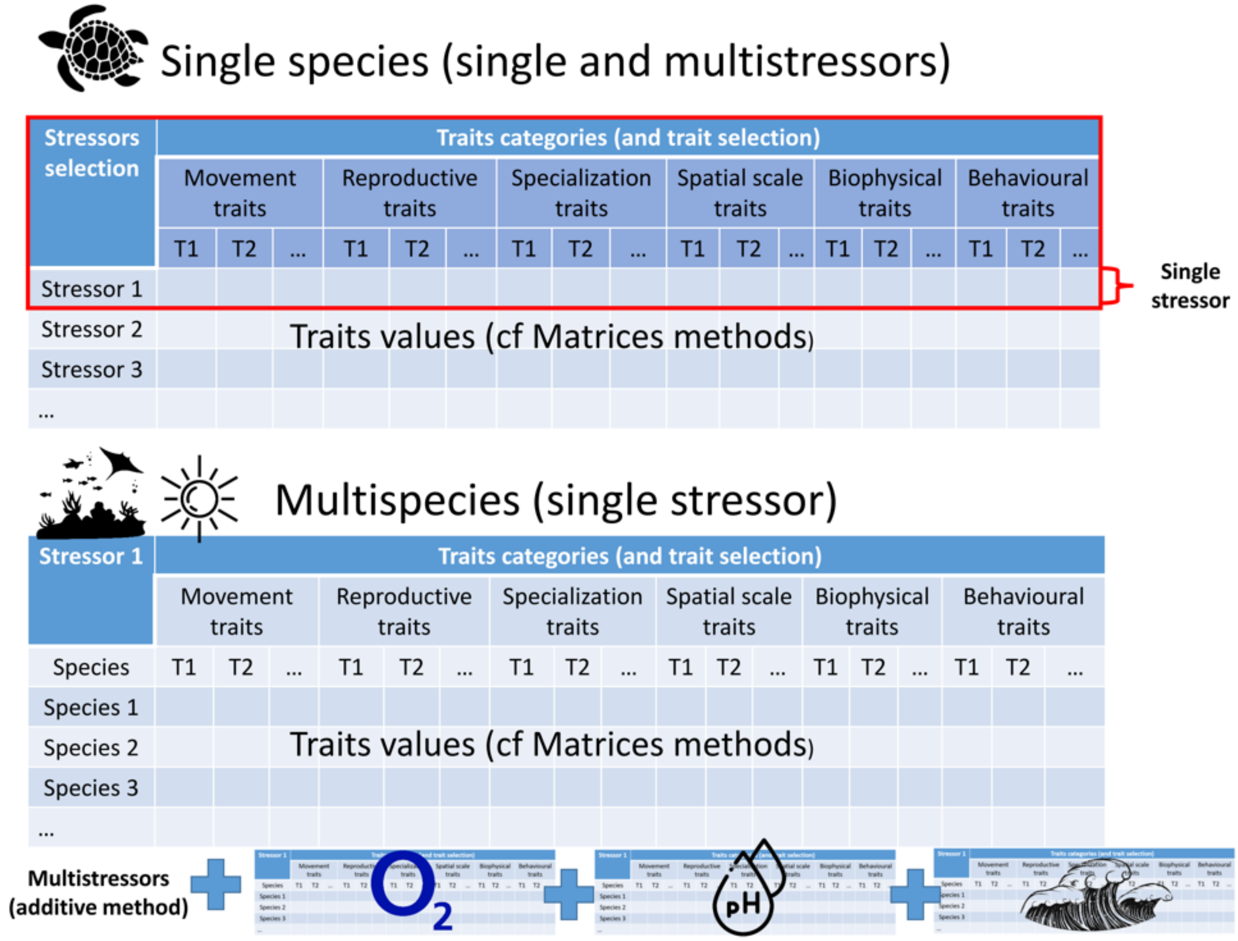
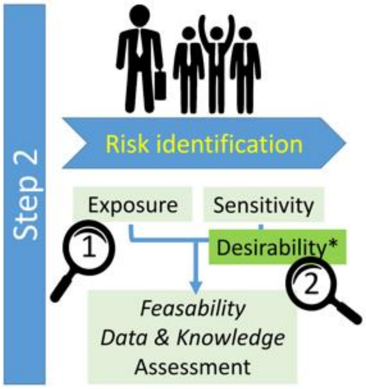


Figure 11 – Example of the different type of matrices existing regarding the needs for: one (up) or several species (down) and considering one or several stressors. In this guidance, we recommend the creation of one matrix per species and stressor (single species, single stressor, in red). The traits used in this type of matrix will be selected and filled depending on the species (possession or absence of each trait and trait value associated) and stressor chosen (relevance of the trait for the stressor). In more integrative cases, a set of matrices (one per stressor and species) is created and sensitivity scores are calculated using additive method.

In the case of multistressor analysis, the number of traits considered in the analysis will in general be more important without being an issue for the analysis. The question arises when a value should be attributed to a trait that is commonly influenced by different stressors. In that case, there will be several possibilities regarding the local knowledge available in the area of interest. First, the influence of stressors on the trait will act on opposite on the trait ("mutually exclusive", same sensitivity level but opposite incidence) and theoretically annulate the effect of climate change on the trait. In that case, the trait should be excluded from the analysis in the chosen framework. On the contrary, several chosen stressors could influence simultaneously the trait, increasing the effect of climate change on it or only partially reducing CC impact if the opposite stressors' effects are not of the same intensity ("non-mutually-exclusive traits") (Debortoli et al., 2018; Hamilton et al., 2020). In that case, the best way to take the variability of response into account is to attribute a probability for each trait concerned and to simulate different final evaluations (Butt and al., 2022). Another way, more uncertain but that could help to perform a more rapid final reading of results, will be to conserve the score of the dominant stressors on the taxa of interest regarding the theoretical ranking of stressors and the considered timescale.



Objective 2. In parallel to the creation of the sensitivity matrix, we strongly advise to create a similar tool compiling the traits that confer advantages (Resistance, Resilience or Adaptivity) regarding the same stressor(s). Resistance could be defined as the capacity of an organism to absorb disturbance or stress without changing character (Holling, 1973). On the contrary, resilience (or recovery) is the ability of a receptor to recover from disturbance or stress (Holling, 1973). Finally, according to the United Nations Climate Change, Adaptivity is the capacity to *adjust in response to actual or expected climatic stimuli and their effects*. *It refers to changes in processes, practices and structures to moderate potential damage or to benefit from opportunities associated with climate change* (United Nations Framework Convention on Climate Change (UNFCCC), 2023).This second matrix, which we call *Desirability Matrix* will represent an asset for the Risk assessment phase (*see Step 4*). This *Desirability Matrix* can be found in the literature as *Adaptivity Matrix* but we prefer to refer to it as *Desirability Matrix* due to terminology issues. Indeed, in the literature, *Sensitivity traits* could be found interchangeably under three terminologies *Vulnerability Traits*, *Sensitivity Traits* and *Adaptivity Traits.* This phenomenon probably stems from the fact that, strictly speaking, *Sensitivity* includes all traits influenced by the climate (Dawson et al., 2011), whether the influence is negative or positive, and that, as a result, adaptability traits can appear as subsets of sensitivity traits (Spencer et al., 2019). Moreover, the distinction between resistance and resilience is sometimes blurred between studies and depending on the field of research, making it difficult to compare results. (Fisichelli et al., 2016). This *Desirability Matrix* could be included in the Sensitivity calculation or used as side tool (see section 3.3.2.1 - *Desirability Matrix*). The question of the relevance to create a separated second matrix including the adaptivity and resilience traits as an alternative to sensitivity instead of including it as two attributes used to better characterize species sensitivity arises. In fact, this choice depends on the knowledge

available about the species of interest. Here, we consider that sensitivity traits are traits that make a species sensitive to the chosen climatic stressors (observed traits), whereas resilience and adaptability traits are traits linked to the supposed capacity (inferred traits) of the species to return to a pre-disturbance state or even to adapt to the effects of a stressor, which remains more hypothetical. Resilience and adaptation capacities are often not sufficiently assessed, and their inclusion in the sensitivity calculation can lead to a high level of uncertainty. The difficulty of evaluating some of the traits (Foden, 2016) partly explains why most of the studies define their own sensitivity matrix that complicates the inter-sites comparison. The choice of calculation method therefore depends entirely on the framework chosen (including the level of uncertainty acceptable), the main limit being to keep the same calculation method for all the species considered in the study and among test-sites and a coherent definition of each category.

Here we propose a sensitivity approach at three levels of analysis: species, areas/habitats and ecosystems level. Each of these levels implies new traits and modalities (i.e. level of traits), areas/habitats and ecosystemic traits being less documented.Three lists of traits are proposed in this guidance according to the level of analysis (i.e., species, ecosystems, areas) and their modalities) from a dedicated literature review focusing on recent synthesis (e.g. Aurelle et al., 2022; Bates et al., 2019; Boyce et al., 2022; Butt et al., 2022; Chatzimentor et al., 2022; Li et al., 2023; Marine Life Information Network. Plymouth: Marine Biological Association of the United Kingdom, 2006; Quigley et al., 2022; Sunday et al., 2015; Tsimara et al., 2021; Tzanatos et al., 2020) that could be selected to assess the sensitivity of species to the various climatic stressors. The traits are provided at species, ecosystem, and area level since the management questions, and indeed the analysis, can target one of the mentioned levels or all of them at once. These matrices are also accompanied with a list of concrete examples to help understand the purpose of the work and how to assess the different type of sensitivity matrix regarding the type of data.

The sensitivity analysis will provide two main results: a first ranking of species/areas by sensitivity to chosen climatic stressor(s) corresponding to conservation prioritization and a sensitivity score to integrate in the vulnerability assessment. The sensitivity matrix should be designed and implemented by planners supported by a chosen panel of experts. In each case, we highly recommend verification of the matrix design by dedicated experts before performing the vulnerability assessment.

The structure of the sensitivity sub-chapter is summarised in the figure (*Fig. 12*).

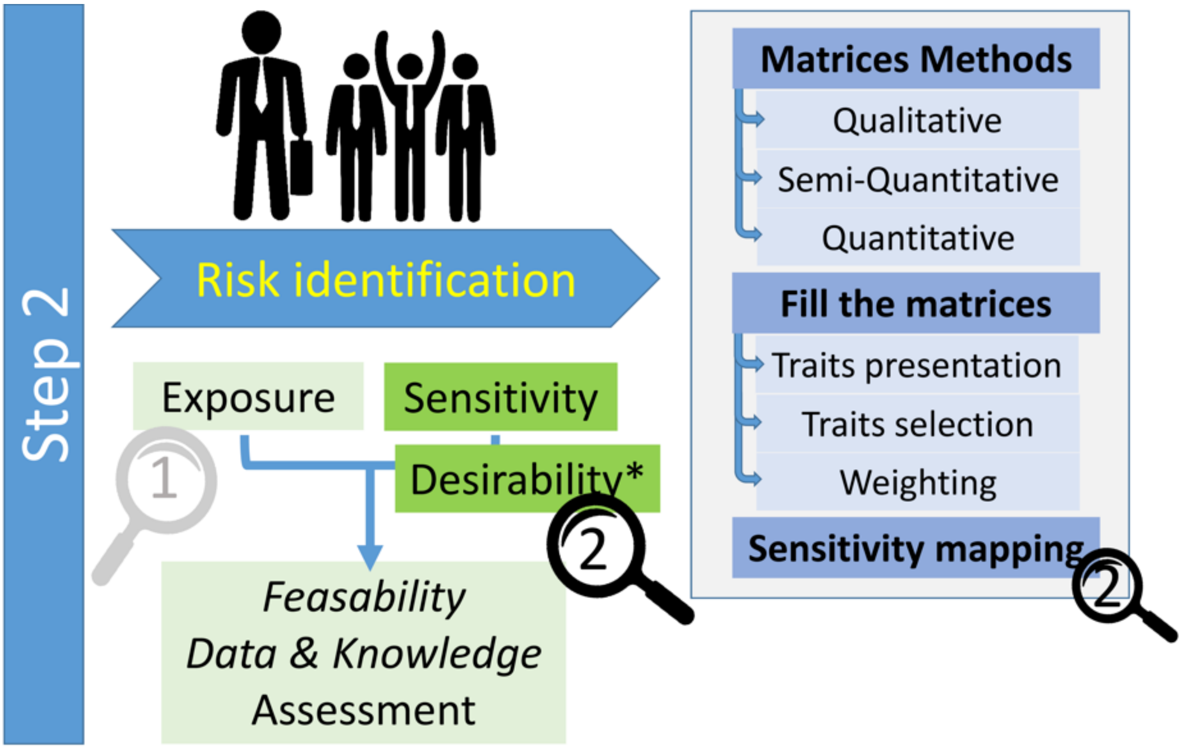
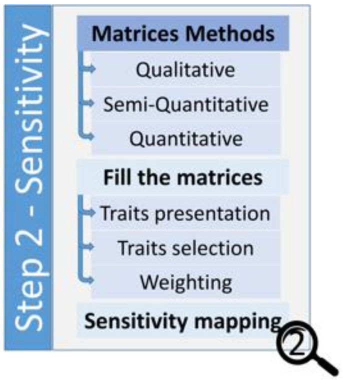


Figure 12 – Structure of the Sensitivity/Desirability subchapter (blue box, magnifying glass n°2) and position of the subchapter in the guidance flowchart. The subchapter is divided into three parts: the presentation of the methods used to create the sensitivity matrix according to the type of Data (Matrices Methods), an explanation of how to fill in a matrix (Fill the matrices) and an explanation of how to transform matrices into spatial data (Sensitivity mapping).

3.3.1 Trait-based matrices methods regarding the type of Data

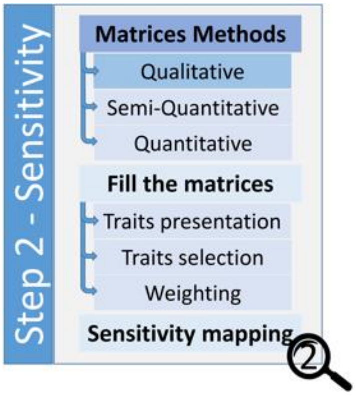


General objectives: The objective of the trait-based sensitivity analysis is to select a list of relevant traits to be compiled and then analyzed in the sensitivity or sensitivity-desirability matrix. The two matrices have the same structure but differ in the list of traits considered. If, the sensitivity matrix will include only the traits of sensitivity regarding one or several stressors (climatic and/or human), the sensitivity-desirability matrix by including traits of resilience and adaptivity will also include a proxy of the potential of a species'/area's response to drivers of change. This chapter consist of the most difficult step to perform for a vulnerability assessment as it needs to mobilize all the current knowledge on the ecological component but is also one of the most flexible and interesting tools as the sensitivity traits can be selected directly linked to each management challenge and broadened to include also economic or social components (e.g. the species sensitivity to different fishing trades).

Choosing the methodology of the sensitivity assessment is a fundamental step as it will define the type of input that will be provided in the vulnerability assessment.

The trait-based sensitivity analysis can be performed through three different approaches, depending on data and knowledge availability (Foden, 2016): i) a qualitative analysis, ii) a semi-quantitative analysis, or ii) a quantitative analysis.

3.3.1.1 Qualitative assessment



The qualitative assessment is one of the most used for trait-based analysis. It aims to create a matrix of traits (*Table 5*) and to assign to each trait a qualitative level of sensitivity (generally *High*, *Moderate* and *Low* or even including a fourth or a fifth level as *None/Very Low* or *Very High*) to the specific climatic stressor (e.g. Lettrich et al., 2023; Marine Biological Association (MARLIN), 2023). The attribution of the level of sensitivity can be defined based on local ecological knowledge (LEK-based), expert knowledge or literature review (Giddens et al., 2022). If there are already some databases of traits that provide the modalities per traits and related level of sensitivity (e.g. Marine Life Information Network. Plymouth: Marine Biological Association of the United Kingdom, 2006) it is recommended to validate the matrix along with local experts to verify that the designed sensitivity-matrix is correctly adapted to the area of concern. As scored methods, this methodology is strongly recommended for rapid assessment for sites with no data or where the quality of exposure maps is too broad to perform a fine scale assessment.

Table 5 - Example of Qualitative-based method sensitivity-matrix structure for two species (Species1 and Species2), considering a single stressor (SST) (from Chatzimentor et al., 2022)

List of species	**Trait selection considering SST as stressor**				**Sensitivity score**		
	Trait1	Trait2	Trait3	Trait4	Number of traits with "Low" values	Number of traits with "Moderate" values	Number of traits with "High" values
Species1	Low	High	Moderate	Low	2	1	1

Species2	High	High	Low	High	1	0	3
Species3	Low	Low	Low	Low	4	0	0

The final level of sensitivity could be defined with an empirical method using the idea that in the case of a qualitative assessment, the objective is to define a relative ranking among the species to define management priorities and identify hotspots of vulnerable or resistant species instead of defining a fixed absolute methodology (e.g. O'Hara et al., 2021). Thus, in general, the final level of sensitivity of one species will be defined regarding the pool of species selected in the analysis framework, among several taxonomic groups or a group (Harper et al., 2022). Several methods could be developed to define the pools of species of each sensitivity level, one of them is to use classification approaches based on the number of traits of each value "Low", "Moderate" and "High" to identify groups of individuals and search from the class break-up values among the score of the species pool for each sensitivity level that will be defined as thresholds. A similar methodology is used for example by Chatzimentor et al (2022). In this case, the threshold of each sensitivity level (i.e. Low, Moderate or High Sensitivity) can be iteratively defined using the number of species that are classified in each sensitivity level as metric. In that example, the number of traits necessary to belong to a given sensitivity level (e.g. High Sensitivity) increases along the x axis and the number of species considered as Highly sensitive is ploted using this number of traits as threshold, searching from the curve plateau (*Chatzimentor et al., 2022 supplementary*).In *Figure 13* , the number of highly sensitive species decreases considerably when the threshold number of traits associated with high sensitivity is higher than three (*Fig. 13*). The sensitivity threshold for the High Sensitivity category can be set at having at least 3 highly sensitive traits for the chosen stressor (≥3).The final hierarchy of the species among levels will be the species presenting the highest number of traits of the same level, e.g. Among the species defined as *Highly sensitive* regarding the management framework, the species that is the most sensitive of the pool selected will be the species that comport the highest number of traits considered as *Highly sensitive*.

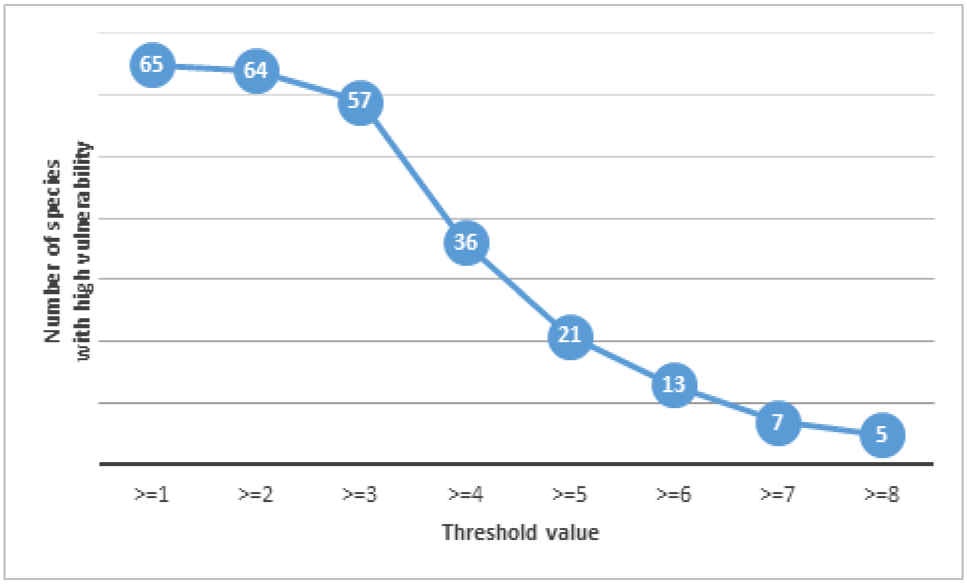
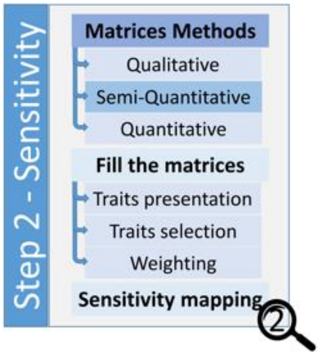


Figure 13 – Example of threshold assessment in qualitative studies (Chatzimentor et al., 2022)

3.3.1.2 Semi-quantitative assessment



The semi-quantitative (or score-based) assessment is similar to the qualitative assessment but is frequently used for two main reasons: it simplifies the calculation of the final index with the possibility of automatizing the process and for introducing a more detailed assessment than those of the qualitative assessment. Indeed, it gives the possibility to introduce a more detailed scale of the relative importance of features in relation to each other and the possibility to weigh the traits of interest (see section 3.3.2.3 – Weighting the traits). Most of the scales were relatively simple including between 3 and 5 levels of precision and not exceeding 10 levels as the scale should be easily readable (*Table 6*) and easy to read and fill in, avoiding vague terms (Cannizzo et al., 2023; Ellison, 2016). Excluding the weighting process, each trait will be assigned a value from 0 to 1 to avoid overexpressing one trait relative to the others in the final score (Butt et al., 2022). The score could be defined using the literature review and verified by experts, or defined by experts and averaged by the planners based on the decision of the complete expert panel (Giddens et al., 2022).

The final score of sensitivity is calculated as the sum of the traits score according to the following equation (Butt et al., 2022):

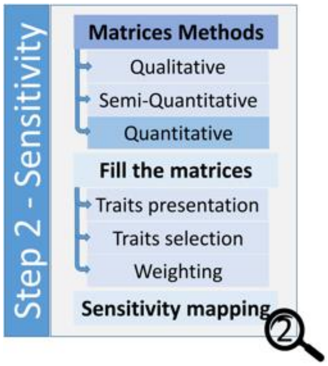
$$\text{Sensitivity score } S_{ij} = \sum_{k} s_{jk} t_{ik}$$

With sjk = sensitivity score (from 0 to 1) and tik= informative trait for the species (yes=1, the trait is conserved; no=0, the sensitivity score will be equals to 0). The species most sensitive to climate change will be the species with the highest score. The degree of sensitivity of species could be defined regarding the repartition of score for the species of interest and based on the percentiles (Jones et Cheung, 2017).

Table 6 – Examples of score matrix at five levels (Ellison, 2012): Rapid assessment for mangroves. The responses given by the Expert are highlighted in Blue in that example and used to calculate the final score of each mangrove trait (in green)

Rank	1 (*Very Low sensitivity*)	2 (*Low sensitivity*)	3 (*Moderate sensitivity*)	4 (*High sensitivity*)	5 (*Very High sensitivity*)	Final score
Mangrove condition	No or slight impact	Moderate impact	Rather high impact	High impact	Severe impact	5/5 = 1
Recruitment	All species producing seedlings	Most species producing seedlings	Some species producing seedlings	Just a few seedlings	No seedlings	1/5=0.20
Final sensitivity score						(0.20+1)/2= **0.6**

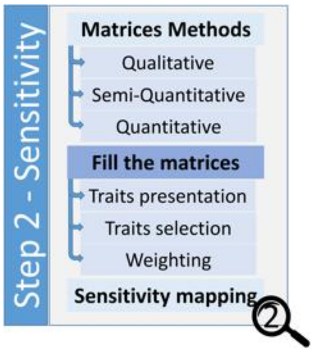
3.3.1.3 Quantitative assessment



The Quantitative assessment presents two advantages and one major disadvantage compared to the Qualitative and the Scoring methods. The advantages are mainly due to the fact that the quantitative method seeks to standardize indicators as much as possible, and to move away from expert opinion to focus on a small number of indicators that can be translated into numerical values from recognized databases. These prerequisites simplify comparisons between studies and are particularly relevant for broad-scale studies, but greatly limit the number of indicators that could be taken into consideration in the sensitivity analysis and may limit the consideration given to local issues. A quantitative assessement is also highly recommended at broad spatio-temporal scales and/or for studies comparing a high number of species from very different taxa to limit computing time. As the quantitative assessment could be based on numeric-spatialized indicators, using that sensitivity method is particularly relevant for marine spatial planning approaches.

For the quantitative assessment, four indicators could be sufficient to provide a level of sensitivity of a species in each location (Boyce et al., 2022): the *Safety margin* of the species under the chosen climatic(s) threat(s), the *Vertical habitat use*, the *Level of Anthropogenic stressors* and the *Conservation status*. In general, at small-scales the element that will be the most subject to variation will be the level of anthropogenic pressures that are assessed using the Cumulative Impact Index (Furlan et al., 2019). The HI index integrates 17 global anthropogenic drivers of ecological change, including fishing pressure, pollution, invasive species, eutrophication, climate change, and others. The HI estimates were available at a global 1km^2 native resolution. A detailed calculation and standardization of these for indicators is given in the supplementary material of Boyce et al., 2022. The final sensitivity score will be average among the four indicators in each cell of presence of the species of interest.

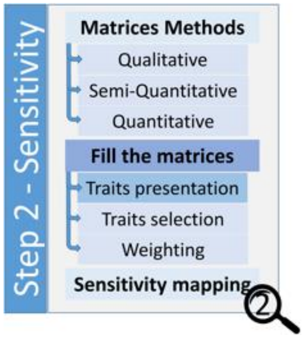
3.3.2 Fill the Sensitivity and Desirability matrices



Once the method has been chosen based on the study objectives and available data, the Sensitivity and Desirability matrices must be filled. This section is devided in three parts: *Trait presentation* in which a list of databases and features by level of analysis (specific to ecosystem) is provided for Sensitivity and Desirability matrices; *Traits selection* in which the 4 main analysis criteria to consider when selecting traits for the matrix are presented (stressor importance, temporality, climate-proof scenario, ecological level) and *Weighting*, presenting the interest of weighting some traits in the analysis process.

3.3.2.1 Traits presentation

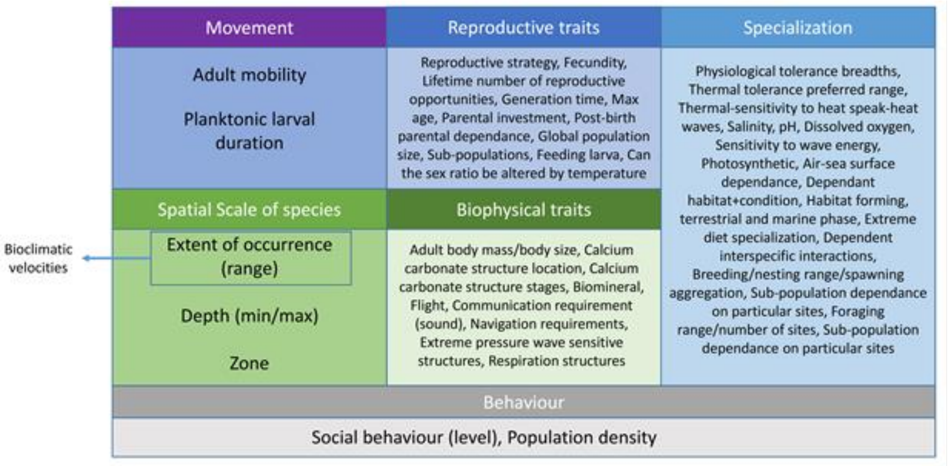
3.3.2.1.1 Traits Databases per level (from species to environment)



Once the method has been chosen based on the study objectives and available data, the sensitivity-traits must be selected and the sensitivity matrix completed*.*

At species level

In this guidance we identify 43 species traits of sensitivity/adaptivity (*Fig. 14*) at species level that could be classified in 6 categories: Movement traits, Reproductive Traits, Specialization traits, Spatial scale traits, Biophysical Traits and Behavioural Traits. The list of these main traits and their modalities could be found in the supplementary of Butt et al., 2022, which presents a synthesis of traits at species level. This list can be completed using the databases listed below (*Box 3*). This figure does not distinguish between adaptability and sensitivity traits because, as Li points out in his own trait analysis (Li et al., 2023), many traits could represent both adaptability and sensitivity factors, depending on the modalities associated with them.



Movement	Reproductive traits	Specialization
Adult mobility Planktonic larval duration	Reproductive strategy, Fecundity, Lifetime number of reproductive opportunities, Generation time, Max age, Parental investment, Post-birth parental dependance, Global population size, Sub-populations, Feeding larva, Can the sex ratio be altered by temperature	Physiological tolerance breadths, Thermal tolerance preferred range, Thermal-sensitivity to heat speak-heat waves, Salinity, pH, Dissolved oxygen, Sensitivity to wave energy, Photosynthetic, Air-sea surface dependance, Dependant habitat+condition, Habitat forming, terrestrial and marine phase, Extreme diet specialization, Dependent interspecific interactions, Breeding/nesting range/spawning aggregation, Sub-population dependance on particular sites, Foraging range/number of sites, Sub-population dependance on particular sites
Spatial Scale of species	Biophysical traits	
Extent of occurrence (range) Depth (min/max) Zone	Adult body mass/body size, Calcium carbonate structure location, Calcium carbonate structure stages, Biomineral, Flight, Communication requirement (sound), Navigation requirements, Extreme pressure wave sensitive structures, Respiration structures	
Behaviour		
Social behaviour (level), Population density		

Bioclimatic velocities

Figure 14 – Table of species sensitivity traits identified in the literature

For each species the modality from each trait could be filled using IUCN to assess the level of conservation of the species, FishBase for fish traits, SeaLifeBase for the marine animals other than fish, WOrld Register of Marine Species (WORMS) and Aquamaps (*see Box 1*). The specific demand for traits databases from MSP4BIO test sites are summarized in *Box 3*.

Box 3. *Specific demand from MSP4BIO*

Regarding test site needs in the MSP4BIO framework, a first screening of the bibliography highlights some databases of interest. For benthic species, a census of traits of importance, with already filled matrix for British Isles and the main species of interest *Lanice conchilega*, can be found on the Biological Traits Information Catalogue (BIOTIC) (Marine Life Information Network. Plymouth: Marine Biological Association of the United Kingdom, 2006). For Açores and the priorities highlighted on fished nektonic species, especially *Pagellus bogaraveo*, a pre-filled but non-exhaustive sensitivity matrix could be found in the supplementary materials of the following articles (Tsimara et al., 2021; Tzanatos et al., 2020).
Marine Species Traits (Marine Species Traits editorial board, 2023) is a database of marine species searchable by biological and ecological traits, which also provides a database of traits searchable by taxon; the Lifewatch Data Explorer (Marine Species

Traits editorial board, 2023). Some traits databases are available which concentrate on certain taxonomic or functional groups, such as AVONET (birds), Sharkipedia (elasmobrachs), and (benthic species). There are also databases which focus on certain traits, such as bioturbation (Queirós et al., 2013). Thermal tolerance databases are particularly relevant to this deliverable; they include GlobTherm, the Thermal Affinities for European Marine Species (Webb and Lines, 2018), and EMODnet Biology thermal traits. https://opendata.eol.org/dataset/queiros-et-al-2013 The databases described here are included in the data inventory compiled by T2.1 and were extracted for T3.1 (sharepoint 1 – *Ecological traits*) to provide data availability context for the improved ecological criteria identified in D3.2.https://opendata.eol.org/dataset/queiros-et-al-2013

Specification for fishing species (pressure traits to be add to species inner traits): in addition to these generic traits that still include most climatic and human stressors both, it is possible to decline some of them regarding the activity of concern. For example, for fisheries inclusion, recognized as the first stressors on marine species for all the taxa and across all the test sites a series of traits could be used to evaluate the fishing pressure on the species. These proxies are *Stock Size and status*, *Abundance/CPUE*, *Fish Price*, *Exploitation level*, *Catch volume/rate*, *Spatial concentration of catch*, *Threat Level/Fishing intensity*, *Distance to Fishing Region*, *Fishery Type*, *Population Viability* (Li et al., 2023).

Trait-based approach for habitat level

In general, the literature on habitats sensitivity is quite extensive, but very disparate between the different habitat types (e.g. a focus on coral and mangrove habitats), and there is above all a great lack of overall assessment (Halpern et al., 2008). Most of the time, the habitat level could be apprehended as a species as they are often provided by engineer species and the same traits list will be used both for species and habitat level. Nevertheless the following traits can be considered as specific to habitats to evaluate their sensitivity *Photosynthetic*, *Total Surface*, *Mortality Rate*, *Observed Disease* (Vitality Index), *Regeneration Capacity, Adjacent to another habitat that could exert the same function*, *Grazing pressure* and to take into account the bioclimatic velocities of the known invasive species that can exert a pressure on the habitat of interest to see if it could be an overlap between their potential expansion and the habitat of interest at near or long term (Zhang et al., 2020).

3.3.2.1.2 Traits selection for Desirability matrix

In addition, the creation of the sensitivity matrix will be a great opportunity to analyze the desirable traits of the species, habitat or area of interest to assess which pathway a species will follow under climatic stressors (resistance, migration, adaptivity or progressive degradation) and to create a second matrix called *Desirability Matrix*. The *Desirability Matrix* will compile the traits linked to stressor Resistance, Resilience, Adaptivity or will be particularly of interest to escape the area under stress. Resistance could be defined as the capacity of an organism (or higher level to ecosystem) to absorb disturbance or stress without changing character (Holling, 1973). Resilience (or recovery) is the ability of a receptor to recover from disturbance or stress (Holling, 1973). Finally, according to the United Nations Climate Change, Adaptivity is the capacity to *adjust in response to actual or expected climatic stimuli and their effects*. *It refers to changes in processes, practices and structures to moderate potential damage or to benefit from opportunities associated with climate change* (United Nations Framework Convention on Climate Change (UNFCCC), 2023).

The *Desirability Matrix* could be directly integrated in the final vulnerability assessment or will represent a side additional tool that will be of prior interest for the *Risk Assessment* step. The choice of integrating the *Desirability Matrix* or not will depend on the management target but also the level of uncertainty considered tolerable in the framework of the analysis. Integrating the *Desirability matrix* will add an important level of uncertainty as the capacity of resistance, resilience or adaptivity are mostly theoretical depending on the species of interest (Hendry, 2016), especially regarding the considered stage of life. Indeed, most of the knowledge on resilience and recovery trajectories came from a limited number of species (e.g. corals) (Tittensor et al., 2019). Nevertheless, not considering *Desirability matrix* in the Vulnerability analysis could be of limited interest (Wade et al., 2017), even if this reduces the level of uncertainty in the global analysis. It is especially relevant when the management question fix the geographical range of the analysis (area used as climate-lab). For example, if the subject of interest will be to focus on existent defined areas (e.g. existent MPA) or fixed communities. In that case, it could be interesting to add adaptive traits to answer questions such as “Will the benthic community of my MPA survive climate change?”.

We recommend using only the sensitivity matrix and retaining the desirability matrix as a decision support tool when possible. If, on the other hand, you choose to incorporate the desirability matrix, there are three points to bear in mind: avoid redundancy with the sensitivity matrix as certain traits can be found in both categories or overlap (Wade et al., 2017), limit the number of traits of desirability to not overexpress desirability in front of sensitivity or normalize (Butt et al., 2022) the score between the *Sensitivity* and the *Desirability Matrix* to obtain a final score, traits the two matrix as additive component as integrated then as combined element will add a supplementary level of uncertainty. If not, it is possible to find a method of combining *Desirability Matrix* and *Sensitivity Matrix* in the *Marlin Guidance* (Tyler-Walters et al., 2023) for quantitative and score method based on fuzzy matrix (Cheung et al., 2005; Jones and Cheung, 2018). For quantitative method, you need also to consider that the final equation to assess the Sensitivity score should be modified as:

$$Combined\ sensitivity\ score\ sc_{ij} = \frac{s_{ij}/s_{maxj}}{1 + A_{ij}/A_{maxij}}$$

In this case the normalized combined sensitivity score sc for the species i, regarding the stressor j, will be considered as the difference of the normalized sensitivity score s_{ij}/s_{maxj} with sj being the sum of trait-scores for the species of interest divided by the sum of the maximum scores reachable for the traits' composition s_{maxj}. This value will be divided by adaptivity/desirability matrix normalized following the same process (Butt et al., 2022).

To help with *Desirability Matrix* trait selection, we propose here a series of theoretical lists of traits to be considered as *Desirable* for each level of analysis. This list remains generic and theoretical and is not exhaustive. It therefore needs to be verified and completed with the support of experts and a dedicated bibliography screening, but it does have the merit of proposing a basis for reflection.

Species

The species level will be particularly suited to assess species protection, ecosystem conservation, resilience and adaptative trajectories (*Table 7*).

Table 7 – List of potential desirable traits to promote resistance, connectivity and adaptivity at species (considered as individuals) level.

Trajectory	Trait Category	Criteria	Bibliography
Resistance	Main traits for resistance	IUCN status	(Boyce et al., 2022; Butt et al., 2022; Chatzimentor et al., 2022)
		Impact score of non-climatic threats	(Butt et al., 2022; Chatzimentor et al., 2022)
		Habitat non-significant and fragmented	(Boyce et al., 2022; García Molinos et al., 2022; Sunday et al., 2015)
		Independence on calcification processes	(Butt et al., 2022)
		Non-use of habitats likely to be impacted by Sea Level Rise (Absolute dependence on oceanic areas)	(Butt et al., 2022; Chatzimentor et al., 2022)
		Geographic range extent	(Boyce et al., 2022)
Resilience	Main traits for resilience	Recovery capacities	(Tyler-Walters et al., 2023)
Connec-tivity	Main traits for migration (mobile species)	Position in water column (predictor of coastal extension distance) Pelagic>Demersal>Benthic	(García Molinos et al., 2022; Sunday et al., 2015)
		Trophic category (predictor of latitudinal extension)	(García Molinos et al., 2022; Sunday et al., 2015)

		Adult mobility (+)	(García Molinos et al., 2022; Sunday et al., 2015)
		Range size	(Boyce et al., 2022; García Molinos et al., 2022; Sunday et al., 2015)
		Reproductive mode	(García Molinos et al., 2022; Sunday et al., 2015)
		Habitat non-significant and fragmented	(Boyce et al., 2022; García Molinos et al., 2022; Sunday et al., 2015)
Adaptivity	Main traits for Adaptivity	Diversity (e.g. Genes, microbiomes)	(Aurelle et al., 2022; Horta e Costa et al., 2022)
		Generation Length	(Aurelle et al., 2022; Horta e Costa et al., 2022)
		Body Size	(Aurelle et al., 2022; Bates et al., 2019; Horta e Costa et al., 2022)
		Specific adaptive capacities (e.g. switch symbiont)	(Quigley et al., 2022)
		Microhabitats variation/exposure, Thermal Habitat variability	(Beissinger and Riddell, 2021; Boyce et al., 2022)

Habitat – Engineer species

Globally, there is a lack of detailed traits to assess habitat potential resilience without directly embracing an ecosystem point of view and adaptivity as more studies focus on assessing the pressure on it or on coral system. We also assume that the species-focused matrix could be used for engineer species as habitat former could be used as proxy for habitat sensitivity evaluation.

Population

A population can be defined as *the sum of individuals from the same species that inhabit a given area* (Huntley, 2023). Working at the population level implies introducing new criteria (*Table 8*).

Table 8 - List of potential desirable traits to promote resistance, connectivity and adaptivity at population level.

Trajectory	**Trait Category**	**Criteria**	**Bibliography**
Resistance	Main traits for resistance	Genetic diversity	(Bates et al., 2019)
		Body Size (link to reproduction)	(Bates et al., 2019)
		Increase in Body condition	(Bates et al., 2019)
		Increase in physical performance	(Bates et al., 2019)
Adaptivity	Main traits for Adaptivity	Population plasticity	(Walsworth et al., 2019)

Community/Ecosystem/Area of interest

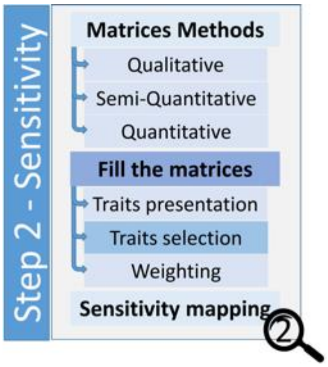
The community level is the sum of population from different species (Huntley, 2023). The species richness and evenness and the trophic relations between the different populations should be taken into account by introducing the notion of keystone species in the selection process. A proxy for assessing sensitivity at a community level will be to consider the mean sensitivity or the sensitivity range of the species selected as key species inside the area of interest, considering the different trophic levels in the scope of species chosen.

For ecosystems, the best proxy of ecosystem sensitivity and desirability will be the sum of traits of the key species for each key component of the ecosystem. It includes function, services and mitigation processes as desirable traits as ecosystem notion promote the inclusion of the exchange of materials between living (biotic) and abiotic components. In the selection of species, the species pool should include several (at list three) species exerting the same function to assess the ecosystem vulnerability. The most important traits for ecosystem sensitivity assessment will be the *Level of anthropic pressure*, the *Redundancy of functions* (at least 3 species or habitat replicates exerting the main function or services is recommended), the *Punctual Influence of Climatic Stressors* and the *Depth Range* (*Table 9*). Regarding the desirability traits, a list is proposed below:

Table 9 - List of potential desirable traits to promote resistance, connectivity and adaptivity at community, ecosystem and area of interest level.

Level	Trait Category	Criteria	Bibliography
Habitat	Traits for resistance	Habitat redundancy (spatial replication)	(Chatzimentor et al., 2022)
	Traits for resistance	Habitat complexity	(Bates et al., 2019)
	Traits for resistance	Increase productivity by protecting habitats former species	(Bates et al., 2019)
Habitat and sessile species	Traits for Adaptivity	Variable CC driver conditions (microhabitat variation)	(Beissinger and Riddell, 2021; Green et al., 2014)
Habitat et sessile species	Traits for resistance and adaptability	Dispersal abilities (area in high current speed, alignment of ocean current with thermal current)	(García Molinos et al., 2022)
All species, Habitats, Ecosystems	Traits for resistance and adaptability	Connectivity	(García Molinos et al., 2022)
All species	Traits for resistance	Increase in the diversity of communities and populations	(Bates et al., 2019)
Species		Food web maintenance by protecting key species (Especially protection of top predators, forages)	(Bates et al., 2019)
Species, Ecosystems		Function maintenance	(Bates et al., 2019)
Habitats, Ecosystems		Functional redundancy	(Bastazini et al., 2022; Bates et al., 2019)
Ecosystem	Traits for mitigation	Promote C sequestration	(Jacquemont et al., 2022)

3.3.2.2 Traits selection criteria



The following four criteria will give a list of sensitivity and desirability traits to be added in the vulnerability analysis or used as support tool. The criteria of *Uniqueness* information (Hossain et al., 2019) is important to avoid undesirable over-representation of some traits in the analysis.

3.3.2.2.1 First criteria: stressors importance

The selection of traits will depend on the stressors chosen (*Table 10*). The following table presents the main traits influenced by a stressor or combination of stressors and intends to aid the evaluation of whether a trait can be integrated to the sensitivity assessment regarding the management framework. It is also recommended to take as much as possible a comparable number of traits in each categories (Movement traits, Reproductive Traits, Specialization traits, Spatial scale traits, Biophysical Traits and Behavioural Traits) to avoid overexpressing certain categories for which the number of traits is greater than for other categories (similar to the approach promoted by Mammola et al., 2021), due to a difference in the associated level of knowledge.

Table 10 – Table of combination of climatic and non-climatic stressors influencing the same traits (expanded from Butt et al., 2022)

Traits	Sensitivity to climatic stressors	Combination with non-climatic stressors	Taxon and main species concerned	Type of traits
Low Adult Mobility	Acidification	Eutrophication, Inorganic pollution (sediments), Light pollution, Noise pollution	Corals, Echinoderms, Molluscs, Cephalopods, Marine Arthropods	Specific adaptive capacity
Air-sea surface dependance	SST, Increasing Air T°, UV	Biomass removal, Entanglement, Organic pollution, Plastic Pollution	Turtles, marine mammals, sharks, seabirds, intertidal molluscs embryos, floating eggs	Sensitivity
Biomineral (biomineralisation pathways/shell formation)	Ocean Acidification, Changes in Salinity, Storm Disturbance,	Inorganic Pollution (sediments)	Oyster, Bryozoa	Sensitivity (Mg calcite especially)

	Increasing Water T°			
Dependance of calcium/Carbonate structures	Ocean Acidification, Increasing Water T°	Eutrophication, Inorganic Pollution	e.g. Corals, oysters, clams and mussels	Sensitivity
Low Body Size/Body Mass	Increasing Water T°, Deoxygenation	Biomass removal, Habitat loss and degradation, Organic pollution, Plastic pollution, Poison/Toxin (e.g. Cyanide), Sedimentation	Smaller organisms	Sensitivity
Depth range	Ocean Acidification, Oceanographic processes, Water Temperature (SST), Deoxygenation, UV	Biomass removal, Inorganic pollution, Organic pollution, Plastic pollution	Depend of the species of interest and stressor considered.	Exposure modifier
Extreme diet specialisation	Oceanographic processes, Increasing water temperature	Eutrophication, Habitat loss and degradation, Plastic pollution	Copepods, Invertivores	Sensitivity
Feeding larva (≠ lecithotrophic larvae phase)	Invasive species, Ocean acidification, Oceanographic processes, Salinity, Sea-level rise	Inorganic pollution, Light pollution, Plastic pollution	e.g. Marine invertebrates, Fish	Sensitivity
Flight	Increasing air T°, Storm disturbance, Invasive species	Marine traffic, WindFarm	Birds	Sensitivity
Interspecific interactions dependance (+ communication dependance)	UV, Water T° increasing, Ocean Acidification	Inorganic pollution, Noise, Organic pollution	All species presenting social behaviour or needs (e.g marine mammals, schooling species).	Sensitivity
Larval dispersal and recruitment	Air Turbulence, Oceanographic processes	Marine Traffic	Especially planktotrophic species	Sensitivity and General Adaptive Capacity

				regarding value of the trait
Temperature narrow environmental tolerance (including thermal sensitivity to heat spikes, thermal-sensitive spawning, physiological function regulates by T°)	Invasive species, Water temperature (increasing)	Inorganic pollution, Organic pollution	Depend of the species	Sensitivity
pH tolerance	Ocean acidification	Eutrophication	Corals, oysters, clams and mussels Bryozoa, Sponge	General adaptive capacity, Exposure modifier
Post Larval Duration (PLD)	Air turbulence, Oceanographic processes, UV (increasing)	Eutrophication, Inorganic pollution, Organic pollution, Sedimentation	Planktotrophic larvae	Specific adaptive capacity
Reproductive strategy	Invasive species	Pollution	Short-lived, highly productive species	General adaptive capacity
Respiration	Deoxygenation	Inorganic pollution, Organic pollution, Plastic pollution, Sedimentation	Marine mammals, all the species that need O2 to breathe	Sensitivity
Sex ratio (e.g. Feminisation/Lower fertility)	Ocean Acidification, UV, T° increasing	Pollution	Reptiles, Fish	Sensitivity
Terrestrial and marine life stages (including use of intertidal areas, Shallow areas, Laguna phase)	Invasive species, Oceanographic processes, Storm disturbance, Water T° increasing	Plastic pollution, Fisheries	Fish (such as eels), moving species	Sensitivity

3.3.2.2.2 Second criteria: the importance of the temporal scale in traits selection

The selection of traits will also depend on the level and the temporality considered. Indeed, the level of sensitivity (and so the ranking) of each trait could change regarding the temporality chosen as new stressors could co-influence or add to these traits (*Table 10*). The traits influenced by multiple climatic stressors could become much more important in long-term analysis than in the near-term when the effect of climate is detected.

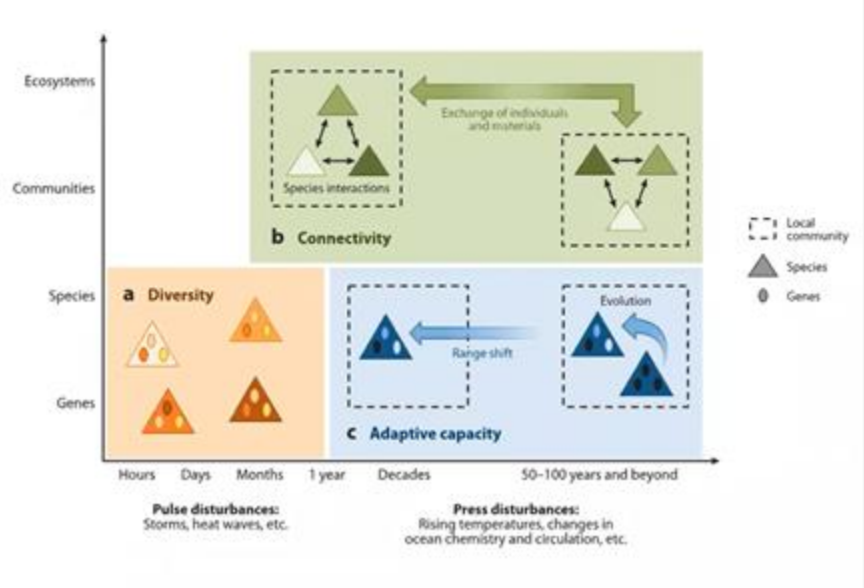


Figure 15 – Main component desirability regarding temporality and exposure intensity (from Bernhardt and Leslie, 2013)

Moreover, if resilience and adaptivity are taken into account, the desirability of traits (=traits that confer an advantage) will evolve from early change to established pressure and design a sequence of priorities (*Fig. 15*). For example, for species, near-term desirable traits will be all the traits linked to resistance (generally diversity) while the traits for adaptivity will be more of interest in the long-term (Bernhardt and Leslie, 2013). It is specifically true for non-mobile species that cannot escape from areas under climate pressure. The selection of those traits in the analysis (or their weight) is therefore of prior interest in the vulnerability assessment. On the contrary, at community and ecosystem level, the traits linked to connectivity (adult and larval) are of prior interest at each scale as it also represents the only management lever except the regulation of human additive pressures.

3.3.2.2.3 Third criteria: the importance of the chosen climate-proof scenario for trait selection (mitigation, resistance or resilience trajectories)

The selection of traits will also depend on the scope of the analysis, i.e. management scenarios. Defining scenarios is a valuable tool to support management policies and promote the emergence of novelties (Totin et al., 2018). The chosen scenario will define the scope under which the results should be evaluated in the risk assessment and help to reach climate-proofing measures. According to the European Union Climate Policy Info Hub, climate proofing could be defined as an analysis of current mitigation and adaptation development strategies and programs through a climate lens (Climate Policy Info Hub, 2023). In the framework of MSP4BIO, this climate proofing could be extended to MPA management strategies and scenarios. In 2015, Arkema et al defined three main scenarios that synthetized the different main pathways of thinking: the Conservation scenario, the Development scenario and the Informed management scenario (Arkema et al., 2015; Verutes et al., 2017) that could be associated with the vision of Blue Growth (Eikeset et al., 2018). These scenarios could be translated into priorities and limitations for the choice of pathways in the risk assessment.

> *The Conservation scenario represents a vision of long-term ecosystem health through investment in conservation and restrictions to coastal development. The Development scenario presents a vision of rapid economic development and urban expansion. The Informed Management scenario blends strong conservation goals with current and future needs for coastal development and marine uses. This scenario was refined over time through iterations of ecosystem-service modeling and stakeholder review.*
>
> (Arkema et al., 2015)

These scenarios could be implemented by a fourth Future Climate Scenario that promote long-term Adaptation and Mitigation while the notion of Informed Management Scenario could be broadened to climate change including this fourth pathway in an Integrative Informed Management vision, combining the different components of the system inside spatial planning.

These scenarios should be tested under different IPCC scenarios to assess their robustness and could be dichotomized in two different scopes: Problem focused (from a management question), Actor Focused (e.g. focused on fisheries entry) or Reflexive interventionist scenario that combines the first two approaches (Butler et al., 2020).

Among each of the scenarios, different trajectories could be chosen (*Table 11*) that will be linked to different levels of analysis and trait priorities.

Table 11 - *Example of management trajectories to be chosen to prioritize pathways under climate (adapted and implemented from* Wedding et al., 2022)

Target **(trajectories)**	**Desired outcomes**	**Science needs**	**Theoretical example**	**Conservation**	**Human Development**	**Bibliography**
Species protection (locally)	Protect a species (or a pool of species) of interest chosen in the framework (*Step 1*) and	Develop a vulnerability assessment integrating climate and different threats. Identify the	E.g. Protect the gorgonian population inside the Natural Marine Park	Species-centered, Conservation is a priority, create reserve networks including	Probable short-term restriction of human activities (especially fisheries), sustain-long	(adapted from Bernhardt and Leslie, 2013; Wedding et al., 2022)

	define management strategies and priorities to conserve it.	pathways that the species will follow at short and long term (adapt, resist or death) using trait-based analysis. Necessity of better connectivity assessment (larval).	of the Gulf of Lion	stepping-stone and promote high connectance	term human activities (e.g. spill-over)	
Species protection (moving species)		Develop a vulnerability assessment, search from pathways using climate velocities and migratory capacities (eventually develop network models). More studies are needed about adult connectivity and migratory capacities.	E.g. Protect the Bottlenose dolphin in the Mediterranean Sea			
Habitat conservation	Protect unique and key habitats for promoting the stability of ecosystem functions and services, favour habitat complexity	Develop a vulnerability assessment based on ecosystem engineers traits, better assess the services and the functions given by each of the habitats to prioritize conservation targets. Identify threats by areas.	E.g. Protection of Deep-sea corals reefs	Habitat-centered, Priority	Probable short-term restriction (e.g. closure) of human activities (including trawling) or development of alternative method (e.g. sustain – long-term human activities)	(adapted from Wedding et al., 2022)

Ecosystem conservation	Protect the key function and species in the ecosystem to promote its temporal stability. Protect ~20% of each habitat in each conservation area. Should be of prior importance regarding climate change.	Better integrate connectivity and trophic interaction in vulnerability assessment. Test the use of combined prey-predator velocities to better assess trajectories. Include invasive species. Necessity to better identify functional areas and species hotspots.	E.g. Conservation of flatfish nurseries in the Baltic Sea	Promote Risk spreading by promoting the inclusion of redundant species/habitat at delivering ecosystem functions, services and from each trophic level inside the area	Decrease human pressure, Multiplication of fishing strategies and target, spread the pressures among the different components of the ecosystem by promoting diversification of uses. Sustaining long-term human activities	(Halpern et al., 2007; McLeod et al., 2009)
Sectoral regulation	Reduce the level of stress which results from certain sectors while sustaining the activity	Better assess the need of each activity and their incidence on marine ecosystem (e.g. better identify the overlapping areas between species needs and essential activities areas), anticipate the behavioural change. Better take into account large pelagics.	E.g. Regulate fishing fleet under climate change	Protect species/ecosystems from human uses to reduce cumulative pressure and promote resistance and adaptivity	Reduce carbon emissions of activities, Develop compensatory measures, promote polyvalence of fishing unities and favour small scale fleets, spread pressure among the different components of the ecosystem	(Corrales et al., 2018; Petrik et al., 2020; Wedding et al., 2022)
Spatial planning	Flexibly protect marine ecosystems by reducing cumulative pressure and developing a patchy network of climate-	Develop ecological knowledge (both LEK-based and traditional) to reduce uncertainty and avoid	E.g. Development of climate-smart MPA networks	Promote adaptive management and engagement of local stakeholders or	Better share the sea among activities, avoid or manage cumulative pressures.	(adapted from Wedding et al., 2022)

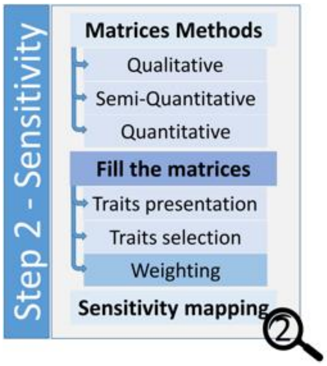
	smart areas (from the typology)	unanticipated impacts. Better project the effects of climate change on biotic components and on human behavior (especially practices). Test networks. Better assess interactive pressures.		representatives.		
Resilience trajectory **(consider Diversity Erosion scenario)**	Favour Diversity (Functional redundancy, response diversity), Connectivity (high connectance, population connectivity, ecosystem connectivity, biological legacies, modularity)	Develop habitats state of health global assessment, Identify ecological corridors and stepping-stones, Identify highly resistant species	E.g. Promote resilience of species under acute heat waves	target areas with high species diversity and high habitat complexity, create reserve networks, restore degraded habitats and avoid habitat fragmentation, protect climate refugia	Limit human pressures or distribute extraction across trophic level, limit land-based pollution, limit post-disturbance extraction and extraction of highly resistant species	(Albouy et al., 2020; Bates et al., 2019; Bernhardt and Leslie, 2013; Petsas et al., 2022)
Adaptive trajectory	Promote the protection of adaptive species and include adaptive areas inside MSP, Promote adaptive capacity (plasticity, dispersal ability, population size, genetic variation) as resilience component, Include the 3D	Identification of Adaptive species through large screening, test the inclusion of supposed adaptive areas (to be identified) inside the MPA networks, Develop dedicated monitoring. Include different depth in the area of	E.g. Integrate Adaptive areas inside MPA networks	Protect climate refugia and adaptive areas, maintain genetic diversity and habitat heterogeneity, place networks along climate gradients, create large and connected reserve networks,	Decrease human pressure, Assess the vulnerability and the potential of adaptation of actual human activities to new environmental conditions	(Albo-Puigserver et al., 2022; Bernhardt and Leslie, 2013; Bridge et al., 2014; Brito-Morales et al., 2022)

	component inside the design of reserves	interest to promote survival rate and adaptation. More bibliography is needed on highly migratory and large species.		manage for evolutionarily significant units		
Mitigation trajectory	Promote the inclusion of Mitigation areas in MSP	Identify the potential of mitigation of the different marine engineer (especially sediments)	E.g. Reach the theoretical full potential of mitigation by protecting marine habitats (mitigate 12% of the emissions)	Protect and promote good health of mitigation areas	Decrease human pressure on mitigation areas	(Jacquemont et al., 2022; Pessarrodona et al., 2023; van den Burg et al., 2023)
Development trajectory	Develop new climate-smart practices, promote Blue Growth	Identify opportunities (especially for mitigation and restoration sectors)	E.g. Develop human activities to enhance mitigation, Development of windfarms	Find trade-offs between conservation and the development of new activities	Develop new climate-smart activities, transform/adapt the existing activities to promote sustainable exploitation	(van den Burg et al., 2023)

3.3.2.2.4 Fourth criteria: the chosen *Ecological level*

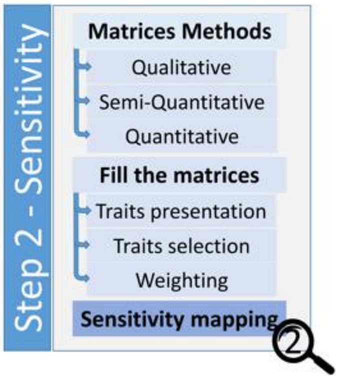
The selected level of analysis (from species to ecosystem point of view) will define the pool of species of interest in the analysis framework but also the desirability traits to be chosen (e.g. include trophic criteria).

3.3.2.3 Weighting or not weighting the traits?



By default, all the traits need to be normalized (score from 0 to 1) to be considered equivalent in the analysis and not introduce uncertainty in the ranking of traits (Laidre et al., 2008). It is nevertheless possible to weigh some of the traits (Ofori et al., 2017) if defined as prevalent in the framework of the analysis (e.g. what factors are the most responsible for species vulnerability?). The weight of traits in the vulnerability assessment is recommended in the analysis of disaster risk reduction (e.g. tsunami) (Papathoma-Köhle et al., 2019) and could be based on literature or expert knowledge. Ranking traits could be applied to elements on which the literature is abundant (e.g. main fished species, traits largely recognized as predominantly sensitive) but is not recommended when the literature is scarcer or for complex processes (e.g. ecosystem) as the ranking could be partial. In each case, it is possible to perform two vulnerability analysis, weighted and non-weighted, and compare the number of species within the various vulnerability categories (Ofori et al., 2017).

3.3.3 Mapping the results (special case of qualitative and score methods)



For Score and qualitative data, the sensitivity will be of prior interest for multiples species (basically community or ecosystem level) as it will provide a priority between species and highlight the sensitive spot for climate change (e.g. Crossman et al., 2012). Indeed, the addition of layer of current species distribution related to their sensitivity score identified through the analysis of sensitivity will highlight if the repartition of high sensitivity will be localized in a particular area or diffused across the area of interest (Hu et al., 2019). The easiest and quickest way to create the maps of sensitive areas from a species of interest when data availability is low is to apply the calculated sensitivity score for the species on all the cells of the current distribution where the species is present and a score of zero when the species is not present. Then the layers for each species in the pool of species of interest could be superposed and a chosen metric (sum of all the scores, mean of all the species scores, range of scores, number or percentage of species of High Vulnerability inside the cell) applicated to each cell of a new multispecies layer, the areas with the highest score designing the area that will concentrate the sensitives species and considered as sensitive areas in the chosen framework (*Fig. 16*).

The qualitative and scoring methods are also particularly of interest at single species level for habitat or non-moving species as it could be some variation link to subpopulation or pressures to take into account, it is therefore particularly relevant to spatialize the exercise by asking experts to duplicate the scoring for the same species across different areas or to point out the areas of highest sensitivity.

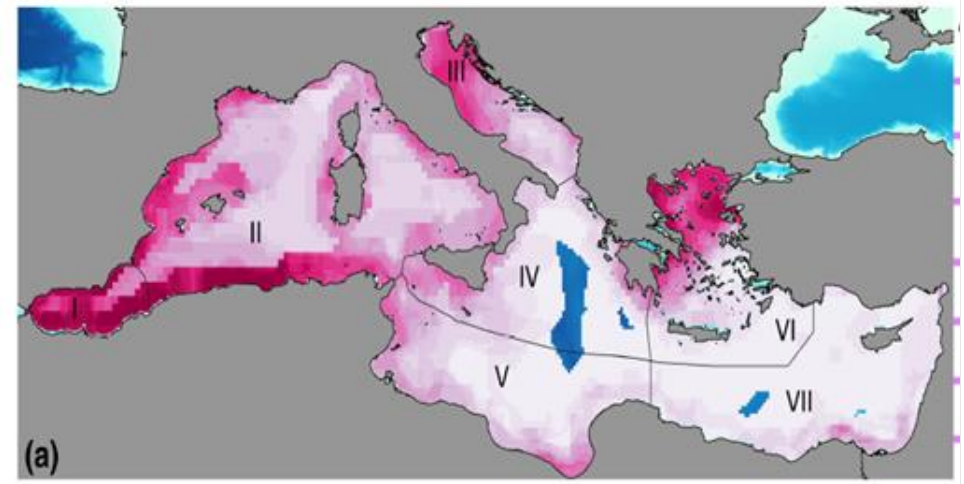
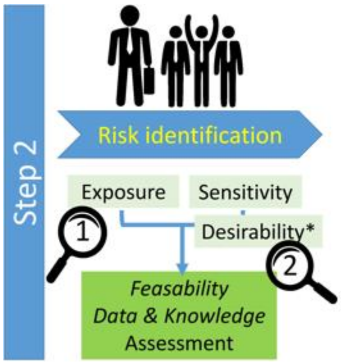


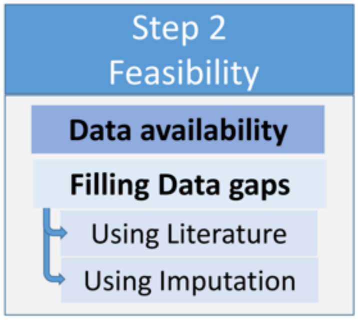
Figure 16 – Example of maps that could be created only by taking into account the sensitivity score and the species current distribution. The areas in red are the areas where sensitive species are concentrated (from Chatzimentor et al., 2022)

3.4 Feasibility

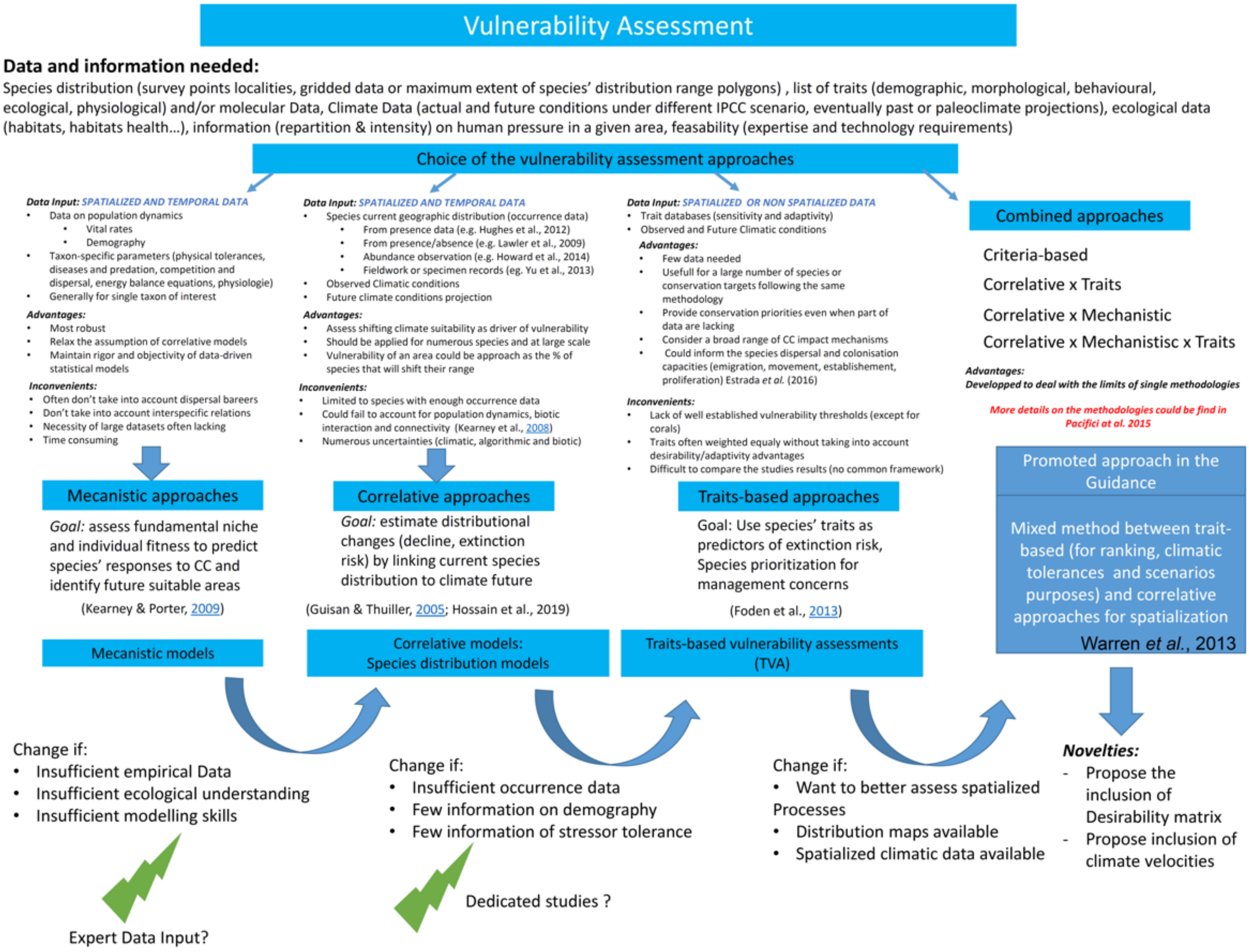


The feasibility screening consists of a phase where planners and experts will determine the vulnerability assessment methodology to be applied regarding the type and the quality of data available in the area. A general overview of data availability per test site and data type was provided in D2.1, and data availability specifically related to risk identification will be discussed in this chapter. We also present different types of vulnerability analysis and propose theoretical ways to deal with an absence of data, especially in trait-based matrices.

3.4.1 Analysis of data availability



Before performing the vulnerability assessment, the method should be chosen regarding data availability and management priorities (Foden, 2016). The creation of the trait matrices and the development of exposure maps should already give an idea about what is missing. Four main methods of vulnerability assessment regarding data availability exist: correlative models, mechanistic models, trait-based models and mixed approaches (Foden, 2016; Foden et al., 2019; Hossain et al., 2019; Pacifici et al., 2015). Three components need to be considered in the choice of the methodology used: the desirable spatio-temporal scale of analysis (broad range or locality), the type of data (e.g. from Expert or Local Ecological Knowledge, Qualitative or Quantitative) and the expertise (from both ecological and analytical points of view) for analysis performance and results assessment. The principles, advantages and inconveniences of each method and the list of necessary data for each of them are summarized in the following figure (*Fig. 17*). In *Annex 1*, we also provide the table of generic management needs and related methods to support the decision process from the *IUCN guidance* (Foden, 2016). The type of analysis chosen will also depend on the data availability and the possibility to complete the dataset by additional monitoring (personnel, resources and time available) or by imputations when data are missing. Before initiating the analysis, it is also recommended to design and highlight a conceptual model to improve comparability at a glance and help to assess the uncertainty of the results (Wade et al., 2017).



Vulnerability Assessment

Data and information needed:

Species distribution (survey points localities, gridded data or maximum extent of species' distribution range polygons) , list of traits (demographic, morphological, behavioural, ecological, physiological) and/or molecular Data, Climate Data (actual and future conditions under different IPCC scenario, eventually past or paleoclimate projections), ecological data (habitats, habitats health…), information (repartition & intensity) on human pressure in a given area, feasability (expertise and technology requirements)

Choice of the vulnerability assessment approaches

Data Input: *SPATIALIZED AND TEMPORAL DATA*
- Data on population dynamics
  - Vital rates
  - Demography
- Taxon-specific parameters (physical tolerances, diseases and predation, competition and dispersal, energy balance equations, physiologie)
- Generally for single taxon of interest

Advantages:
- Most robust
- Relax the assumption of correlative models
- Maintain rigor and objectivity of data-driven statistical models

Inconvenients:
- Often don't take into account dispersal bareers
- Don't take into account interspecific relations
- Necessity of large datasets often lacking
- Time consuming

Mecanistic approaches

Goal: assess fundamental niche and individual fitness to predict species' responses to CC and identify future suitable areas

(Kearney & Porter, 2009)

Mecanistic models

Change if:
- Insufficient empirical Data
- Insufficient ecological understanding
- Insufficient modelling skills

Expert Data Input?

Data Input: *SPATIALIZED AND TEMPORAL DATA*
- Species current geographic distribution (occurrence data)
  - From presence data (e.g. Hughes et al., 2012)
  - From presence/absence (e.g. Lawler et al., 2009)
  - Abundance observation (e.g. Howard et al., 2014)
  - Fieldwork or specimen records (eg. Yu et al., 2013)
- Observed Climatic conditions
- Future climate conditions projection

Advantages:
- Assess shifting climate suitability as driver of vulnerability
- Should be applied for numerous species and at large scale
- Vulnerability of an area could be approach as the % of species that will shift their range

Inconvenients:
- Limited to species with enough occurrence data
- Could fail to account for population dynamics, biotic interaction and connectivity (Kearney et al., 2008)
- Numerous uncertainties (climatic, algorithmic and biotic)

Correlative approaches

Goal: estimate distributional changes (decline, extinction risk) by linking current species distribution to climate future

(Guisan & Thuiller, 2005; Hossain et al., 2019)

Correlative models:
Species distribution models

Change if:
- Insufficient occurrence data
- Few information on demography
- Few information of stressor tolerance

Dedicated studies ?

Data Input: *SPATIALIZED OR NON SPATIALIZED DATA*
- Trait databases (sensitivity and adaptivity)
- Observed and Future Climatic conditions

Advantages:
- Few data needed
- Usefull for a large number of species or conservation targets following the same methodology
- Provide conservation priorities even when part of data are lacking
- Consider a broad range of CC impact mechanisms
- Could inform the species dispersal and colonisation capacities (emigration, movement, establishement, proliferation) Estrada *et al.* (2016)

Inconvenients:
- Lack of well established vulnerability thresholds (except for corals)
- Traits often weighted equaly without taking into account desirability/adaptivity advantages
- Difficult to compare the studies results (no common framework)

Traits-based approaches

Goal: Use species' traits as predictors of extinction risk, Species prioritization for management concerns

(Foden et al., 2013)

Traits-based vulnerability assessments
(TVA)

Change if:
- Want to better assess spatialized Processes
- Distribution maps available
- Spatialized climatic data available

Combined approaches

Criteria-based

Correlative x Traits

Correlative x Mechanistic

Correlative x Mechanistisc x Traits

Advantages:
Developped to deal with the limits of single methodologies

More details on the methodologies could be find in Pacifici at al. 2015

Promoted approach in the Guidance

Mixed method between trait-based (for ranking, climatic tolerances and scenarios purposes) and correlative approaches for spatialization

Warren *et al.*, 2013

Novelties:
- Propose the inclusion of Desirability matrix
- Propose inclusion of climate velocities

Figure 17 – Summary of the different vulnerability assessment methodologies including their advantages, limits and the data necessary to run it.

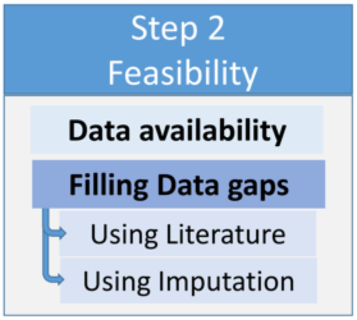
In the context of this guidance, we will focus on a mixed method based on climate velocities and Trait-based Vulnerability Assessment (TVA). We chose TVA knowing that the methodology will be applied to a broad range of management issues by a broad audience, so it needs to stay modulatory. TVA is well adapted to this purpose as the method was initially developed to extend vulnerability approaches to the largest pool of species, especially those for which knowledge is scarce (Foden et al., 2013). Among the

TVA, the analysis of the vulnerability could be separated into three categories: *Trait-based*, *Trend-based* or *Mixed-methods*. The trait-based vulnerability assessment could include both life-history and spatialized trait data from distributional range (e.g. thermal range) whereas the trend-based method will primarily assess the changes in distribution or abundance under climate threat rather than using the traits for risk assessment (Wheatley et al., 2017). In this guidance, the trait-based vulnerability assessment will provide a ranking of the species and a proxy of response of each species under climate change regarding their traits (Sensitivity and eventually Desirability matrix). Spatialized, the vulnerability analysis including species tolerance will also enable to identify and quantify the range while the analysis of climate velocities in parallel will define potential migratory routes for species. In this way, our approach is in line with mixed analyses combining correlative and TVA approaches (e.g., Thomas *et al.*, 2011; Young *et al.*, 2011a; Smith *et al.*, 2016; Allyn et al., 2020). The equation of the vulnerability assessment could also combine the different elements (Exposure, Sensitivity and eventually Adaptivity) or use them additively. We chose to promote the additivity method to avoid the introduction of too much uncertainty linked to eventual combinations. The summary of the analysis process can be found in Annex 3.

The availability of data related to the trait-based and trend-based methods of vulnerability assessment was analysed using the data inventory compiled by T2.1. 19 databases and data platforms containing ecological trait data relevant for the trait-based method were extracted and shared with T3.2 (sharepoint 2 – *Ecological traits (cluster)*). Marine Species Traits and Lifewatch Data Explorer both provide useful data on the life history traits of marine species; they are also integrated with OBIS and use the World Register of Marine Species (WoRMS) as their taxonomic backbone. Several trait databases specific to certain taxonomic or functional groups were also extracted, such as FishBase, AVONET, and a copepod trait database. Thermal tolerance data, highly relevant for the trait-based method of vulnerability assessment, can be accessed from GlobTherm (Bennett et al., 2019). Derived thermal affinities for European marine species are also available (Webb and Lines, 2018).

To provide an overview of data availability for the trend-based method, 16 sources of data on species population trends were extracted from T2.1’s data inventory and shared with T3.2 (Sharepoint - *Species population trends*). The availability of trend data from species monitoring programmes across different countries, taxa, and timeframes can be patchy, since such programmes are often biased toward vertebrates and are more common in high-income countries (Moussy et al., 2022). The most comprehensive sources of species population trend data include the EU's birds and habitats directives monitoring data and the Living Planet Database, which contains population abundance data for vertebrates. Some limited spatial data are also available from the IUCN, and datasets from some local-scale monitoring programmes, such as ACCOBAMS in the Mediterranean, were also extracted.

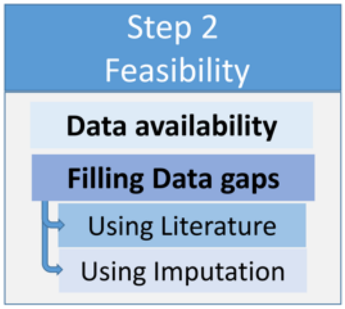
3.4.2 Dealing with Data missing in trait-based dataset



Once the methodology is chosen regarding the type of data available, the second step of feasibility screening will be to identify the gaps in the dataset (quantity, repartition and type of missing data) prior to performing the vulnerability analysis. There are three type of missing data: missing completely at random (MCAR, is not likely to introduce biases), missing at random when the missingness is linked to already identified variables (MAR) and missing not at random (MNAR) when a scheme is observed in the missing data but cannot be explained by available information (Little and Rubin, 2019). Classifying the type of data missing will help to identify potential biases in the analysis and to choose the correct method to fill the matrix. There is no perfect method to complete datasets and the choice will be highly site and data-type dependent. In each case, we recommend first to do a specific screening of the bibliography or implement specific surveys to complement the missing data when possible before patching the dataset with statistical analysis.

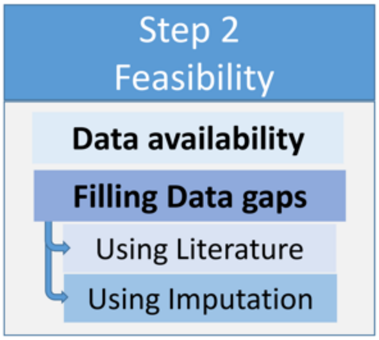
The elements that are the most likely to be missing are the traits as many species are still scarcely known (Schrodt et al., 2015) and as more traits are selected in the in the analysis, more the probability of missing elements is important. That is why it is very important to limit the number of traits included in the analysis as the best imputation approaches cannot balance for biases when more than 40% of the values are missing in trait-based matrix (Johnson et al., 2021) and as the number of species considered Vulnerable will increase in parallel with the number of traits included in the analysis (Hossain et al., 2019).

3.4.2.1 Filling the gaps using dedicated literature screening or expert knowledge



In general, a screening of the literature could be sufficient to complete the missing data for the species of high economic interest (e.g. fished species). This step could be complicated because of a lack of central commune databases concentrating traits even if the development of the big data area promotes their emergence (Devictor and Bensaude-Vincent, 2016). For species of lesser human interest, the best is (when possible) to dedicate studies to fill the gap or mobilize expert knowledge.

3.4.2.2 Filling the gaps by using imputation methods



For traits of prior importance for which no equivalent traits could be found, it is important to impute the missing data. Imputing means using *alternative values in place of missing data* following a certain number of rules. In case of few selected species or few observations, imputing is better than erasing the line of data missing. To know if a trait should absolutely be conserved (even with missing data), it is important to assess the list of traits that *contributes the most to species vulnerability to climate change and how the relative contribution of traits corresponds to data gaps in those traits* (Hossain et al., 2019)*.*

The *IUCN SSC guidelines for Assessing Species' Vulnerability to Climate Change* (Foden, 2016), list imputing methodologies to deal with traits missing data when specific research could not be implemented.

3.4.2.2.1 Impute using the redundancy of information between traits (single species scale)

If it is not possible, the first option is to not select the traits concentrating missing data and to favour the inclusion of related traits bringing a similar input in the analysis (Johnson et al., 2021). Indeed, some traits could be redundant in the analysis (see section 3.3.2.2 - *Selecting the traits*) and this redundancy can be assessed using classical statistical correlation index (e.g. Pearson's correlation coefficient r) (Pearson and Lee, 1903). If the information is strongly correlated between two traits, it is possible to select the one with the fewest missing values to fill the gap or part of the gap.

3.4.2.2.2 Impute using the phylogeny (several species with similar trait composition)

Another way to impute data missing on traits is to take into account the trait repartition similarity among closely related species (Debastiani et al., 2021; Schrodt et al., 2015 and references therein). The principle of the methodology is to fill the traits gaps for the desirable species using the most probable modality for the same traits in the identified pool of related species. The repartition of modalities within the pool of related species (percentage in the total population for each modality for the traits where data is missing) will provide the probabilities for the species to present each modality of the trait. To use this methodology, we can only recommend using species from the same geographical locality as an evolutionary process could question this relationship. Clustering approaches on data matrix are particularly suitable to identify groups of similar species and propose options of replacement as some clustering methods are relatively robust to missing data. The trait-based clustering approach is also spreading in the evolutionary models (Bastazini et al., 2022), as a method to identify and anticipate potential competition with exogeneous species (D'Andrea et al., 2019) or to define functional groups (Fong et al., 2023; Mutshinda et al., 2020). These trait-based clustering methods could also help to select some key species to be implemented in the final analysis at community or ecosystem level, highlighting potential flagship species for which there are abundant data in each of the groups.

3.4.2.2.3 Impute by adding an arbitrary score to missing values

When any equivalent could be found between traits and species, it is possible to add an arbitrary specific score for each missing value such as a "no effect" score (Foden, 2016). Nevertheless, it is important before using that method to verify that the missing data are spread among the dataset (MCAR) to avoid biases in the vulnerability analysis by mis-scoring (down or up-weighting) species or traits that are concentrating the "no effect" scores. This method should be limited to datasets with few missing data.

3.4.2.2.4 Impute by statistical analysis and loops when score is attributed to missing data

In general, a widely spread method to fill the gap while reducing the uncertainty linked to the method chosen will be to perform several vulnerability assessments varying the score attributed to missing data or performing loops of imputation models to define an interval of confidence. A mean to evaluate the quality of the imputation is to compare the true (y_{Tr}) and imputed values (y_{Im}) for a test dataset containing N imputed values and estimate the root mean squared error (RMSE) (Johnson et al., 2021).

$$\mathrm{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(y_{\mathrm{Im}} - y_{\mathrm{Tr}}\right)^2}$$

At least 160 methodological R packages exist to fill the gaps and evaluate the outputs by simple or multiple imputations (Josse et al., 2023). This number is increasing with the development of machine learning. Three principal new data-filling methods for trait-based matrices were tested and compared to well established in 2021 by Johnson et al., (Johnson et al., 2021) and are considered as valuable tools: *BHPMF, Mice and Rphylopars* The complete process to determine the efficiency of each method is developed inside the paper and give the framework about how to assess the quality of data filling for trait-based matrix.

4 Risk Analysis (Step 3)

Risk analysis aims to calculate the overall vulnerability of a conservation target taking into account the spatial heterogeneity of species repartition and stressors (climatic and non climatic). In this guidance, Risk analysis is based on a Trait-based Vulnerability Assessment (TVA) linking the Sensitivity Matrix and Exposure. The Risk assessment chapter is divided in three sub-chapters, *Choice of TVA methods*, *Vulnerability Assessment (TVA)*, *Uncertainty and verification process* (*Fig. 18*).

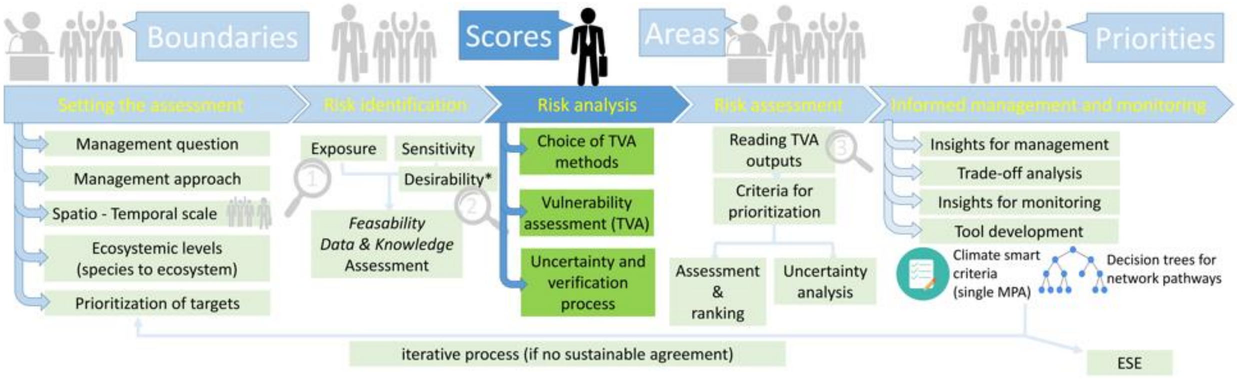
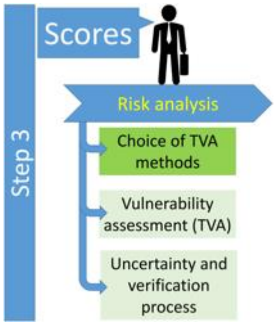


Figure 18 – Risk Analysis represents the third step of the guidance Flowchart and is composed of three sub-chapters explaining the process from the choice of the Trait-based Vulnerability Method (TVA) to the verification of results from the analysis.

4.1 Choice of TVA methods: the Vulnerability Analysis

4.1.1 Presentation of vulnerability assessment regarding data availability



Vulnerability assessment represents a function *of both intrinsic and extrinsic factors and assessments often considering exposure, sensitivity and adaptability in combination* (Pacifici et al., 2015). In fact, the vulnerability function will make the link between the Exposure score, the Sensitivity matrix and, eventually, the Adaptivity/Desirability matrix (*Fig. 19*).

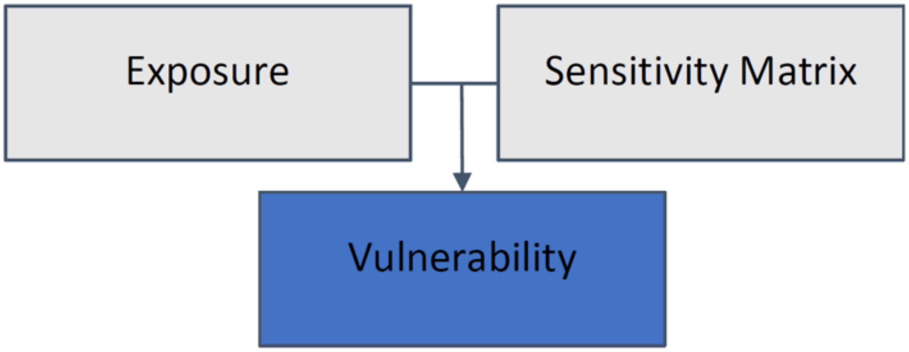


Figure 19 – Generic Flow of the vulnerability assessment

As presented in the Feasibility assessment, this guidance focuses on a mixed approach. The trait-based vulnerability assessment (TVA) will determine the sensitivity, but the results are reinforced and spatialized using species geographical range, climate analogs and climate velocities to meet the needs of the Marine Spatial Planning. In this part, we will concentrate on the presentation of different TVA methods depending on data availability in each site.

The generic equation of the vulnerability (additive method) will be (Cannizzo et al., 2023):

Vulnerability = (Exposure + Sensitivity) - Adaptive Capacity

considering that the Adaptive/Desirability are not necessary taken into account. In each case, it is better to normalize each of the indices to facilitate the inter-species comparison.

For weighted metrics, the equation will become (e.g. Boyce et al., 2022):

$$V_{s,c} = \frac{\left[S_{s,c} \times \omega S_{s,c}\right] + \left[E_{s,c} \times \omega E_{s,c}\right] + \left[(1 - A_{s,c}) \times \omega A_{s,c}\right]}{\omega S_{s,c} + \omega E_{s,c} + \omega A_{s,c}}$$

4.1.2 The different types of Trait-based Vulnerability Assessment (TVA)

4.1.2.1 Qualitative and scoring approaches

Pre-requisite: Transforming the Exposure into score or exposure levels

The problem with these methods is that they need to transform quantitative values, e.g. level of Exposure or certain traits such as maximum length, into qualitative or scored values to include them in the *Vulnerability assessment* bearing in mind that this transformation could lead to supplementary uncertainties. To take this uncertainty into account it is possible to develop categorization methods following different scales from expert or numerical tools or use existent methods, such as fuzzy matrices (e.g. Jones and Cheung, 2018). The fuzzy methods are used to deal with fluctuant categorization, for example to deal with undetermined thresholds, admitting that an observation could belong to different categories with a certain probability (degree of membership) to be attributed to one or the other category using heuristic rules (Gigerenzer and Gaissmaier, 2011; Mathevet et al., 2018). The uncertainty of the fuzzy membership function will be the degree of overlap between the fuzzy categories called fuzziness. Cheung et al., advise using trapezoid functions for upper (High or Very High depending on the chosen scale) and lower (Low or Very Low) categories and triangular fuzzy membership functions for intermediate categories (Cheung et al., 2005). For Exposure, the low level is defined when the conditions will not change from a period of reference (no Anomalies or climate hazard) (Foden et al., 2019). Following that method, score (binary or along a scale) could be attributed to each stressor considered in the analysis and will lead to the creation of an exposure map in which each cell will receive an exposure score or modality per stressor considered in the analysis. We will not calculate yet a final Exposure modifier as sum of stressors' score as the traits will not react the same way to different stressors.

Now the value of vulnerability can be calculated in each cell.

4.1.2.1.1 Vulnerability method based on ordination (qualitative, less recommended)

The Vulnerability method based on ordination will attribute a quantitative value to each of the species regarding the three criteria: Exposure, Sensitivity and eventually (Adaptivity). In general, this method is chosen when the sensitivity criteria are qualitatively determined.

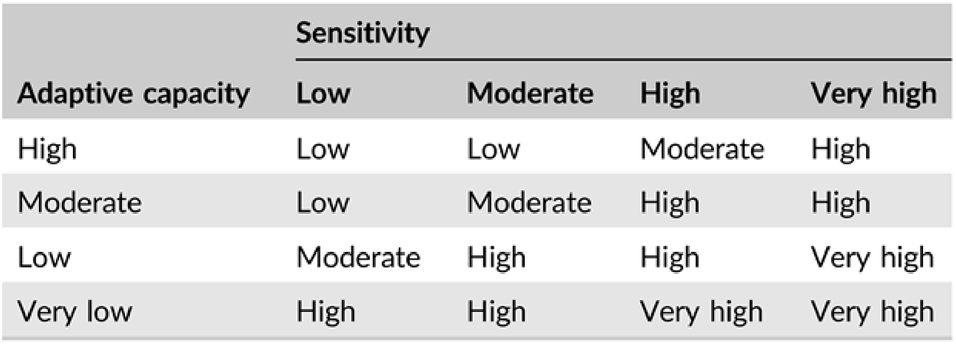
Necessary inputs of the Method:

- Quantitative Exposure layer
- Qualitative Sensitivity Matrix
- Eventually Qualitative Desirability Matrix

In this method, we consider the *Sensitivity* and (eventually) *Desirability/Adaptivity* as qualitative indices. Each species will have a *Sensitivity* value ranging from *Very Low* to *High Sensitivity* and/or a *Desirability/Adaptivity* value ranging from *Very Low* to *Very High Desirability/Adaptivity*. The final value of vulnerability will be a combination of exposure and sensitivity scores (or Exposure x Sensitivity X Desirability) depending on a set of heuristic arbitrary additive rules (e.g. *Table 12* and *Table 13* from (Jones and Cheung, 2018)) and/or validated by expert. For conservative point of view, we recommend, if use of sensitivity and adaptivity, to consider sensitivity value always predominant on adaptive values using a scale one level behind.

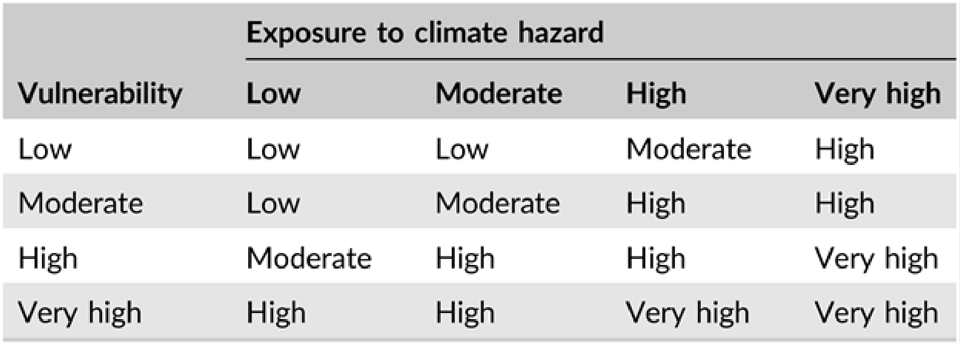
e.g. A species with Very High Vulnerability ***AND*** High Adaptivity will have a High vulnerability

Table 12 - *Matrix of rules that determine the level of vulnerability based on species' sensitivity and adaptive capacity to one or several chosen stressors* (from Jones and Cheung, 2018).



	Sensitivity			
Adaptive capacity	**Low**	**Moderate**	**High**	**Very high**
High	Low	Low	Moderate	High
Moderate	Low	Moderate	High	High
Low	Moderate	High	High	Very high
Very low	High	High	Very high	Very high

Table 13 - *Matrix of rules that determine the risk of climate impacts based on species vulnerability defined thanks to table 11 and exposure to a chosen climatic stressor*



	Exposure to climate hazard			
Vulnerability	**Low**	**Moderate**	**High**	**Very high**
Low	Low	Low	Moderate	High
Moderate	Low	Moderate	High	High
High	Moderate	High	High	Very high
Very high	High	High	Very high	Very high

Nevertheless, this methodology will not be recommended because it makes the studies less comparable as most of the thresholds are arbitrarily designed. It is nevertheless highly spread when data are scarce or for preliminary studies (e.g. TOPSIS).

4.1.2.1.2 Vulnerability method based on ordination and additive scoring method (medium)

The most commonly used method to deal with qualitative, semi-quantitative data (e.g. score data) or mixed-data (including quantitative data) is to use a vulnerability based on scoring methods (see section 3.3 - *Sensitivity*). Equations could change and be developed somewhat depending on the chosen framework but in general, the final score of the Vulnerability will be the sum (when interaction between trait and stressors will not be considered) or the product of the different components of the analysis divided by the number of elements entered in the equation. We advise to normalize (e.g. from 0 to 1) the score from the different component (sensitivity, adaptivity, exposure) to take into account that the number of traits/stressors in each category could influence the ranking and facilitate comparison between species.

Considering one stressor (adapted from Butt et al., 2022):

$$Vulnerability\ v_{ij} = sts_{i,j} \times E_j$$

In this case, the vulnerability of the species i to the stressor j will be equals to the standardized sensitivity score (see section 3.3 - *Sensitivity*) of the species i to the stressor j multiplied by the intensity of the stressor j. In case of the vulnerability assessment will include Desirability/Adaptivity traits, must be replaced by the standardized combined sensitivity score (see section 3.3.2 - *Desirability section*).

For several stressors, the final vulnerability score will be the standardized sum of vulnerability score for each pressure considered in the analysis (additive method).

4.1.2.2 Vulnerability method based on quantitative data

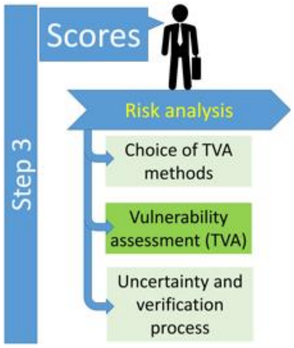
The vulnerability matrix based on quantitative data presents the advantage of facilitating analysis by limiting the number of transformations required (a single type of data used), especially for Exposure which is generally quantitatively assessed (e.g. *Projected time of climate emergence*, *Projected ecosystem disruption*) (Boyce et al., 2022). It also facilitates the calculation of vulnerability thresholds and the comparison among studies by proposing a common and standardized framework. Quantitative vulnerability assessment tries to emancipate itself as much as possible from expert opinion even if it remains a valuable and inescapable source for most of the studies because of a great lack of traditional scientific knowledge in each of the different component included in the analysis, especially regarding climate change (e.g. 44% of dataset categories coming from expert knowledge on the australian quantitative climatic vulnerability assessment of the mackerel, *Scomber scombrus,* Champion et al., 2023). On the other hand, vulnerability analyses based solely on quantitative indices limit the number of factors that can be integrated into the analysis, especially for Desirability, which could be restricting for non-moving species.

In that case, the quantitative criteria chosen for assessing sensitivity will generally focus on categorizing the habitat suitability (e.g. *Safety margins* and *Vertical use*), the level of non-climatic pressure that will be exerted on the species (e.g. *Cumulative Impact index*), and a proxy of species inner sensitivity (e.g. *IUCN Species Red List conservation status* when available and sufficiently assessed). In that sense, they will be similar to correlative approaches. For moving species, the criteria chosen to assess adaptability will be reduced to two different components: the size potential future available niche (e.g. *Geographic range extent and thermal variability and use*) and a proxy of the probability to reach new favorable habitats linked to connectivity (e.g. *Geographic habitat fragmentation*) and migratory capacities (e.g. *Reproductivity* and migratory criteria generally summarized by the *Maximum Body Length* single traits and/or *Time of Larval Duration*). For non-moving species, the Adaptivity will be generally assimilated to a recovery potential following different set of generic (e.g. *Size distribution*, *Species* *richness*, *Diversity* or *Habitat cover*, *Substrate complexity*) and species-specific indicators (e.g. *Calcifying to non-calcifying cover* for corals) including potential competition (e.g. *Coral to macroalgae cover*) (Cinner et al., 2013). The Exposure indices will serve to localize, asses and quantify when climatic conditions will begin to have an influence on the targeted species (e.g. *Projected time of climate emergence*), how much they will erode the local system (e.g. *Projected ecosystem disruption*), where they exceed species tolerance (e.g. *Projected loss of suitable habitat*) and finally which pathways the species could follow (e.g. *Climate velocities*). The methodology to calculate, standardize and combine these different indicators is presented in the following papers (Boyce et al., 2022; Trisos et al., 2020).

All these elements will be calculated and standardized per cell of the grid and use to assess the vulnerability assessment following the generic equation (for additive purpose):

Vulnerability = (Exposure + Sensitivity) - Adaptive Capacity

4.2 The Vulnerability assessment: defining Vulnerability thresholds and calculating Climate Risk



The vulnerability score, obtained using the methods described above, by itself will provide a classification among the area or species of interest but is not sufficient. Indeed, the score should be translated into Vulnerability categories for quantitative and scored methods to evaluate climate risk. To assess climate risk, each species and each grid cell must be assigned to a Vulnerability category from Low to High Vulnerability. This classification requires to define risk thresholds. These thresholds, as traits categories thresholds, aren't often categorized but could be determined by the distribution of scores or values within the pool of species or cell of interest.

Halpern et al. proposes a simple decision-support classification which summarizes the methodology used in numerous vulnerability assessments (Harper et al., 2022). The classification reasoning could be similar when considering a pool of cell or a pool of species (*Fig. 20*).

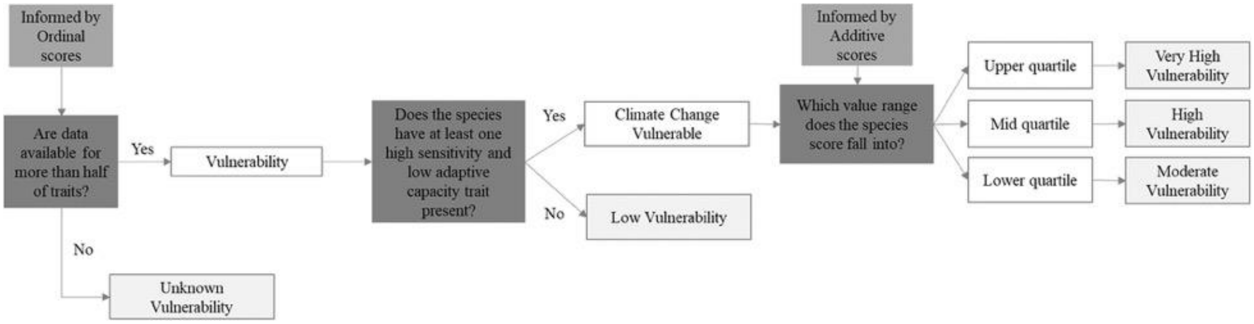
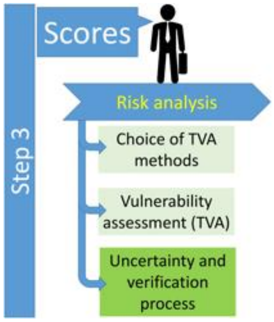


Figure 20 – Flowchart used by Harper et al. to assign each species to a vulnerability category (Harper et al., 2022).

The thresholds could also be defined using the statistical distribution of the inner indices. Generally, when a clear basis is lacking, the thresholds are set regarding the 50th, 10th and 90th quantiles of the indices values distribution (Boyce et al., 2022).

4.3 Uncertainty and Verification process



This stage aims (i) to list the potential sources of uncertainty at the various levels of the analysis and to propose solutions where it is possible to compensate in part for these uncertainties (ii) to list the main criteria for measuring the confidence to be placed in the VAT results.

4.3.1 Uncertainty analysis

After performing the vulnerability assessment, it is of prior interest to identify uncertainties for each step of the vulnerability process regarding the chosen methodology (*Table 14*). This step will allow to propose solutions to deal with these uncertainties. The uncertainty part of the analysis could be evaluate following a certain number of criteria at each step of the process:

Table 14 – List of uncertainty sources identified in the literature for the vulnerability assessment and potential method to compose with the uncertainty source.

Type of uncertainty	Rationale	Method to validate the results	Bibliography and Methodologies
Provenance of data used	*Low uncertainty:* Based on extensive peer-reviewed literature or grey	Assess the concordance of the results of the vulnerability assessment with other	(Tyler-Walters et al., 2023)

	literature from recognized agencies *Medium uncertainty:* Based on some peer reviewed papers but a majority of grey literature or expert knowledge is involved *High uncertainty:* Only based on Expert judgement	studies from literature or by comparing to other methodologies of vulnerability assessment based on the same dataset	
Uncertainty linked to data missingness	Missing data lead to fluctuation of score for vulnerability, sensitivity and Exposure score	Compare the scores by varying the rate of data missingness on a dataset sample to evaluate the missingness tolerance of each component of the analysis	(Boyce et al., 2022)
Uncertainty in species distribution and abundance	False-absence or false-presence linked to projection methods	Difficult to correct when data are scarce, possible to compare maps from different dataset when available	(Foden, 2016)
	Error linked to species identification (especially for dataset from participatory sciences)		
	Algorithm uncertainty linked to methods used to predict species distribution	Apply a variety of different statistical methods and model structures, thereby summarizing predictions across all models to generate ensemble forecasts for example, model-averaged prob-ability of presence and confidence intervals	(Carvalho et al., 2011; Guisan and Rahbek, 2011; Pacifici et al., 2015; Réale et al., 2003; Visconti et al., 2016)
Uncertainty about biotic assumptions	Species' distributions are assumed to be in equilibrium with surrounding climates and these relationships are	Hypothesis to accept in the analysis framework, uncertainties arise when these conditions are not matched	(Harrison et al., 2006; Pacifici et al., 2015)

	assumed to persist in the future		
	The relation between theoretical and realized niche is unknown. The theoretical niche is assumed using species requirements and tolerance but does not include all the environmental factors. That is why the realized niche is generally smaller.		(Guisan and Thuiller, 2005; Pacifici et al., 2015)
Uncertainty in traits selection (representiveness)	The selection of traits and the research of uniqueness information could lead to erroneous vulnerability assessments due to the omission of features of fundamental importance.	Measure the completeness of information for each traits	(Boyce et al., 2022; Hossain et al., 2019)
		Measure the contribution of traits in the vulnerability assessment	
		Test different traits composition and test the goodness-of-fit and robustness of the alternative models to indicate the most interesting combination	(Foden, 2016)
Uncertainty in traits modalities attribution (lack of confidence about the assessment of a state of traits)	The transformation of quantitative values of traits to qualitative traits or simply the panel of expert chosen could influence the modality under which each trait is considered	Promote fuzzy approaches, compare the expertise of different expert (prefer a panel of expert than a single expert)	(Jones and Cheung, 2018)
Uncertainty in traits combination and interaction	Traits could combine and act in synergy or as antagonists	Don't take into account traits combination and prefer additive methods when sour literature isn't available	(Foden, 2016)

		Develop more mechanistics models	
Uncertainty linked to the weighting process	An absolute ranking is missing for all the component of the analysis (especially among traits) but could be developed based desirable on scenarios, actual (and so partial) knowledge including literature and expert knowledge	Develop laboratory experiment to better assess the relative importance of traits, test the effect of unweighting and different weighting system on the outcomes of vulnerability assessment	(Foden, 2016; Ofori et al., 2017)
Uncertainty of climatic models (often missing)	Each climate model contains its own uncertainty and will lead to different climate scenarios.	Take projection from at least 3 different climate models, choose a robust subset of climate models output	(Foden, 2016; Jones, 2000; Pacifici et al., 2015; Snover et al., 2013; Wade et al., 2017)
Uncertainty of climatic scenarios	More Climate scenarios in a realistic range of future used higher is the confidence interval	Test TVA result using several climates scenarios	(Foden, 2016; Hossain et al., 2019)
	Take into account an increasing uncertainty with distance in time.	Discount the Exposure score. The discounting aims to deal with great uncertainty associated with unknown future states and the fact that the uncertainty will increase with the distance to the present. Applying a discounting rate to each climate scenarios will allow to reduce uncertainties linked to the climate projections.	(Boyce et al., 2022)
Uncertainty in model predictors	The chosen predictor could influence the intensity of the exposure and model performance	Use more than one predictor to include confidence intervals	(Pacifici et al., 2015)
Type of vulnerability assessment method chosen	Correlative models are known to under-estimate the potentially realizable	Cross these methodologies carefully with TVA as they could lead to important	(Foden, 2016)

	niche but overestimate vulnerability	underestimations of vulnerability to climate change (especially when sensitivity indices will be linked to distribution loss quantification)	
	Correlative models are known to over-estimate the potentially realizable niche but underestimate vulnerability	Compare the trajectories and ranking with climate-analogs when available	
Classification of vulnerability score (uncertainty linked to arbitrary thresholds)	The fact that the species or areas will be spread between arbitrary categories could lead to over-estimation or under-estimation of the overall vulnerability	For quantitative traits analysis, randomly scored 25% species as presenting high vulnerability and compared the results to the standard TVA	(Hossain et al., 2019; Ofori et al., 2017)
Uncertainty linked to score and indices transformation	To ensure that indices are ecologically grounded, the transformation applied to standardized indices will depend on the type on data manipulated and are not standardized from an indice to another (subjectively derived). It is so important to verify their efficiency.	Evaluate quantitatively the impact of alternative transformation functions on the calculation of vulnerability, its indices and dimensions under different levels of observation missingness	(Boyce et al., 2022)
Integrate Adaptivity inside the vulnerability framework	Adaptivity will lead to an increasing level of uncertainty as their potential to reduce the incidence of climate change on species is more supposed than proved. Moreover, the capacity of traits	Assessment without taking into account the Adaptivity should be performed first. Then the results including Adaptivity could be carefully assess, considering the variability of empiric proofs regarding the species of interest (e.g.	(Foden, 2016; Wade et al., 2017)

	to evolve is not yet assessed.	more studies on coral adaptivity)	

4.3.2 TVA results' verification process

The easiest method to assess the quality of the results and calculate the level of confidence is to use different vulnerability assessement and verify the concordance between the results. The results could be compared between vulnerability assessment from the same dataset (higher confidence) (Foden, 2016) or literature review (lower confidence) (*Table 15*). The confidence interval attributed to literature comparison will be reduced as the framework of the literature will deviate from the initial framework. The highest confidence for literature comparison will be attributed when the assessments compared are based on the same pressure acting in the same framework (species and spatio-temporal scale) (Tyler-Walters et al., 2023). The Applicability of the results of the analysis to other test sites will follow the same scale and should be carefully tested as vulnerability assessment should be confronted to empirical data (Wade et al., 2017).

Table 15 – Criteria (Degree of concordance) used to assess the quality of the vulnerability analysis.

Degree of concordance Between studies and/or between vulnerability assessments (confidence)			
Low	Medium	High	Bibliography
Results of the vulnerability assessment do not agree on direction or magnitude (impacts or recovery)	Agree on direction but not on magnitude (impacts or recovery)	Agree on the direction and magnitude (impacts or recovery)	(Tyler-Walters et al., 2023)
The composition and the number of species ranked in each vulnerability categories varies between methods	Most species (composition) ranked in each vulnerability categories remains in the same category between methods	The number and the composition of species ranked in each vulnerability categories stay the same between methods	(Tyler-Walters et al., 2023)

5 Risk Assessment (Step 4)

The risk assessment phase (*Fig. 21*) consists of a spatialized joint analysis of the results of the vulnerability assessment and the intermediate results (traits and exposure) to evaluate the potential of the different areas/measures to be of conservation interest regarding the initial framework defined in step 1. Risk assessment phase generates a portofolio of climate-smart management scenarios that can be translated into management measures and used as a tool for discussion with skateholders to support Marine Spatial Planning development. The risk assessment will bring together all the maps from different scenarios and regarding different stressors and species chosen in the framework. The different maps should be compared in the case of additive pressure to create a typology of areas for each management concern, to create different possible designs of MSP and to add a probability for each of the scenarios proposed. This step involves experts, planners and managers of the site that could better apprehend the potential trade-off necessary to find regarding each of the proposed scenarios.

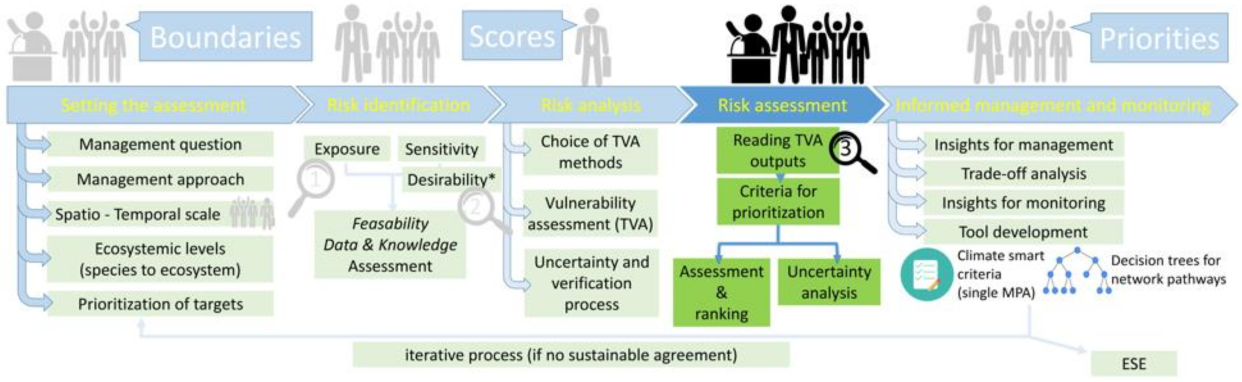
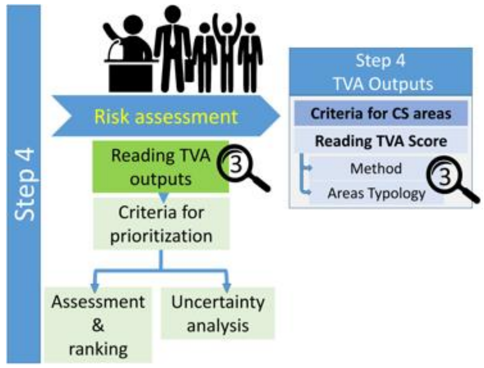


Figure 21 - Risk Assessment represents the fourth step of the guidance Flowchart and is composed of four sub-chapters explaining how to read the TVA results and how to transforme them into a portofolio of climate-smart management scenarios.

5.1 Reading TVA outputs

The objective of the step is to propose different MSP scenarios taking into account climate change and connectivity. This step should be realized by planners.

5.1.1 Criteria for climate-smart areas identification and prioritization

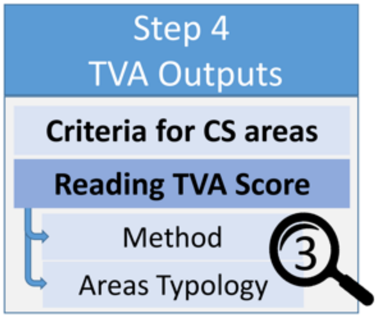


There are very few criteria to assess climate risk on areas or species identification for conservation purposes. To identify areas of conservation interest, 4 criteria must be taken into account. The first criterion is the *Temporality* of targeted management measures; it is fundamental to determine if the measure to be implemented will be temporary or must be permanent as the tool to be implemented will change regarding related policies. For example, for fisheries management in French regulations, an MPA could be implemented as a long-term conservation measure as they are not planned to be removed in the legislation whereas fishing “cantonnement” is a temporary measure. A fishing “cantonnement” is a generally temporary-limited (must be renewed regularly) delimited area at sea in which the capture of marine species is either prohibited, limited in time or reserved for certain fishing gear/vessels but is not considered as an MPA (MEDAMP, 2024). *Temporality* is also a fundamental criterion for risk assessment as the Exposure could change regarding the chosen temporality and for the success of management measure as “Earlier is Better” (Hopkins et al., 2016). Ideally the climate component should be included in the decision process as soon as possible to maximize the chances of success. The second criterion is the *Vulnerability* of the areas which also emphasized a third criteria, the *Severity of exposure,* ideally cumulative and allowing the separation of human and climatic pressures, as it is advisable to first target areas where the reduction of human pressures is possible. It is especially the case for fisheries and pollution as they represent direct and rapid management levers, are the main stressors on the marine ecosystem and add and even synergize with climate change. Therefore, areas where it is too difficult to find trade-offs should be identified in agreement with managers and taken out of the analysis. This phenomenon leads to the implementation of a fourth criteria: the *Degree of control* that managers have on each chosen area regarding the main stressors acting on it (Song and Lee, 2022).

Once similar areas of interest are identified, they should be prioritized. For climate-smart areas presenting similar scores from the prior criteria prioritization, the criteria to be taken into account are the Concentrative Potential of species of interest, their Potential for Mitigation, their Potential for Adaptation, their Connectivity Potential to benefit to adjacent areas and more broadly the Repetitivity of function and habitats inside the area as proxy of stability. The criteria *Promoting the Heterogeneity* and the *Redundacy* criteria regarding climate change are also of prior interest regarding MPA network as integrating a patchy component at different scales, from habitats to species level, could maximize the chance of resistance and resilience whereas promoting the possibility of sustaining human activities by allowing a theoretical distribution of pressure on redundant species (*risk spreading*) (McLeod et al., 2009; O’Regan et al., 2021).

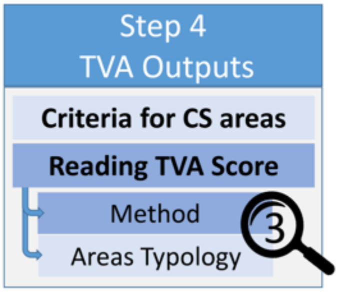
Regarding species prioritization under climate change, three types of criteria should be taken into account to identify management priorities: the Services criteria (role that the species deliver to human, including social and economic indicators), Ecological criteria (role that the species exerts in the environment and trophic networks that could also be linked on species traits) and Climate criteria linked to species *Sensitivity* (including Resistance, Recovery and Adaptive Potential) link to their inner traits (see trait section). From a community or ecosystem point of view, a Stability Index regarding climate change could be added regarding the redundancy of function or species exerting the same function. The ecosystem services criteria are generally ranked by the users themselves or their representatives (declarative importance, WP4 deliverable) while ecological criteria were identified in Deliverable D3.2. The three rankings will provide a final score that could highlight the species to prioritize regarding the creation of management patterns.

5.1.2 Step-by-step reading of vulnerability score



This work aims to support the panel of experts, planners and managers to read the results both from the vulnerability analysis and the sensitivity-trait selection to propose first prioritizations of area of prior interest that would be discussed with the actors on step 6 (trade-off analysis). The analysis of vulnerability score will highlight four different types of areas: low vulnerability areas, high vulnerability areas, climate refugia and intermediate areas. To go further, the combination of vulnerability score and sensitivity traits will help to discriminate between intermediate areas and two other types: stepping-stone areas and adaptive areas. A sixth type, mitigation areas could also be promoted based on the current knowledge, but this type of area is still not clearly identified in the literature so the guidance on this point could be taken carefully. Moreover, the assessment phase will also highlight, by identifying some species corridors or potential trajectory of evolution of the area of interest, potential collaborators (e.g. managers of other MPA) whose experience could prove crucial in helping to define the future management framework as their own MPA has undergone similar development (past temporal climate-analogs) or will be a recipient of species of interest in the future (connectivity). This analysis reposes on two main step: (i) identifying the typology of each grid cell in the study area and their potential interest for conservation purpose (ii) define the potential of each grid cells as MPA or part of a climate-smart network by creating a set of climate-management portfolios (see section 5.2.2 – *Management Pathways*).

5.1.2.1 Step 1. Reading the results of the vulnerability analysis and combining with intermediate outputs (climate-analogs and sensitivity-matrix)



The vulnerability analysis (as seen previously) will provide the following information: score or indices of species vulnerability that will give you the possible priorities of conservation between species/areas by providing a ranking from the less vulnerable to the more vulnerable, a map that will provide the possibility to identify and quantify the current loss of repartition range (*Fig. 22*) and, associated with an analysis of climate-analogs (even bioclimatic velocities to quantify at which speed your species will reach the area of target) to identify the possible corridors your species will follow or to anticipate the trajectory of evolution of the area of the interest by identifying climate-analogs.

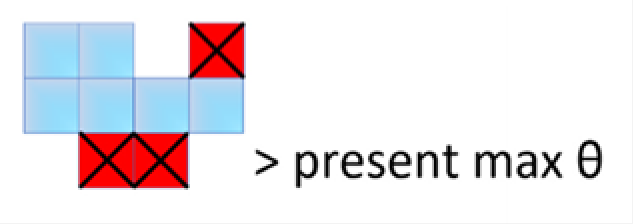


Figure 22 - Loss of repartition range from *Chatzimentor et al., 2022*

If the complete vulnerability analysis (integrating all stressors) will help to rank the species of interest or to evaluate the intensity of future threats to the species/area of interest, complementary analysis could be performed to identify the management levers. To assess the results correctly, it is advisable to analyse the contribution (output of the model) of each indicator entered in the vulnerability analysis or to duplicate the vulnerability analyses in the case of scored or quantitative analyses, distinguishing the type of stressor (one analysis per stressor, or separating anthropogenic stressors from climatic stressors) so as to be able to compare the vulnerability of the area or species of interest to the various stressors and identify potential levers.

To help the process, it is possible to use categorization tools to summarise for a given area the contribution of for each criterion *Exposure*, *Sensitivity* and *Vulnerability* for each of the stressors (additive method) (*Fig. 23*). Here, we chose to present the categorical method coupling Risk categorization matrix with Heuristic Decision making (Cochrane and Al-Hababi, 2023) as this process is visual, integrative of most of the components of interest, can be used by planners from all research field without too broad knowledge on computation and is, fundamentally, the process derived by the other tool.

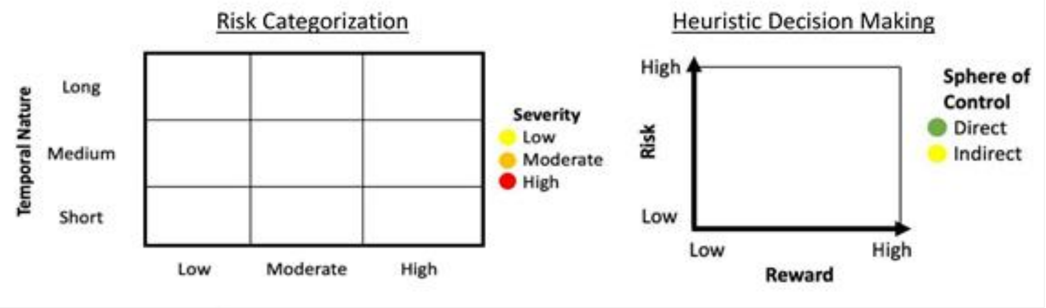


Figure 23 - Support Decision Tool for categorical risk assessment adapted from Cochrane et Al-Hababi, 2023

Here, two elements must be considered: the Risk assessment matrix and the Heuristic Decision Making Tool. The Risk assessment matrix is a decision support tool that will summarize the output of the criteria of prioritization (*Exposure*, *Sensitivity*, *Adaptivity/Recovery* (if added), and *Vulnerability*). This risk assessment matrix includes the projected time and the severity/desirability for each of the criteria. The matrix could be repeated under different climate scenarios (SSP or RCP) to increase the robustness of results. The risk assessment will help to characterize MPAs along a gradient from low to high vulnerability regarding the chosen stressors and/or the chosen area. The second element to be taken into account is the Heuristic Decision Matrix. The Heuristic tool aims to define simple decision strategies based on few relevant predictors knowing that a part of the available information is missing (Gigerenzer and Gaissmaier, 2011). In this example of tool, the Heuristic Decision Making is a cost-benefit approach to evaluate the potentiality and the interest to try to control the climatic risk using direct levers (generally very few for climate change, that is why the effort concentrates on reducing the cumulative pressures) and indirect levers (the actions that the other component could bring to mitigate the climate stress) (*Fig. 24*).

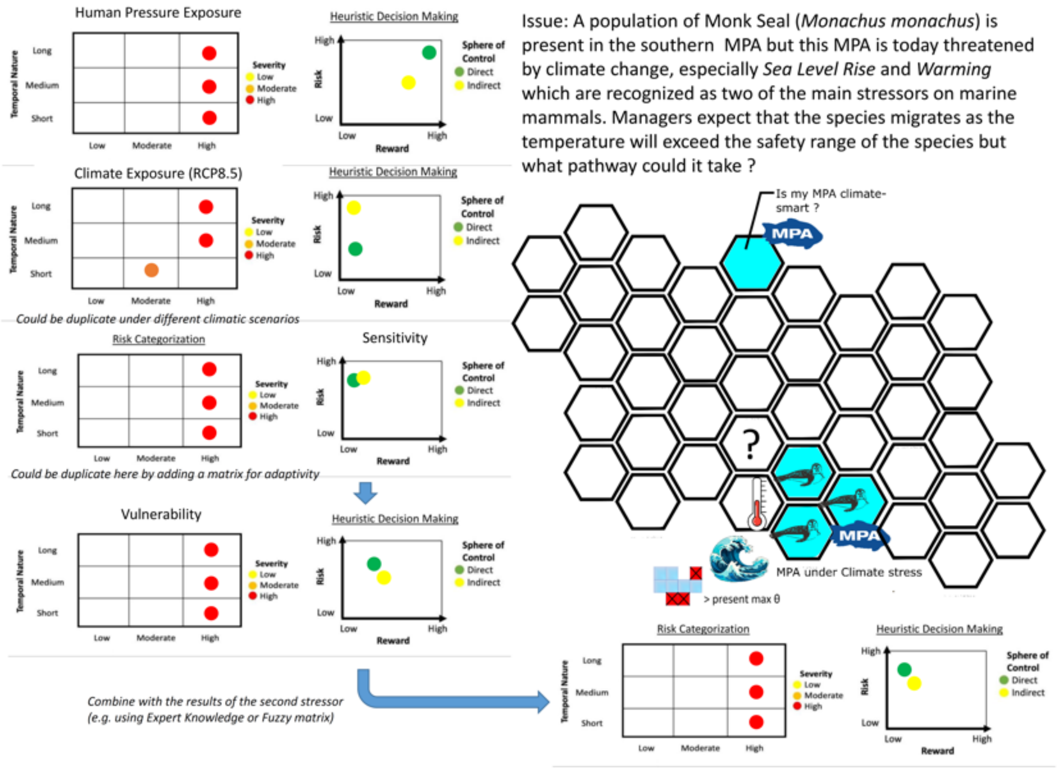


Figure 24 - *Theoretical example of Risk Assessment regarding climate management issues (here the Monk Seal in Mediterranean Sea). The risk assessment indicates a High risk (high vulnerability to the stressors due to both High Human Pressure Exposure, High Climate Exposure and High Sensitivity of the species for the stressor) and a high difficulty to implement management for a low reward inside the cell of interest. So, this cell is not of prior interest regarding the management question. The same analysis could be performed (and automatized for each cell).*

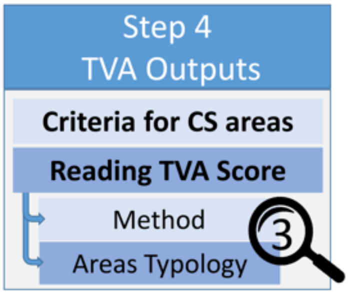
This tool, coming from human sciences, is traditionally used in marine spatial planning but could be also replaced by simple models and spatial tools promoting iterative processes (Lombard et al., 2019). These models apply nevertheless the same reasoning as they are based on spatial assessment of the risk, the benefices (e.g. using ecological production function (Bruins et al., 2017)) and assessing the results (Verutes et al., 2017).

Comparison of methods

The method presented here is a categorical classification of proposed zones of conservation and management actions based on map comparison. The principle of the method is to compare the different maps for which each cell is characterized by a colour and a value on a scale integrating Low and High Values to identify areas. There are also some tools that could automatized or simplify the process using Marxan or dedicated packages such as Zonation, most of the Decision Support Tools (DST) for site selection assistance (Pınarbaşı et al., 2017). Comparative studies seem to demonstrate that similar results are achieved using the different methods (Allnutt et al., 2012). The interest of map comparison is that it is a black-box free process and that the methodology could be applied directly with actors on small scale helping the decision process.

5.1.2.2 Step 2. Defining the typology of areas

5.1.2.2.1 Low vulnerability (area/species) [score ~ from 0 to 0.3-0.35[1]]



The Low vulnerability areas are the easiest to assess, there is theoretically no special management need regarding climate and human pressure. The area or species under consideration will undergo little to no change within the framework of the chosen analysis. To be associated to this category, it is better that the low vulnerability is assessed under the worst climate scenario (RCP 8.5 or SSP5-8.5 *Business as usual*).

5.1.2.2.2 Climate refugia (area)

A Climate refugia is a particular area of low vulnerability. It could be defined as an area that will maintain stable condition in the future. This means that targets of conservation will theoretically less suffer from the effect of climate change in those areas. The future dimension means that to identify a climate refugium, the vulnerability analysis score should remain the same or similar in the low vulnerability range both under different scenarios but also at different time scales (from short term to long-term). Climate refugia could also be assessed by analyzing climate change velocity-based hotspots, where Backward and Forward velocities will present the lowest values (Lai et al., 2022). The climate refugia should be protected inside the final design of the MPA networks from a conservative point of view as they will probably be receivers of all the sensitive species that could migrate. Moving from this idea of resistance strategy (Millar et al., 2007), climate refugia are also of prior concern in the development of networks as they can represent desirable stepping stones to sustain climatic migration (Hannah et al., 2014; Morelli et al., 2020). It is also suggested that these areas could be of interest to promote adaptation by giving time to species to adapt (Wilson et al., 2020) but it is nevertheless subject to discussion, as climatic refuges are also likely to represent trap zones for species and are limited in the time (McHenry et al., 2019).

5.1.2.2.3 Stepping-stone/corridors (include the connectivity – importance as source of sink)

The climate stepping-stone areas should be defined as a sequence of areas of unusual microclimate where a population could persist and that are placed along a climate-migratory pathway to accompanied progressive range shift of species under climate change (Keppel and Wardell-Johnson, 2015). A range shift is an adaptation (change) of a species distribution (geographic or depth) to follow their preferred climatic conditions (McHenry et al., 2019). Stepping-stone areas can be identified thanks to biotic velocities to define a potential future destination of the species and a sour analysis both of migratory capacities regarding species traits as well as by editing maps of future sustainable condition taking into account the species stressors tolerance as presented in the guidance (Exposure) to define their potential pathways. These pathways should be proposed as theoretical climate-migration corridors. A corridor could be defined as a hypothetical connection between two places along the one species may migrate (Carling, 2010). When the corridors are identified, a probability could be given regarding the position of the areas in line with prevailing currents, the maps of desirable habitats, the potential biotic velocities of main preys and the repartition of human pressures for example, eventually coupling *Ecopath* and *Ecosym* approach with existing tools such as EcoImpactMapper.

Incorporating stepping-stones into MSP policy may significantly benefit migratory species by addressing their dynamic migration patterns. A key strategy involves minimizing or, where feasible, rerouting human activities in specified migration corridors to reduce mortality rates, similar to existing approaches for non-climate-related migration. Additionally, it's crucial to conduct in-depth studies to determine the potential advantages of establishing MPAs in these areas. Notably, stepping-stones are designed for temporary use, in contrast to the more permanent nature of MPAs as stipulated in existing marine policies.

5.1.2.2.4 High vulnerability (area/species) [score ~ from 0.6-0.68 to 1[2]]

A high vulnerability score could be linked to three main components: a high vulnerability to human pressure, a high vulnerability to climate pressure or a very high inner sensitivity (traits mainly evaluated as *Highly* sensitives). In general, a very high score involves each of these three components. The high vulnerability target of concern should receive more attention regarding their relative importance at different scale of interest (from local to global point of view) to evaluate if implemented management measures could be relevant or not. For areas or non-moving species, two elements have to be taken into account, the major type of pressure and the relative importance of the area/species for the scale of concern. High climate vulnerability could be assessed by analyzing climate change velocity-based hotspots, where Backward and Forward velocities will present high values (Lai et al., 2022). High human pressure intensity could be identified using the Human Pressure Index (Halpern et al., 2008). If the major type of pressure in the area is human pressure such as fisheries and banning fishing is enough to reduce the vulnerability score sufficiently, then setting up an MPA or regulating fishing pressure seems an appropriate measure. If not, it is necessary to assess if the species/area present some traits of adaptivity that suggest they could benefit from the time that protection will provide to potentially develop or spread these traits in the population. If they do protection could be theoretically envisaged but should not be the priority regarding other types of areas (except from a conservative point of view). It is also important to assess the uniqueness of the area/species in a broader context to evaluate if other species could exert the same function and replace it. As it is not possible to do it for each species or area, it is better to target the high vulnerability hotspots that concentrate most on vulnerable species or only highly vulnerable habitats/species when they are providing key functions or services without other replicate of the same function in the same areas. If not, implementing MPA in that position will probably not be a priority. For mobile or highly mobile species, analysing the potential migratory pathway of the species is of prior interest as the role of managers will be to support migration based on the migratory range and the potential pathway the species will take (using climate-analog results and by doing a dedicated review of current knowledge on the connectivity pathways of these species or mobilizing dedicated experts).

5.1.2.2.5 Adaptive areas (by looking of traits desirability)

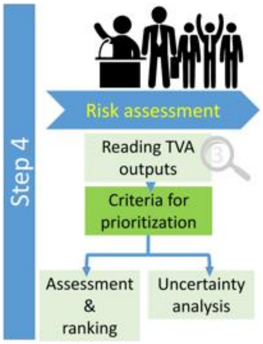
The adaptive areas could be defined as areas where species or habitats presenting adaptive or desirable traits under climate change are concentrated. These areas should theoretically suffer from a moderate influence of climate change as some studies suggest that a diffuse or punctual influence of climate change could promote the development and the spread inside the population of the desirable traits (Kelly and Griffiths, 2021) on the same principle as vaccination or spill-over. If this type of area remains to be tested, a set of these areas should be (at least for experimentation) included in the final decision of the design of the networks as it could be one of the future avenues for developing climate-smart MPA networks. This new type of area is also the opportunity to implement for the first time climate as an early key element in a MPA design which could be much more efficient than trying to integrate climate into already existing MPAs where climate was not included in the initial plans (Hopkins et al., 2016). Ideally, adaptive areas should so be selected among the area of moderate vulnerability and ideally upstream the current to beneficiate to adjacent areas.

5.1.2.2.6 Mitigation areas (habitat-type areas)

The mitigation type areas could also represent an interesting avenue of research in the field of climate-smart MPAs. According to the European Environment Agency, the mitigation is defined as the pool of measures that make "*the impacts of climate change less severe by preventing or reducing the emission of greenhouse gases (GHG) into the atmosphere."* and could be achieved by *"reducing the sources of these gases or by enhancing their storage"* (European Environment Agency, 2023). Although little literature exists on combining adaptation and mitigation approaches in the marine environment, mitigation actions could contribute to 12% of Paris agreement goal emission reduction by 2030 (Trebilco et al., 2022) that could be added to the 25% of anthropic CO2 emission already absorbed by oceans (Le Quéré et al., 2018). If the question of the relevance of

MPAs for promoting mitigation arises, recent literature (e.g. Jacquemont et al., 2022; Pessarrodona et al., 2023) suggest that the protection of certain habitats (e.g. mangroves) through MPA implementation could promote Carbon sequestration and also mitigate other climatic effects such as limiting the incidence of acidification and protecting the coast. One of the most interesting results of the synthesis of current knowledge of MPA potential to mitigate climate change is the potential of sediments to act as carbon sinks (Jacquemont et al., 2022). This result reinforces a recent trend among MPA pushing to better assess the role of sandy areas as they are often sacrificed to trawling (Roberts et al., 2017) since their dynamics and relative importance are less well known as those of rocky areas or heritage habitats. Moreover, the potential of MPAs for climate mitigation remains probably under-estimated as the possibility of developing and promoting dedicated sustainable human activities inside MPAs (e.g. algae culture including mitigation issues) is currently not taken into account (van den Burg et al., 2023).

5.2 Criteria for prioritization: Prioritization of management concerns regarding actual knowledge on climate-smart MPA



5.2.1 Prioritization by species/area

When the scope of analysis is defined, it is possible to initiate the prioritization phase. This prioritization will depend on the vulnerability score and an assessment of desirability criteria (post-hoc trait consideration) (Willis et al., 2015) depending on the framework and the scope analysis chosen. Regarding climate change, three main pathways emerge: the conservative/resilient pathway (e.g. Kaplan et al., 2014), the adaptive pathway (e.g. Wilson et al., 2020) and the mitigation pathway (Jacquemont et al., 2022). Each of these three pathways will set a different series of priorities (targets) that could be translated into trajectories and management measures. These priorities could then be critically analyzed taking into account the existent current management levers. For this exercise, we will take as unity of analysis each grid cell (same unity at species, ecosystem and areas scale) and consider four different types of species/areas regarding the level of sensitivity to climate (C) and anthropogenic stressors (HP) (*Fig. 25*).

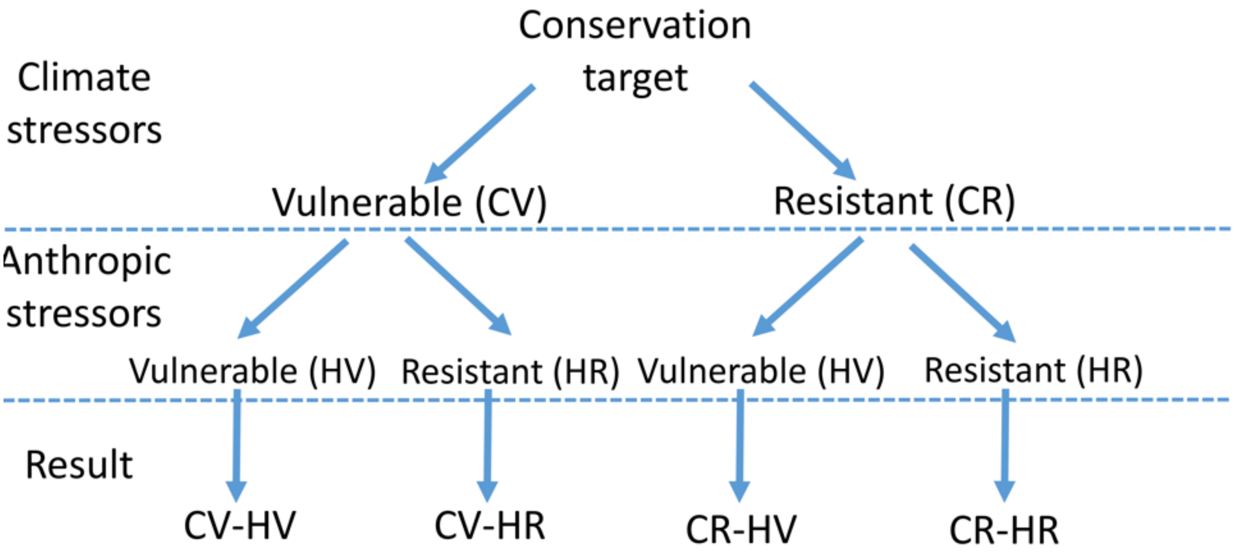


Figure 25 - Potential type of species/areas regarding their sensitivity to climatic and human stressors. This could be assessed by analyzing the weight of Human Exposure and Climatic Exposure inside the Vulnerability Assessment model, using two different vulnerability assessments or following scoring by expert. For this example, Vulnerable modality includes species/areas with High or Very High vulnerability to the concerned stressors while Resistant modality includes species/areas with Medium or Low vulnerability to the concerned stressors.

5.2.2 Management pathways for prioritization

5.2.2.1 The conservative pathway

The conservative pathway will focus on vulnerable species and aims to create (networks of) MPAs to increase the survival rate of those species (see *Scenario and Trajectories*). For areas and ecosystems, the vulnerability could be expressed as the percentage of highly vulnerable key species (identified in the framework). The conservative pathways will then generally focus on the species and areas described as *Highly Vulnerable*. The principal tools used in conservative pathways are MPAs, and more recently the MPA network, as they are broadly recognized as the one of the most promising approach for marine conservation (Langton et al., 2020).

5.2.2.1.1 Species priorization and conservation

For species conservation, the vulnerability assessment will provide a ranking of species regarding their future at different timescales but to develop realistic goals four criteria must be taken into account to determine for which species it is possible to define management levers and for which there is no possibility to support their survival. For each cell of the distributional range of each species considered, it is important to ask:

- Does the projection indicate that climate condition increase in the area upon survival range?
- Does the projection indicate that climate condition increase in the area upon stress-range?
- Does my species migrate?
- Will it resist climate change if the human pressure decreases in the area?

Globally, these questions will lead to two different conservative management pathways (*Fig. 26*): the *Management for persistence* pathway (single MPA scale) and the *Network* pathway (multi-MPA scale). They will also highlight the trajectories for which management will not be a priority or where no management lever could be found to increase the species' chances of survival in a purely conservative vision.

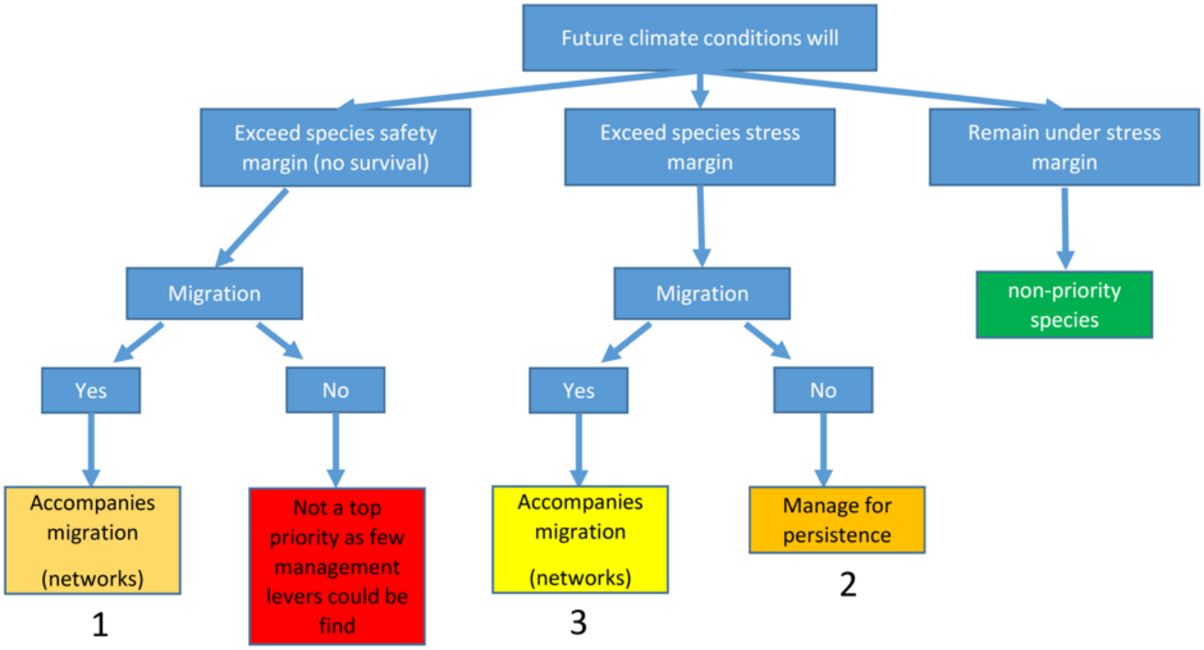


*Figure 26 – Theoretical decision tree for highlighting priorities of conservation. The pathway in red lead to a scenario where very few could be done regarding **strictly conservative** pathway as the future conditions will probably not be suitable for the species in the future*

5.2.2.1.2 Response 1: Translocation

When future conditions will exceed the safety margin and the species is not able to migrate (*Fig. 26*, red pathway), it is still possible to deploy rescue measures such as transferring individuals. This measure should be avoided as much as possible as to avoid spreading disease (Cunningham, 1996) and should be deployed when populations are already critically endangered and have good transport survival capacities. This method has been already used recently for the Fan mussel (*Pinna nobilis*, Linnée, 1758) with limited success (van Tatenhove et al., 2021).

Identifying areas of favorable stable condition (climate refugia) for the species of interest is a good way to identify potential transplantation areas. Moreover, regulatory frameworks and better assessment of likelihood of success are still to be implemented (Katsanevakis, 2016; van Tatenhove et al., 2021).

5.2.2.1.3 Reponse 2: Conservative management for persistence – case of areas and non-moving species (pathway 2)

The management for persistence is the current general management deployed in the MPA. Management for *persistence* aims to maximize the resistance and perennity of the species among an area. In that specific case, the protection will not target directly the effect of climate as there is currently no direct management lever to address its effects. Moreover, there is no clear evidence of the effectiveness of implementing MPA for promoting species/habitats resistance and recovery neither in our literature screening nor in the recent dedicated studies (Bates et al., 2019). Resistance and recovery seem to be more inherent to intrinsic species traits. Nevertheless, climatic drivers will be monitored inside the area as well as the health status of species and habitat populations and management measures will be implemented to decrease the anthropogenic pressures on marine ecosystems. Indeed, decreasing pressure will theoretically increase the survival rate of species by decreasing the cumulative pressure. The main measures targeted will be fisheries and pollution considered as the major stressors for all the taxa (Butt et al., 2022). This type of management may include adequate human restoration processes if necessary.

The *Conservative management for persistence* is suitable for CV-HV (direct and indirectly) and CR-HV (directly) species/areas so two thirds of the partly vulnerable species. This type of management should be a priority when few populations of the species of interest are identified (e.g. isolated MPA for Deep Sea corals) or when they could be included or are included inside a network (larval dispersion or juveniles should be included) (see section 6.1.2 - *Network* and 6.4 - *Future research*). Among the areas suitable to *Conservative management for persistence*, a hierarchy could be found regarding criteria of uniqueness, late switch (or absence of switch) toward conditions that will exceed survival rate as a diffuse climate pressure could enhance adaptation, inclusion of different bathymetry, the known presence of key services and functions in the areas, the redundancy of functions and ecosystems in the area or the level of health of the ecosystem (especially non-mobile species) but also the difficulty of fing trade-off with human activities. We advise following current guidance on designing an MPA to identify current hierarchization criteria adding time component (late switch, complex 3D component) and adaptation potential to prioritize between similar areas (see section 6.1 – *Insight for management, Designing climate-smart MPA and MPA network*).

5.2.2.1.4 Response 3: Accompanies migration – identification and prioritization of pathways (pathways 1 and 3)

The objective of this management goal is to facilitate and accompanies species migration under climate change but also to identify and protect future habitats. In the case of mobile or highly dispersive species, we can design two criteria that must be considered: the migratory potential of the species and the presence of potentially favourable habitats to be used as stepping-stones or migration targets (climate refugia or previous conditions climate analogs). The migratory potential will be assessed by the analysis of the Desirability matrix regarding traits favorizing migration (e.g. García Molinos et al., 2022) whereas the potential migration route could be evaluated by biotic climate velocities and area categorization (*Fig. 27*). The analysis of biotic climate-velocities will propose different pathways to which it is possible to link a probability of success regarding identified dispersal limits (such as human pressure intensity), key habitats location and prey availability (Lascelles et al., 2014). A pathway could be considered as realistic when the species will still find suitable conditions at the maximum of its daily migratory potential. Among the realistic pathways, we can consider the shortest pathways matching with same projected future areas of food availability as the most probable. The interconnexion with prey availability should be one of the main drivers for migratory marine predators and could be assessed using projection of productive waters (Abrahms et al., 2018).

Such inclusive models are still needed to better assess potential future pathways. Moreover, more literature is needed on climate-change migration as the behaviour of escaping non favorable conditions should probably be more individual-dependent (Abrahms et al., 2018; Bolnick et al., 2003; Dall et al., 2012; Gallagher et al., 2015) and as the fidelity with site used to model trajectories will become an unfavorable trait, making them less predictable (Sydeman et al., 2013). Additionally, the migratory potential of many marine species is not well assessed. Another criterion to be defined is the potential time that a species could tolerate undesirable conditions to better define potential pathways.

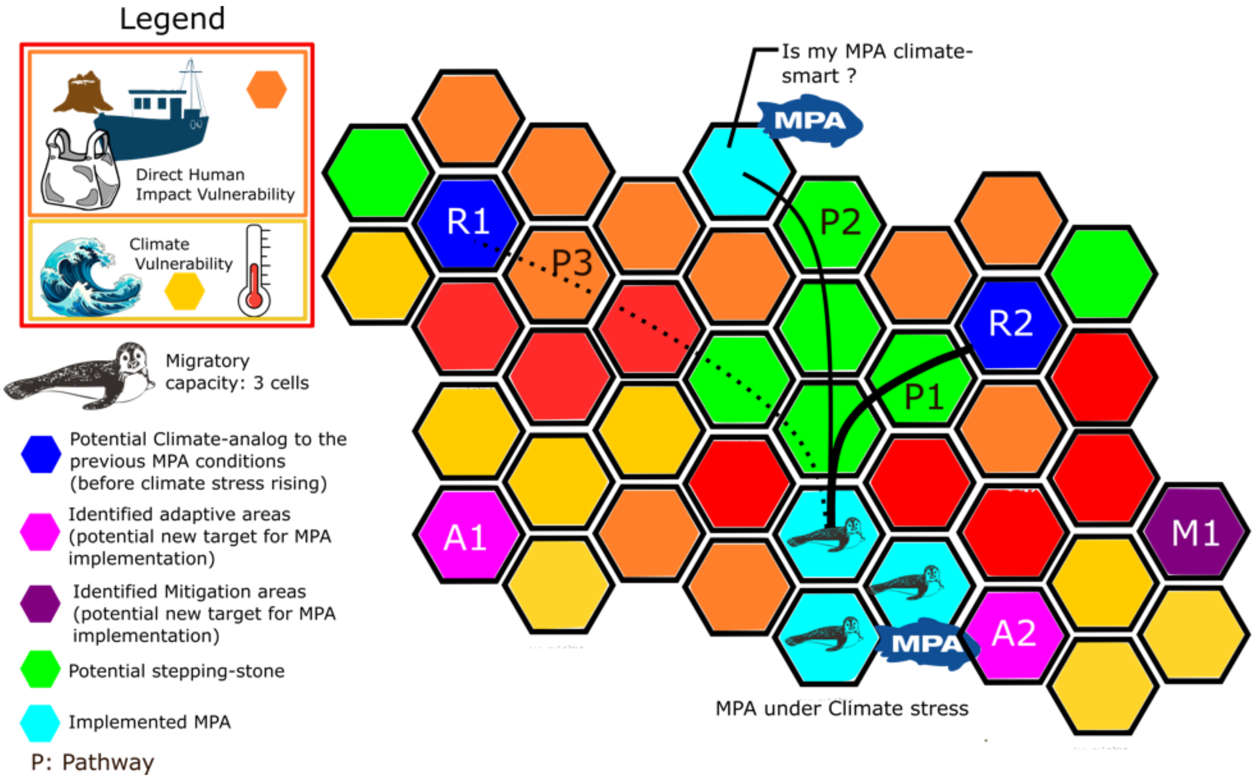


Figure 27 - Example of the result of vulnerability assessment under climate change from the previous case study. Here three pathways are possible for the monk seal to migrate under climate change. The pathway P1 is considered as the most probable as it is the nearest to the actual population location and as the stepping-stone area will remain suitable in the future. The second pathway P2, linking the two MPA, is probable but the third pathway P3 is less likely to be used by the species as it goes through non suitable and under pressure areas and is the longest for the species to migrate.

For migratory assessment and future modeling, we strongly advise collaborating with the European Tracking Network to develop forecasts based on real, high-quality telemetry data, and develop and generalize the inclusion of larval dispersal models in decision-making.

5.2.2.1.5 Response 4: Special case of Climate-refugia

As highlighted in the typology of areas under climate-change, climate refugia are of prior interest in species conservation and could be included in the MSP conservation final design.

All general flowcharts assessing which pathways an area or species will follow are synthetized in the following diagram from Willis et al. (*Fig. 28*) (Willis et al., 2015).

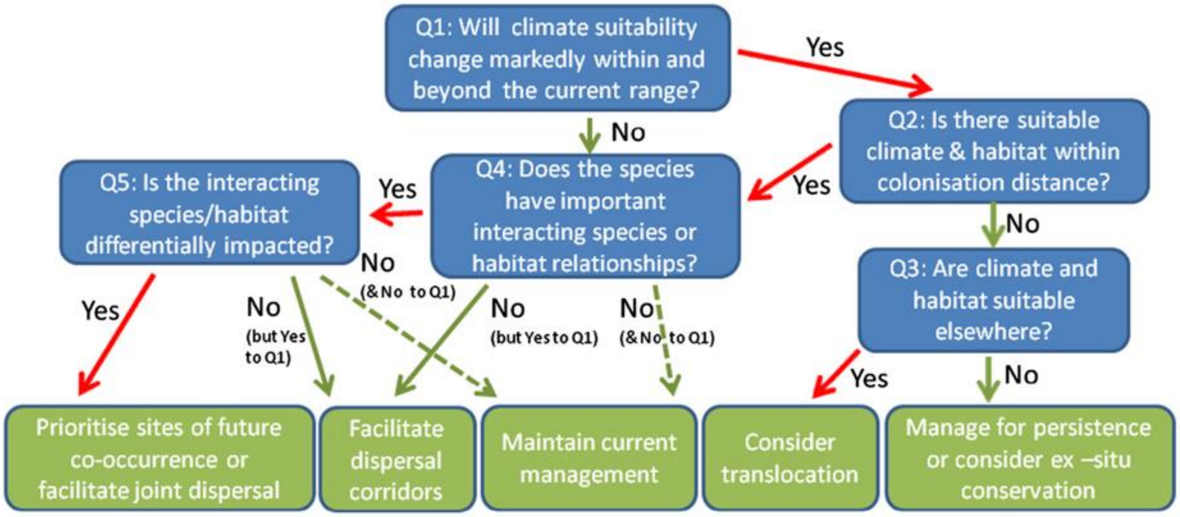


Figure 28 – Flowchart from Willis et al., 2015 indicating the different elements (in blue) the coupled approach between spatial approaches (and specially Species Distribution Models) and classical TVA promoted in this guidance could answer and the potential translation of that pathway into management measures.

5.2.2.2 The adaptive pathway

The second type of broad scenario for climate change is a long-term scenario called the adaptive pathway. If conservation could lead to adaptation by promoting the survival of the highest diversity, the adaptive pathway is less well defined even if it is presented as a key element for the future of nature and humanity (Intergovernmental Panel on Climate Change, 2021; United Nations Environment Program, 2021). Three different levels could be targeted for theoretical adaptation target: Species, Areas and Ecosystem. The evaluation of the adaptivity potential of each level could be assessed using the desirability matrix. It is nevertheless important to keep in mind that there is a great lack of scientific evidence for most of the species of the real adaptive potential.

5.2.2.2.1 Species

The first potential measure to promote adaptivity is to monitor and guarantee sustainable exploitation of the species with theoretical high adaptivity potential. Adaptivity potential is highly related to genetic diversity in the literature (e.g. Nielsen et al., 2009), versatility (trophic generalist, habitat non-specific, phenotic plasticity) (Butt et al., 2022) but also reproductive criteria (generation length, body size) (Aurelle et al., 2022) or specific adaptivity traits (see *Desirability section*). The need for special measures to protect these species as the potentiality to switch a part of human exploitation of these more adaptive species will depend on the monitoring carried out, as it is likely that their adaptive traits make them less sensitive and more adaptable to anthropic pressures. Before determining the potential long-term interest for protection and exploitation, it is necessary to assess if the adaptivity potential could spread among the population (inheritability) as we can distinguish two different mechanisms of how a plastic species can respond to climate change: adaptivity (or microevolution) and acclimatization (Foo and Byrne, 2016). Acclimatization will promote short-term resilience in individuals' lifetimes linked to individual plasticity but could be passed to the offspring. It is theoretically easier to assess and test and will play a fundamental role in short-term availability and resistance to shock (e.g. heat waves). Adaptivity is less studied as it is a masked genetic evolutionary process that will be observed over generations at different speeds regarding species (Hoffmann and Sgrò, 2011). To be efficient, the rate of adaptation needs to follow the change in climatic conditions (Hoegh-Guldberg et al., 2017). These processes and their importance for long-term general adaptation are not well studied and understood and should be studied in depth for species identified as potential good candidates.

5.2.2.2.2 Areas

As specified in the typology, an adaptivity area need to fill two main criteria: concentrating potential adaptable species and be subjected to microhabitat variation (presenting different climatic conditions and bathymetry in the same area) (e.g. Doxa et al., 2022). The adaptivity potential could be assessed by monitoring short life individuals (copepods, benthic species) (Hoffmann and Sgrò, 2011). Once identified, the adaptive areas could be ranked regarding both their benefice for the socio-economical component (services) but also the global benefits it can provide to a network (see section 6.1.2 – *Designing a climate-smart MAP Network*).

5.2.2.2.3 Ecosystem: respect ecosystem integrity

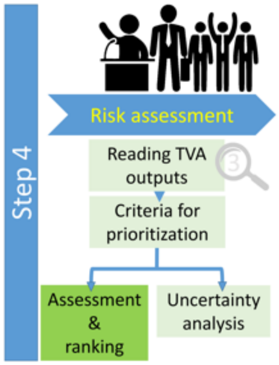
The main management goal to promote ecological adaptation is to reach the ecosystem integrity (Elsen et al., 2023) in future conditions. Defined as *the ability of an ecological system to support and maintain a community of organisms that has the species composition, diversity, and functional organization comparable with those of natural habitats within a region* (Parrish et al., 2003), maintaining Ecosystem integrity under climate change means to assess the potential stability of an ecosystem under climate change. Assessing the redundancy between key components (elements of composition, structure, function, and ecological processes) or anticipating potential arrival of species that can perform the same role in the ecosystem is a way to evaluate the future stability of a given ecosystem. This type of modeling is still missing for many areas but could be assessed using backward climate-analogs to evaluate how similar areas under similar threats have evolved today. Management priorities will include adaptive species such as each key species, both for ecosystem functioning (habitat) and along the trophic networks, especially apex predators that could buffer climate-induced stability (Roberts et al., 2017). To help the identification of key species, a list of ecosystem functions is provided by WP3.1 and a list of key services by WP4.

5.2.2.3 The mitigation pathway

The mitigation pathway will prioritize the protection of direct mitigation areas (see typology), especially coastal habitats and sandy seafloor (Jacquemont et al., 2022) as the first objective of mitigation is to promote carbon sequestration at a global scale to reduce the effects of global change (Maxwell et al., 2020). Mitigation pathways should also tend to protect animals that will indirectly promote carbon sequestration and climate effect mitigation. The associated management measures are to sustain healthy trophic networks, especially by preserving apex predators and long-lived animals, and to protect teleost fish (Roberts et al., 2017; Schmitz et al., 2014). Among the potential management levers, banning trawling could be one of the first vectors to be implemented to switch toward a mitigation pathway (Hoppit et al., 2022).

5.3 Assessment and ranking among pathways

5.3.1 The importance of prismatic scenario implementation



There is no clear prioritization between the three climate-smart pathways (conservation, mitigation and adaptation) as each of them present their own interests and limits at different timescales. The conservative pathway appears more effective in the near-term whereas adaptivity and mitigation pathways are more relevant for mid-term and long-term adaptation (Elsen et al., 2023). Moreover, the conservative pathway seems less uncertain because it is based on empirical knowledge over years of expertise in MPAs, although it seems to be insufficient in the long-term (Maxwell et al., 2020). Adaptation areas could represent future fishing “bright spots” (i.e. *areas where species may find improved habitat conditions in the medium term, that may be seized upon within marine conservation strategies and sustainable fishing management*) (Queirós et al., 2021) whereas mitigation areas are of prior interest to reach carbon reduction goals (Maxwell et al., 2020). The prioritization process will highly depend on the conservation target (e.g. identifying future key habitats and refugia for a species chosen on the IUCN list). In the absence of a clear targeted species or objective, the best climate-smart design regarding the future uncertainty will be to create marine spatial plan integrating a patchwork of areas of prior interest under each of the three pathways. The representation of each type of key areas is the main point to assess regarding framework priorities.

There are no clear rules to establish the perfect climate-smart design for MSP but we can assume that the principal criteria highlighted for the creation of MPA network could applied considering the species and the areas highlighted by several scenarios as top priorities. In this case, it could be recommended to protect at least 20-30% and at least three geographically separate replications of each key area type highlighted by the typology, including adaptivity areas, coastal habitats likely to promote mitigation, different bathymetry (Venegas-Li et al., 2018) and areas under diffuse climatic pressures. The biodiversity hotspots (present and future) could also be protected as the key functioning areas (when identified). The minimum size of the MPA will depend on the targeted goal as a diameter of 4 to 10km will be a relevant minimum size to protect the diversity attached to the ecosystem, 10 to 20km is considered as a sufficient size and a size superior as 20km is considered as an ideal size (McLeod et al., 2009). Regarding marine mammals, a protected area of at least 191 km^2 could benefit the species (Conners et al., 2022). These principal criteria are presented in McLeod et al., (McLeod et al., 2009) and recently updated (Arafeh-Dalmau et al., 2021) and are summarized and implemented in the MPA criteria factsheet. Regarding networks, ensuring present and future suitable corridors for species for both adults and larval is presented as a key component. The maximum acceptable distance is today estimated at 15-20km based mainly on larval dispersal models (Mora, 2008; Shanks et al., 2003) but should be reevaluated with the future current changes and the adults' migratory schemes. If connectivity is presented as the key component of adaptive and resilient marine environment, it is important to keep climate-smart isolated areas (e.g. climate refugia biodiversity hotspots) unconnected to prevent potential mass mortality events due to invasive species (Chan et al., 2019).

5.3.2 Creating a climate-scenario portofolio

Spatial prioritization assumes that biodiversity, threats and conservation targets are not distributed evenly in space (Venegas-Li et al., 2018) and can be ranked regarding a serie of previously defined desirable criteria (e.g. criteria of prismatic scenario). The hierarchization could be based on a single attribute (e.g. species richness), multiple attributes (e.g. taking into account additive score or criteria) or on a problem/specific management goal (e.g. representation of every species once) (McGowan, 2018). There are numerous methods to prioritize different design of networks regarding the previously established trajectories (management priorities). The tool used will depend on the type of data included, from prioritization plot (Albo-Puigserver et al., 2022) to marine spatial decision tools such as Marxan (Venegas-Li et al., 2018) or packages such as prioritizeR (Hanson et al., 2023). Each of the methods will compare previously produced layers (e.g. future distribution of the species, index of desirability and eventually socio-economic criteria) including forcings and will propose multiple solutions using different prioritizations to reach the conservation goal of creating a portfolio of protected areas. The key step of the analysis process will be to correctly write the conservation planning problem (*Box 3*).

BOX 3 : Example of problem phrasing using prioritizeR (Hanson et al., 2023)

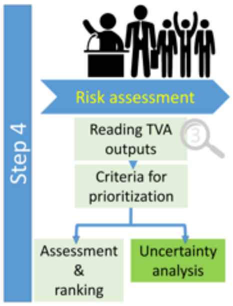
```
## A conservation problem (<ConservationProblem>)

## ├•data

## | ├•features:   "Recurvirostra americana (breeding)"

# multi-layers e.g. distribution of a species of  interest/distribution of each areas from the typologies/desirability score/vulnerability score

## | └•planning units: # Total grid and geodesy

## |  ├•data:     <SpatRaster> (10757 total)

## |  ├•costs:    continuous values (between 0.2987 and 1804.1838)

## |  ├•extent:   -1816381.6182, 247483.5211, -1228381.6182, 683483.5211 (xmin, ymin, xmax, ymax)

## |  └•CRS:      +proj=laea +lat_0=45 +lon_0=-100 +x_0=0 +y_0=0 +ellps=sphere +units=m +no_defs (projected)

## ├•formulation

## | ├•objective:   minimum shortfall objective (`budget` = 8748.4908) # specify the overall goal, need to maximize and minimize some criteria (e.g. set a maximum cost acceptable reaching a minimum closure thresholds)

## | ├•penalties:   none specified

# specify trade-offs against the primary problem objective (boundary, connectivity), mediated by a penalty factor

## | ├•targets:    relative targets (between 0.2 and 0.2)

# % of species distribution to be protected, optimality (20% of each habitat, 30% of waters by 2030, 10% strongly protected)

##  |├•constraints: none specified # invalidate solutions that do not exhibit specific characteristics ## | └•decisions:   binary decision

# Format of desirable decision (binary, proportion of the total planning unit to be protected)

## └•optimization

##  ├•portfolio:   shuffle portfolio (`number_solutions` = 1, …)

# Define the number and the type of proposed networks following the management problem (e.g. generate 1000 potential solutions respecting the relative targets and testing for different prioritization)

##  └•solver:     gurobi solver (`gap` = 0.1, `time_limit` = 2147483647, `first_feasible` = FALSE, …)

# Define the software used to solve the problem regarding run time and solution qualities (Schuster et al., 2020)
```

These different scenarios could be proposed to decision-makers and used for a trade-off exercise to commonly find the concensus of the most desirable approach between all the stakeholders (see section 6.2 - *The Trade off exercise*).

5.3.3 Are Marine Protected Areas (MPAs) an adapted tool for each scenarios?

This guidance aims to provide a methodology to identify key areas of interest under climate change for conservation, adaptation and mitigation purpose and to promote better management of these areas. Considering that this guidance will be applied to the development of the future MPA network to reach the 30 by 30 goal, the first question is to assess the efficiency of MPA for mitigation and adaptation pathways. The analysis of the current literature (Bates et al., 2019; Jacquemont et al., 2022) seems to highlight that MPAs seem to be theoretically more important for the promotion of climate change adaptation and mitigation than for promoting species/habitats resistance and recovery under climate change. Resistance and recovery seem to be more inherent to intrinsic species traits. This was also pointed out by Bates et al (Bates et al., 2019) and is probably also because MPAs were initially created to protect sensitive species from human pressures and not to deal with climate change (Bruno et al., 2018; Wilson et al., 2020; Zentner et al., 2023). Nevertheless, it is commonly accepted that, by decreasing the anthropogenic pressures on marine ecosystems and especially fisheries considered as the major stressors for all the taxa, MPAs remain a key tool to indirectly promote species resistance and recovery as they limit the cumulated pressure (Jacquemont et al., 2022). It is fundamental to include existing MPAs in the development of the climate-smart network as they already actively decrease pressure, and to check whether their design can be improved to integrate climate issues (Grorud-Colvert et al., 2021).

5.4 Uncertainty analysis



All the sources of uncertainty found in the literature have been brought together in the Uncertainty section of the step 3 (section 4.3.1).

Conclusion: At the end of stage 3, a climate-smart portofolio was constructed identifying areas of conservation interest and potential migration routes and future MPA networks. MPAs are also recognised as a promising management tool, including from a climate perspective. The next step is to identify the most promising and acceptable networks and to design these networks in accordance with the criteria identified as climate-smart.

6 Informed management and monitoring (Step 5)

This step focuses on choosing the final scenario for the management of a complete MPA network. The Informed management and Monitoring step (*Fig. 29*) aims to present (i) the criteria to create climate-smart networks; (ii) the management criteria that decision-makers and managers need to consider making relevant judgements and decisions and to develop climate-coherent management strategies taking into account the uncertainty of future scenarios. When MPAs extend across international borders, it's crucial to involve decision-makers, planners, experts, and policymakers from all nations bordering the marine unit (such as oceans or seas) (Arafeh-Dalmau et al., 2023). Additionally, recognizing and addressing existing knowledge gaps is fundamental to enhancing future management practices.

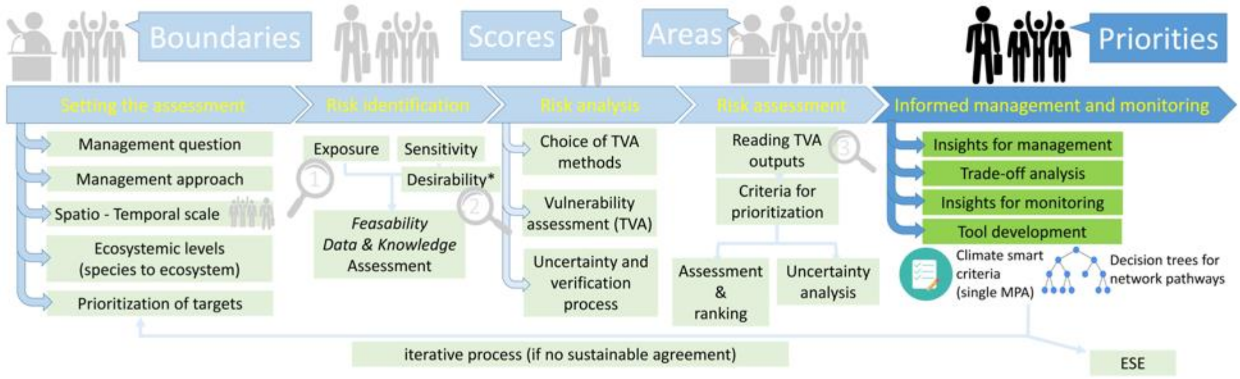
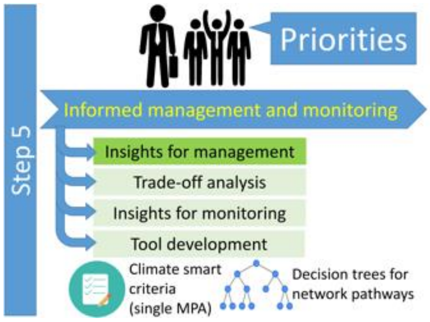


Figure 29 – Content of the "Informed management and monitoring" (step 5)

6.1 Insights for management: Designing climate-smart MPA and MPA networks



Once the potential areas of interest are identified and prioritized, it is important to ensure that the selected areas will be correctly designed to be considered as climate-smart considering the current criteria. In this part, we present the different "climate-smart" criteria at single MPA and MPA network scales to help decision-makers and planners evaluate the outputs of the prioritization process and design their own MPA. These criteria must be updated with the evolving level of knowledge through regular literature screening.

6.1.1 Designing a climate-smart single MPA: review of main criteria

The question of *How to design a climate-smart MPA?* is of growing concern. An important bibliography is developing that assesses the main criteria to be taken into account such as the MPA size, shape, level of protection, number and the design of No Take Zones under climate change, which incorporate their capacity to spread the risk between species and habitats, maintain the ecosystem function and promote adaptive ecosystem-based management (e.g. Arafeh-Dalmau et al., 2021; Brito-Morales et al., 2022; Conners et al., 2022; Edgar et al., 2014; Grorud-Colvert et al., 2021; Horta e Costa et al., 2022; McLeod et al., 2009; O'Regan et al., 2021; Wilson et al., 2020). The main criteria required to design a climate-smart single Marine Protected Area (MPA), as synthesized from literature, are summarized in the decision trees below (*Fig. 30*). These criteria are highly likely to evolve in line with the future increasing of feedback from MPA managers, as very few MPAs have included climate considerations in their management plans whereas 97% of large MPA are today under climate threats (Johnson and Watson, 2021).

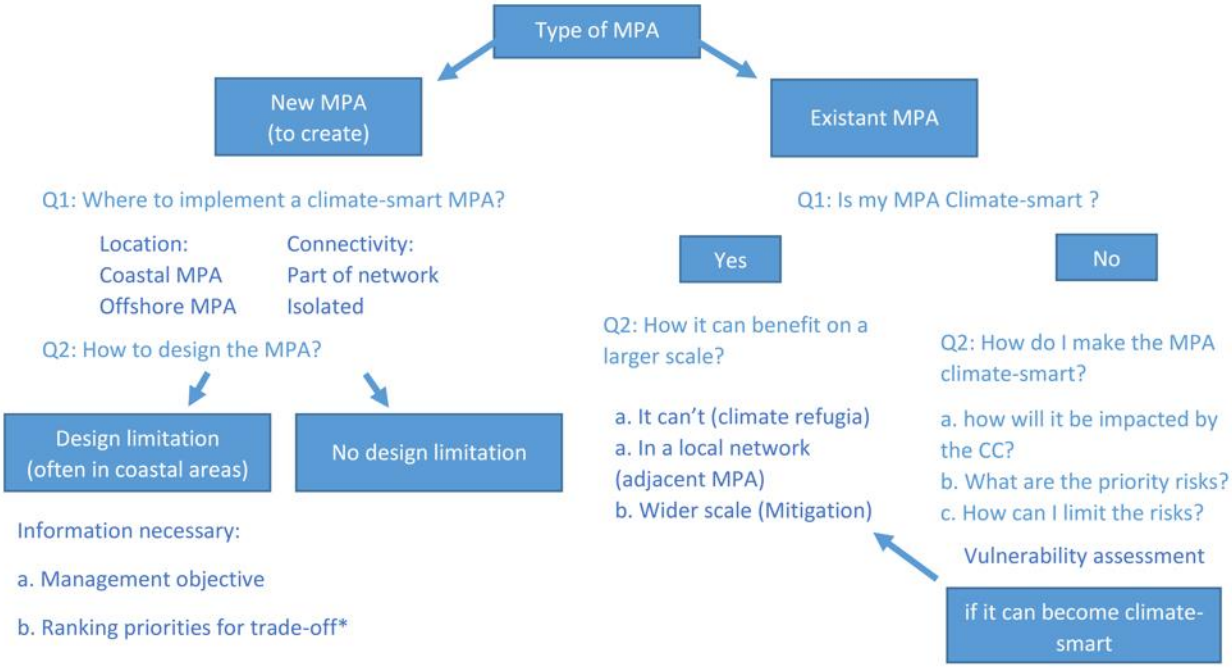


Figure 30 – Possible decision process to include climate in single MPA. For existent MPA, the Q1 answer will be yes if all the answers of the list of criteria attached to this guidance are yes and No if at least one of the criteria is not filled.

List of criteria belonging to each Question of the Decision tree (*Fig. 30*) to guide managers through the decision process:

Q0: Already existent or new MPA to create
Rationale: Old Marine Protected Areas generally don't consider Climate Change so it is easier to create a new climate-smart MPA than to adapt an already existing one.

Pathway 1: Case of an existent MPA

Q1: Is my MPA climate-smart?

Criteria: (i) Stage of establishment (Proposed/Committed Designated, Implemented, Actively Managed), (ii) Age, (iii) Shape, (iv) Size, (v) Human Pressure Intensity, (vi) Protection Level, (vii) No-Take Zone (Existence, Number, Size, Inclusion of a Partially Protected Areas (PPA) buffer, well-managed PPA), (viii) Survey and control existence (number of guards, number of days of survey, number of controls), (ix) includes CC in MPA design (includes CC in MPA designation, in the management plan, existence of climate indicators, existence of climate-related surveys), (x) includes element of resistance/resilience under climate change (critical habitats such as habitat forming species, foraging grounds, breeding grounds, migration routes, nursery grounds, socialization grounds; protection of propagule sources; resistant and resilient species; various bathymetries; different climatic exposure conditions (e.g. wave exposure, variety of temperature range); at least 20/30% of each habitat type; habitat replication (at least 3 replicat); a minimum distance between two replicates (risk spreading); diversity of species; predictable upwelling, (xi) includes CC clear management objectives, (xii) reach the management objectives

Rationale: According to the current knowledge, a climate-smart MPA is (i) Actively Managed; (ii) planned for a long time as it productivity increase with age; (iii) presents a basic shape (square, rectangle) to limit the edge-effect; (iv) has a diameter superior to 20km or even bigger, remembering that size <100km^2 encompasses local species, 100-10,000 encompasses local species and some large size species, 10,000-100,000: encompasses home range of intermediate species, from 100,000-1M: encompasses home range of large species and >1M: encompasses home range of vast-ranging species; (v) Limited Human Pressure; (vi) depends of the management purpose but strong protection is needed in any case; (vii) MPA needs to include at least one NTZ of at least 5km^2. This minimum size is highly discussed and currently a NTZ <5km^2 is considered as insufficient, a NTZ from 5 to 10 km^2 as minimal, a NTZ from 10 to 30.5 km^2 as sufficient but still small and a NTZ >30.5 km^2 as a big one. A plural core (several NTZ inside the same MPA) shall be considered to extend the NTZ and protect a mosaic of habitats; (viii) in the MPA controls and surveys are needed; (ix) CC needs to be considered in the MPA designation (when possible), in the management plan and surveyed using dedicated indicators to benefit adaptive management; (x) a climate-smart MPA needs to include a patchwork of critical habitats, protects larval sources, includes resistant or resilient species (list of resilient attributes in Timpane-Padgham et al., 2017) , spreads risks and includes various exposure conditions (xi) clear CC-related objectives must be inserted in the management plan and they need to be understood by the entire community of actors; (xii) a MPA should achieve all management objectives as possible.

Q2a: How will the MPA be impacted by CC?
Criteria: Location (Geograpical range, depth)
Rationale: See previous sections of the guidance

Q2b: What are the priority risk factors?
Criteria: (i) Identify major stressors and highly vulnerable species; (ii) Analyse the MPA's weaknesses in the light of the criteria set out in question 1
Rationale: (i) See risk assessment section; (ii) identify which criteria are not filled and whether these criteria are impacted by CC according to the analysis framework

Q2c: How is it possible to limit the risks?
For criteria not met: is it possible to fill these criteria? Is there any identified limitation? Is it possible to find trade-off with local actors? Which management levers can be implemented?
Rationale: This will be answered and tested by MSP4BIO WP5 (test sites applications).

When not all the conditions can be met at the level of a single MPA, it is necessary to consider including the MPA in a network to achieve the objectives and meet all the criteria.

Q3: Does the MPA of interest benefit on a larger scale?
Criteria: (i) Distance to adjacent MPA (<20km); (ii) Isolated areas or reticulated (can be connected to international network); (iii) Existence of a connectivity modelisation to choose the best MPA design (Adult, Larval, Both or No); (iv) Management plan includes connectivity.
Rationale: (i) To be connected, an MPA need to be adjacent to another area of interest or already protected (McLeod et al., 2009 propose a maximum distance of 20km between two MPA); (ii) To be included in a network, the area must be reticulated; (iii) To define the best MPA network, the evaluation of MPA potential at larger scale need to be evaluated using spatial models (ideally both for larval and adults stages); (iv) Management plan must include connectivity to facilitate exchange among the network.

Pathway 2: Case of a new MPA (to create)
Q1: Have any design limitations already been identified?
Rationale: If yes, all criteria from the previously described question *(existent MPA)* must be considered. If no, only the question Q1 and Q3 must be considered.

6.1.2 Designing a climate-smart MPA network: review of main criteria

In this section, we propose a decision tree (*Fig. 31*) associated with a list of criteria (*Table 16*) based on literature and expert knowledge to evaluate the interest and potential to include a selected area inside a climate-smart MPA network. These criteria are issued from current knowledge and could evolve with the development of circulation models and telemetry.

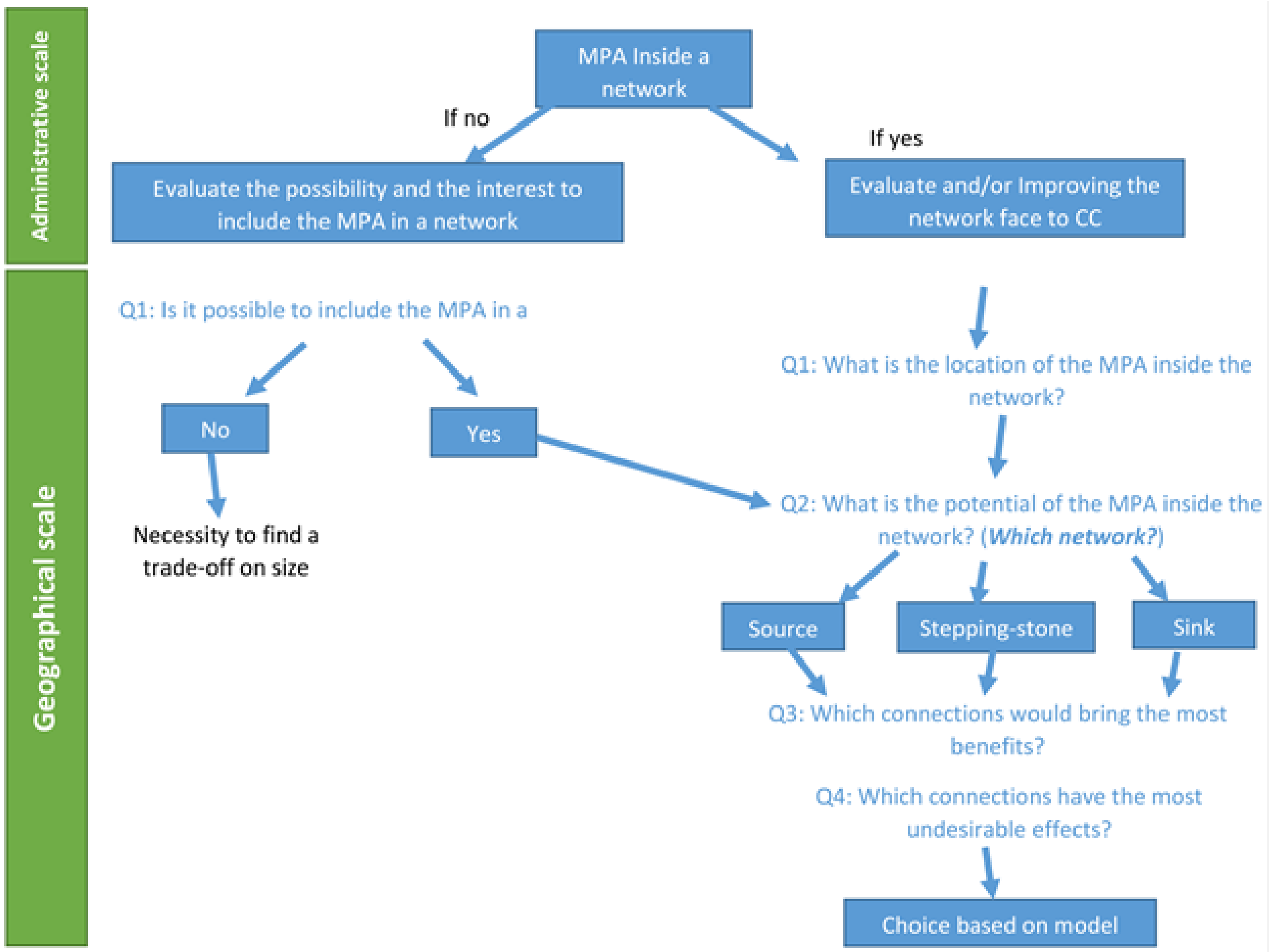


Figure 31 – Decision trees of thinking process and criteria list necessary to determine the interest of the integration of a selected area or single MPA inside a climate-smart network and to define its best position.

List of criteria belonging to each Question of the Decision tree (*Fig. 31*) to guide managers through the decision process:

Table 16 – Step by step approach based on areas-traits to evaluate potentiality of an existent or potential future MPA previously identified to be of interest inside a network (list of criteria based on literature review and Expert Knowledge (EK) from RESMED Project)

Question	**Criteria (Level 1 of answer)**	**Subcriteria 1**	**Subcriteria2**	**Unit (Final Level of Answer)**	**Rationale**	**Bibliography**
Q1: Is the MPA inside a network (administrativ	Not yet	Possibility in Network inclusion		Island (local and self-functioning)/ Reticulate model (MPA	Today, developing a reticulated	(David et al., 2017)

e point of view) ?				part of a broader network)	international network is considered as better. However, with climate change, it is necessary to maintain isolated areas in order to prevent biological invasions.	
		Proximity of adjacent ecosystems	Juxtaposition of sources (where propagula and species come from) and destinations	Yes/No	It is better to connect a source and a sink to maximize benefits	(McLeod et al., 2009)
			Proximity of features	Yes/No	Yes Two MPA should be placed at a sufficient distance for the species of interest to reach it.	
			Replication of features (e.g. habitat type)	Yes/No	Yes Two connected MPA must connect same feature and include replicats of this feature to	

					maximise resistance.	
		Directional alignment of protected areas		Yes/No	Yes, The MPA should integrate natural EC (e.g. stream, channel…)	(Larsen et al., 2012)
	Yes	Location of MPA inside the network		Source/Sink/Stepping-stone	The importance of the MPA will depend of it position inside the network…	Extended from (Balbar and Metaxas, 2019 and references therein)
		Centrality of network	Possibility to use alternative pathways	Yes/No	… but also from the existence of alternative pathways for stepping-stone. If an alternative pathway exist, the importance of the MPA diminishes.	
Q2: What are the favourable traits to define ideal networks position under CC (source or sink) ?	Interest as source	Presence of resistant species	Site already under heat waves	Yes/No	For adaptivie pathways, it is interesting to protect source of resistant species (or as theoretica	(McLeod et al., 2009)

					I prowy, areas with a range of climatic conditons)	
		Climate smart-MPA	See single MPA sheet	Yes/No	If each single MPA is already well-managed, the network's potential for success increases	Guidance, section 6.1.1
		Include a wide range of bathymetry		Yes/No	To improve potential resistance to climate change	(Doxa et al., 2022)
		Include a high diversity		Yes/No	Biodiversity is a key component of the resilience-related pathway	(Jacquemont et al., 2022; Key et al., 2022)
		Upstream of currents		Yes/No	The larvae colonise downstream as they are transported by the current. Adults used partially currents as migration route.	(Gary et al., 2020; Kaimuddin et al., 2016)
		Generally southern location (for Europe)		Yes/No	Species generally migrate northwards under	Guidance, section 3.2.4.1

					climate change.	
	Interest as sink	Presence of cooler area (climate refugia)		Yes/No	Climate refugia are the natural recipients of species that migrate under the influence of the climate	Guidance, section 5.1.2.2.2
		Presence of deeper water		Yes/No	Increases the chances of resistance to episodic stress for mobile species, useful for the search for 3D climatic refugia (in a partially protected bathymetric layer).	(Doxa et al., 2022)
		Benefiting from multisources		Yes/No	Yes In line with the rule of redundancy, benefiting from multiple sources of individuals can increase the resilience of the network in	(Gallardo et al., 2017; McLeod et al., 2009)

					the event of the loss of a source. Nevertheless, it is necessary to prevent the arrival of invasive species in the network to avoid their rapid spread.	
		Downstream the currents		Yes/No	The larvae colonise downstream as they are transported by the current	(Gary et al., 2020)
		Generally northern location for European countries		Yes/No	Species generally migrate northwards under climate change.	Guidance, section 3.2.4.1
	Size of beneficiary network	Local to global scale		Local/Global	Depends of management objective	Guidance, chapter 2
Q3-1: Importance of the area for connectivity priorisation	Considered stage of life			Adult/Larval/Both	Taking in consideration both (adult and larval stage) is better but it is sometimes difficult to take both into considera	(Venegas et al., 2023)

					tion for the same zone of interest. To define the importance of the zone for inclusion in the network, it is important to see what is most lacking and how the zone in question can complement the existing network and which network.	
	Number of species using the area as-stepping stone			Proxy of the network importance	Used to prioritise one area over another (to be analysed in relation to the ecological, functional and climatic importance of the species using the network, see next criteria).	EK
	Importance of species	Climatic		Yes/No	A balance between	
		Functional		Yes/No		

	using the area as stepping stone	Ecological		Yes/No	all these criteria must be found within the MPAs identified for networking.	(Tittensor et al., 2019)
		Economic		Yes/No		
	Temporality /Time of residence			Indices of residence	Gives an indication of the importance of the area for the targeted species	(Kraft et al., 2023; Zimmermann et al., in prep)
	Importance of fluxes	Number of Individuals		Proxy of the network importance	Criteria for Prioritization	EK
		Frequency				
	Habitats	Type of habitat		Proxy of rarity and conservation interest (e.g. VME), indicator of the network to which the area of interest is linked (in relation to the previous "Proximity of feature" criterion)	Criteria for Prioritization	(McLeod et al., 2009)
		Functionality of habitat		Indicator of the network to which the area of interest is linked (in relation to the previous "Proximity of feature" criterion), proxy of habitat health and importance	Criteria for Prioritization	(Tittensor et al., 2019)

		Redundancy of function		Inside the MPA/Inside the network/Unique	Criteria for Prioritization	(McLeod et al., 2009)
	Health of adjacent ecosystems			Good health/Disease	Criteria for Prioritization. Depends on the nature of the damage. In the case of a pathogen, the zone must not be included in a network. In the case of habitat in poor health due to direct damage (e.g. trawling), the potential for ecosystem restoration via connectivity must be assessed.	(Bhatia et al., 2023; Kough et al., 2015)
	Climate stability of the area			Depend of the type of MPA targeted	For Climate refugia, the climate conditions need to be stable. For	(McLeod et al., 2009)

					adaptive areas, integrating a range of climatic conditions is recommended.	
	Current stability face to CC			Yes/No	Criteria for prioritization, expected evolution of current face to CC	Guidance, section 3.2.4.1
Q3-2: Parameters for simplifying institutional set-up	Shared resources (human, materials, studies…)	Existent partnerships		Yes/No	Facility criteria	EK
	Similarity of management way of thinking	Example of common management framework: Bottom-up/Top-down/Adaptive		Yes/No	Equivalent governance approaches to ensure similar levels of protection where possible, especially for Large-scale Marine Protected Areas (LSMPAs) and highly moving-species (e.g. pelagics)	(Christie et al., 2017)
	Common language and vocabulary			Yes/No/Easy way to translate	At the very least (among research fileds and	EK

					institutions). The socio-economic criteria can be further extended, but the use of a common language or translation facilities is a basis for cooperation.	
Q4. Limits to the inclusion of MPA in the network/Parameters to be monitored	Status of buffer zones, pathways	Managed		Yes/No (eventually consider Level from Grorud - Colvert)	The management of MPA borders, and in particular partial protection zones, is of great importance in the context of connectivity to avoid dams (same reasoning as for spill-over).	(Grorud-Colvert et al., 2021)
		Intensity of human pressures		No or Low	Ideally, the protection should be strong or no-take zone (NTZ). In partial protection areas	

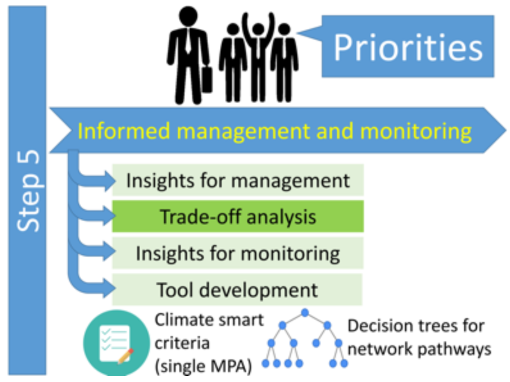
					(PPA) where activities remain authorised, specific restrictions for certain fishing activities (e.g. trawling) must be provided for, as well as for all activities carried out in the MPA (including recreational activities). All these regulations must be applied and controlled.	
	Human connectivity	Importance of maritime traffic		Degree of importance	Marine traffic should be integrate both as a factor of disturbance (especially for marine mammals or seabirds) but also as migratory vector.	Could be included in the scenario and inside the vulnerability assessment (Fliessbach et al., 2019)

	Potential arrival of invasive species	Declared presence/absence on exogeneous species	in the area	Yes/No	High risk of invasion (depending on the answers to the other criteria)	Extended from (Gallardo et al., 2019, 2017; Villero et al., 2022; Zhang et al., 2020)
			in adjacent/connected area	Yes/No	Risk of invasion	
		Importance of fluxes	With the upstream area ?	Yes/No	High risk of invasive species spread	
			With the downstream area ?	Yes/No	Low rish of invasive species spread	
		Installation potential	Reproduction potential of exogeneous species	Reproductive behaviour	Proxy of invasive potential	
			Area of provenance	Current climatic condition similar to the area of interest/No similarity	Proxy of the level (high, medium or low)	
			Potential of the area to become favourable for the exogenous species face to CC (Velocities)	Near-term/Mid-term/Long-term/Not favourable	Temporality of invasive risk (near, medium, long-term)	
		Role in the ecosystem of exogeneous species		(habitat, grazer, forager, predator …)	Proxy of the type of risk (or opportunity if the areas is degraded and the introduce species	

					could occupied an empty niche) in case of species introduction	
		Is/Are the exogeneous species recognized as invasives		Yes/No	Proxy of the intensity of the risk	
		Known invasive species climate velocities indicates a future introduction		Yes/No	Temporality of invasive risk (near, medium, long-term)	
		Type of invasive species potential impact in areas of presence		Assess from management feedback from similar areas where the species is present (assess from past velocities)	Proxy of the type of risk in case of species introduction	
Scientific support	Existence of local literature on connectivity			Yes/No	Facilitation criterion	(Extended from McLeod et al., 2009)
	Existence of a connectivity model			Yes/No	Facilitation criterion	(McLeod et al., 2009)

At the end of the process, the planners have a portfolio (from Step 4) of scenarios presenting different networks of favorable areas for the establishment of MPAs and a list of criteria necessary for their creation and their functioning under climate change and regarding the current knowledge. This portfolio could be presented to decision-makers and representatives of users to commonly define the most acceptable scenarios under climate change or propose alternatives that could be reimplanted and tested in the model.

6.2 The trade-off exercise: propose a concensus-building final MPA network



When the portfolio of management scenarios is defined, the first step will be to find a consensus scenario between the different stakeholders involved in the decision process. This final scenario is considered as the best compromise between the most suitable and the most acceptable final design. The discussion could concentrate on overlays between human activities and key climate areas (e.g. mitigation areas, adaptive areas) highlighted in the analysis framework (Queiros et al., 2021). The trade-off exercise should be organized and animated by informed facilitators (Butler et al., 2020) and we recommend a previous presentation of the different climate objectives and issues to be sure of the level of knowledge of each of the participants included in the decision process.

The main criteria to keep in mind for this analysis are:

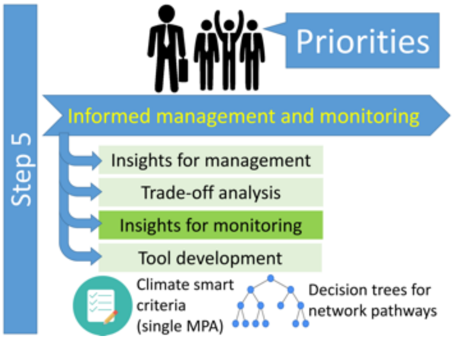
- It does not exist direct levers to regulate climate
- Fishing pressure (especially trawlers for potential mitigation) and pollution are still the most important pressures to be regulated in MPAs
- Strong protection zones (NTZ) are needed and should be big “enough” (see single MPA criteria)
- Risk spreading (redundancy of habitats and functions and prismatic design including different bathymetry) is defined as the key component of Adaptive pathways at single and multiple MPA scale
- Conservative approach will include the *Uniqueness* criteria (unique habitats should be protected) and biodiversity hotspots
- Connected is better for mobile species and areas under climatic threats…
- … But isolated refugia should be conserved in the final design
- Connectivity should include both larval and adult dispersal and should be tested taking into account the possible reduction of marine currents because of climate change. Protecting the source and key larval dispersal routes is of priori interest.
- The management scheme needs to consider the temporal dimension and plan for a long term (see the following section). The coherence of the scenario should be verified under different timescales (from near to long term) and different IPCC scenarios taking into account a range of climate exposure and velocities (Arafeh-Dalmau et al., 2021; Fredston-Hermann et al., 2018).

- To simplify negotiations with the fishery sector, it is recommended to present potential alternative climate bright spots to propose potential zone of activity report in the decision process (Queiros et al., 2021)

These key elements will help to assess the decision process and to select a final design that minimizes vulnerability and promotes climate mitigation, resilience and adaptation through the MPA network management (Frazao Santos et al., 2020; Lopazanski et al., 2023). As the scenario-based decision process will not lead to the optimal adaptation solution (Butler et al., 2020), it is recommended to develop and propose to discuss a portfolio of scenarios based on more ambitious targets than those decided in the initial framework (e.g. 40% on waters protected by MPA to reach 30%) to allow a certain flexibility and facilitate compromise. The long-term coherence and the capacity of the chosen final design to meet the initial management targets need to be retested and statistically verified to highlight its weaknesses and advantages.

6.3 Insight for monitoring

6.3.1 Managing under climate uncertainty: promote the development of a common iterative adaptive management plan



When an initial agreement has been reached, the second step will be to hierarchize temporal and spatial priorities for the implementation of future MPA and of climate-smart MPA measures considering climatic velocities, especially for accompanying migration, the potential evolution of objectives regarding different timescales and the legal calendar. That is why, to offset the urgency of implementing climate-related management and mitigation measures, it is recommended to adapt an existing MPA rather than create a new one, if possible, as regulatory change within an existent MPA will generally remain administratively easier and more readily acceptable to the local population than the creation of a new MPA. It is also strongly advised to first implement MPA in critical conservation areas (identified by a high concentration of Red List species) and to support the migration of the most vulnerable species while developing studies of adaptive potential. The climate smart and adaptive MPA could be then implemented in the second phase of MPA deployment.

This hierarchization will allow an action plan detailing waves of measures (near-term, mid-term and long-term measure) to be deployed along a timetable commonly accepted by the various stakeholders, and to carry out a reassessment of the merits of the initial scenario, following the example of the current operation of marine park management plans. The timeframe for re-evaluating deployment plans could theoretically be based on the frequency with which CMIP datasets are updated (every 5 to 8 years), and immediately following the occurrence of an extreme event, to track temporal shifts in the system and propose an adapted response.

This type of operation would theoretically make it possible to take into account the spatio-temporal dynamics of climate change, which are currently lacking at the level of both MPAs and MPA networks (Lopazanski et al., 2023), and to develop an iterative territorial schema recommended for the development of more optimal adaptation strategies (Wise et al., 2014). This functioning corresponds to the generalization at broader scale of the adaptive management promoted for existing MPAs (Zentner et al., 2023). It is also of prior importance as the participatory process appears to be particularly efficient over short terms (less than 20 years) (Butler et al., 2020) and as the uncertainty increases with time.

6.3.2 Monitoring climate change and short-term missing knowledge (from local to global scale)

To regularly update the scenario and the action plan, it is of prior importance to improve and develop the monitoring of climate change at each scale, from global to local scale.

On a global scale, the quality of satellite surveys is drastically improving notably thanks to the launching of new satellites (Gabarró et al., 2023) (*Fig. 32*) whereas the development of computers facilitates the downscaling process and the prevision of complex systems. Nevertheless, the downscaling effort is still limited and unevenly distributed across the globe. Although partially offset by the local development of in situ monitoring networks, downscaling efforts could be made for temperate and coastal zones which have received less attention from a climatic point of view but could prove to be key areas for mitigation purposes.

Figure 32 - *Earth observation missions developed by ESA [Credits: ESA] from (“Copernicus Program - Sentinel Online,” 2023)*

In terms of connectivity, two key elements are still missing regarding MPA networks and Marine Spatial Planning. First, in-depth studies are still missing to evaluate the effect of climate on MPA spacing as current as expected to unevenly change under climate change (Bashevkin et al., 2020; Venegas et al., 2023). This phenomenon is likely to have a major influence on the distribution of species, affecting the dispersal capacities of both larvae and post-larvae, as well as adults.

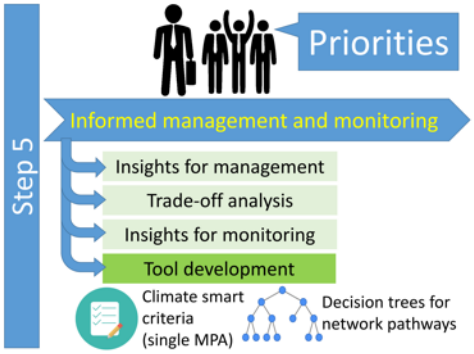
The development of Lagrangian and larval dispersal models (e.g. Roberts et al., 2021; Sciascia et al., 2022; Soria et al., 2014) and the inclusion of an acceptable range of usual and maximum distances as a constraint in MPA network creation models for the pool of species identified by the TVA as vulnerable and able to benefit from the network could represent a significant improvement. In 2022, Sciasca et al. published guidance for simulating larval dispersal that would be informative in this context (Sciascia et al., 2022). Moreover, the minimum distances between MPAs are mainly defined based on larval models, and take very little account of adult movements before the last ten years to identify Ecological Corridors (EC) (Podda and Porporato, 2023). The recent development of telemetry, thanks to the impetus given by the European Tracking Network (https://www.europeantrackingnetwork.org/en), represents a fundamental step forward for better identification and inclusion of the migratory patterns of less emblematic species that are highly vulnerable or may be under fishing pressure (e.g. Mignucci, 2021). A methodology for analyzing migratory distances, using the large barracuda as a test species, is currently being developed in the Mediterranean and should partially inform this question (Zimmermann et al., in prep).

The development of climate-related issues is also driving the consideration of MPAs as 4D models, including bathymetry and the biotic and climatic velocities (Brito-Morales et al., 2022; Doxa et al., 2022), and bringing to the fore the need for better interconnection and collaboration between local and global scales. Better interconnection of networks of scientists and observers would enable the pooling of knowledge and the development of monitoring and warning networks, in particular by facilitating the sharing and centralization of information, as well as the identification of extreme climatic phenomena that could be considered as early warnings for the network (e.g. emergence of deoxygenation waves). They would also enable better coordination of actions, the simultaneous testing of different management measures and the sharing of experiences between different marine protected areas following the same climatic trajectory. Similarly, as selection pressure linked to climate change is expected to gradually homogenize traits, the experience gained from Adaptive Areas could prove particularly useful for redefining criteria for identifying and monitoring the dispersion of adaptive traits, for better understanding the functioning of future oceans, and for testing potential adaptations of human industries and preventing as far as possible future inequalities in access to the resource (Liu et al., 2023).

To enable these improvements, it is vital to first include climate change monitoring and dedicated management measures in each MPA management plan (Lopazanski et al., 2023). This measure should add to the definition of a common trajectory for the entire network to ensure that all the conservation initiatives tend toward the same global goal. This inclusion will come first and foremost from the definition of clear and common management objectives linked to climate change, which will need to be spread out along a clear and realistic timetable based on the most up-to-date knowledge. It is also essential to redefine common protocols and indicators to be used across all MPAs, to ensure the interoperability of results and the robustness of shared experience. This also calls for greater transparency on the part of the scientific community, both with stakeholders and between research teams. This is what the Open Science movement is trying to promote but is encountering obstacles in the internal functioning of research itself.

6.4 Future research and tools needed

If improving the monitoring will help to be more efficient in the response to climate change, integrating climate change in the MPA networks need to compose with a great amount of uncertainty and lack of data. If the development of MSP models including climate change



is likely, it is still not possible to develop completely standardized approaches (despite attemps Stelzenmüller et al., 2015) as quantitative and expert-free indicators are still scarce in all climate-related sectors (social, economic and ecological) (Majszak and Jebeile, 2023; Marín-Puig et al., 2022) and because of a lack of clear climate objectives for the MPA network (few questions reach the Level 3 in Chapter 7). Consideration of the development of new direct or indirect indicators that combine the sciences (e.g. better linking ecology and socioeconomic component) could partially compensate for these shortcomings and enable us to move towards more comprehensive integrated management (Smit et al., 2021) of climate change. Such indicators already exist for fisheries (e.g. CPUE used to approximate stock status) (Cambra et al., 2021; Kayal et al., 2020), and an analysis of the strengths and shortcomings of these mixed indicators could provide initial food for thought and points of comparison.

This lack of quantitative values particularly affects the thresholds of tolerance to different climatic stressors for many species, both because of a lack of knowledge about the physiology of the species and because of a lack of knowledge about the effect of certain climatic stressors (e.g. deoxygenation, acidification). These gaps are gradually being filled for a small number of species with the recent and forthcoming publication (e.g. Frontiers in Marine Science current call of papers on the effect of salinity changes on marine life) of dedicated syntheses. Nevertheless, the combined effect of climatic pressures on these tolerance thresholds is often poorly taken into account, due to the complexity of the mechanisms and interactions involved and the lack of global knowledge. What's more, these thresholds are rarely calculated considering the developmental stage of individuals, and therefore remain relatively uncertain when it comes to their actual chances of survival.

Regarding existent tools, it is necessary to gather knowledge on areas of biological importance (species home range), ecological importance (e.g. functional areas, Vulnerable Marine Ecosystems, Essential Fish Habitats) and anthropogenic importance already identified but dispersed between the various programs and classifications of international conventions, to index and homogenize them and update the nomenclatures. This work will provide a single reference list common to all disciplines, enabling us to propose management priorities integrating all known components of the system, and to check that no Priority Areas for Management (PAMs) (Ortega et al., 2023) have been overlooked in the design of the future MPA network.

Lastly, the integration of climate issues demonstrates the need to consider streamlining MPA implementation processes or, at the very least, the possibility and merits of granting greater legal and administrative flexibility regarding their lifespan. Indeed, while the current view of MPA is that its profitability increases with its age, with the literature proposing 10 years as the minimum age necessary for MPA to be productive (quote), the question of the end of life of an MPA is rarely asked. However, this is becoming particularly relevant as climatic conditions change. It is important to legally anticipate the fact that an MPA may cease to be functional depending on the reason for its initial implementation, for example following the disappearance of an endemic species, or that it may be of a transitory nature in the context of accompanying migration. If this is not possible or complex from a jurisprudential point of view, in view of the major objectives of the Kunming-Montreal Convention on Biological Diversity, it may be necessary to consider the integration and generalization of management measures other than MPAs (e.g. fishing blocks) to meet climatic needs, or to create a new typology of MPAs, providing strong but transitional protection, giving greater flexibility to networks and making it easier to adapt to re-evaluations of implementation plans.

7 How to apply the guidance: policy makers and managers

In this section, we present how the guidance could be applied to answer to a selection of management questions frequently at stake when integrating MPAs in MSP.

These questions arose from discussions with the test sites and the COPs members (collected by T5.2). Some of these questions are directly climate-related (Type 1), some of these questions will need to take into account the new fundamental criteria introduced by climate change (Type 2) and some of them are less related to climate change but could benefit from the guidance (Type 3). We also consider three level of management questions (*Fig. 33*): Level 1 - Broad and non-specific management question (equivalent to the initial stage of the guidance step 1 - *Setting the management*), Level 2 - Test-site specific question, adapted by areas of interest, including a first ranking of accessible goals (intermediate stage of the guidance step 1), Level 3 – Test-site specific question associated with a realistic framework in matter of scale, target and eventually a proposed calendar of actions (final stage of the guidance step 1) (Fig.33).

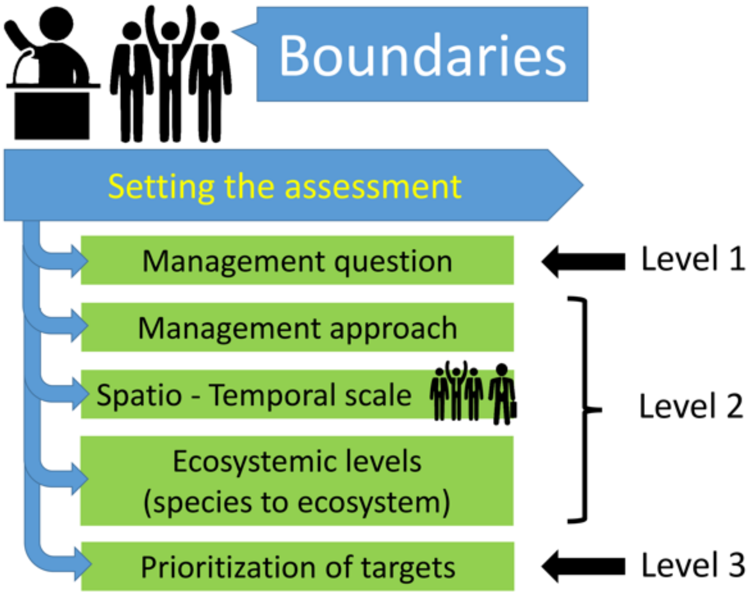


Figure 33 – Different levels of management questions according to the advancement in the framing process.

7.1 Directly CC related Questions (Type 1)

Question 1

Level 1: How to anticipate climate change effects in the MPA network?

Advice about how to use the guidance to answer the question: i) Assess the climate sensitivities of conservation features targeted by MPAs following the guidance D3.3 (Chapter 3 – section 3.3), ii) Criteria for designing climate-smart MPAs and MPA network are included in Step 5 (Chapter 6 – section 6.1).

7.2 Questions benefiting to CC criteria (Type 2)

Question 1

Level 1: How to achieve the strict Protection Area Target (10% by 2030)?

Advice about how to use the guidance to answer the question: Identifying key areas for conservation now and in the future under CC would help inform the selection of strict PA to achieve 10% target. The guidance provides a robust and transparent methodology for this very purpose.

Level 2: What will be the extent of a new Marine Protected Area to achieve the EU Biodiversity 2030 targets?

Advice about how to use the guidance to answer the question: If the question relates to extending existing MPAs, firstly, define key conservation features (Step 1) and then analyze CC sensitivity and exposure (Step 2). This will provide relevant knowledge to re-shape and extend the targeted existing MPA. Actual Climate-smart criteria are synthetized in the guidance (chapter 2.5). Also, instead of extending the existing MPA, consider whether designing a new MPA in an area connected to the existing one would enhance protection in a changing climate (see step 5 – section 6.1).

Level 2: How can we prioritize a location for a marine reserve's designation? (e.g. with criteria, tools)?

Advice about how to use the guidance to answer the question: (i) Define the main targets of the marine reserve as the location will change regarding it (chapter 2, step 1). (ii) Analyse the capacity of each proposed areas to be productive under climate-change (considering different scenarios) as single MPA (chapter 5, step 4) and if it is possible and relevant to enlarge it regarding the local context (iii) Analyse the potential of each proposed areas to the surrounding areas and MPA (chapter 6, step 5) (iv) Consider the ease of finding trade-off with the activities inside the area (chapter 6, step 5) (v) hierarchise and test the proposed scheme (chapter 6, step 5).

Question 2

Level 1: How to identify suitable areas for targeted species restauration or habitat restoration?

Advice about how to use the guidance to answer the question: The Guidance can be applied to every species, i) Analyze sensitivity and adaptability to CC of the targeted species (guidance, chapter 3.3); ii) Identify the future of existent targeted species population and analyse targeted species velocity (future projection without human intervention) to estimate the areas where restoration will be needed or not . iii) Identify future climate analogs favourable for restoration (see method section 3.2.4.1 in the guidance draft).

Question 3

Level 1: How can we improve the protection of a specific habitat?

Advice about how to use the guidance to answer the question: Consider knowledge related to targeted species (engineer species or the species that use the habitat) future distribution/state of health, knowledge of climate analogs, traits and sensitivity of key species.

Level 2: How can we improve the protection of pelagic habitats?

Advice about how to use the guidance to answer the question: The guidance can be applied to pelagic habitats, considering knowledge related to the targeted species future distribution, knowledge of future upwellings, traits and sensitivity of key species.

Level 2: How can we improve the protection of the Vulnerable Marine Ecosystems (VME)* (cf. Glossary)?

Advice about how to use the guidance to answer the question: The guidance provides a method to define functional traits of VMEs and sensitivity of VMEs to CC. The main Life traits linked to CC sensitivity are a slow growth rate, a late age of maturity, a low or unpredictable recruitment and the concentration of long-lived organisms (FAO, 2024b). This is essential to understand potential future climate-induced changes in VME and identify actions to protect them. Moreover, the feasibility and uncertainty analysis are essential to make knowledge gaps and uncertainty explicit in deep VMEs.

Question 4

Level 1: How to improve protection of targeted species in coherence with ongoing initiatives?

Advice about how to use the guidance to answer the question: The guidance provides a methodology to assess exposure, sensitivity, and vulnerability of key species, and to include adaptation in the design of MPAs. The analysis can focus on key sensitive species to cross CC exposure and sensitivity with other existing and future anthropogenic pressures.

Question 5

Level 1: How to assess compatibility of maritime uses and MPAs conservation objectives, considering the local context?

Advice about how to use the guidance to answer the question: i) MPAs conservation objectives are established by policy makers; ii) Make sure that these include objectives related to climate adaptability and/or climate vulnerability of the MPA's key conservation features.

Question 6

Level 1: How to prioritise space use within a multi-use MPA, which could consist of nature protection, nature restoration, aquaculture, renewable energy generation, sand and gravel extraction, fishing or dredging?

Level 2: How can a MPA be used as a living lab to answer these questions?

Advice about how to use the guidance to answer the question: Understanding how the conservation features targeted by the MPA will be affected by CC (in its multiple pressures) is essential i) to assess potential adaptation and mitigation strategies (including restoration), ii) to monitor changes and make MPA a "living lab" in time and space, iii) and to assess potential trade-offs between conservation and other human uses that might emerge in the future under climate-induced changing conditions in species, habitat and human uses. For point iii) take into account the known interaction between human activities (especially inorganic and organic pollution and fisheries) and climatic stressors (section 3.2.2.2 *Table 10*) to help the decision.

Question 7

Level 1: What monitoring approach could be taken to evaluate conservation measures for extensive MPA Networks (especially for deep-sea environment)?

Level 2: How to deal with the knowledge gaps related to water column data (main data is related to the seabed) to support decision-making for conservation measures offshore?

Advice about how to use the guidance to answer the question: The D3.3 guidance mentions a feasibility analysis to assess robustness of the assessment and data/information/knowledge availability in chapter 3.4; uncertainties are assessed in chapter 4.3.1. This will help targeting monitoring and filling up knowledge gaps.

Question 8

Level 1: How can the procedures for MSP plans be clarified to integrate newly classified MPAs?

Level 2: How can we take into consideration the conservation of OECMs* within MSP implementation if there are no legally binding instruments?

Advice about how to use the guidance to answer the question: Understanding sensitivity and vulnerability of conservation features to CC will be essential to assess the potential conservation benefits of OECMs in a changing climate. The guidance can be applied to assess conservation benefits on key features (ie species, habitat, ecosystems) within existing area-based management tools that are candidates to become OECM. The guidance can also be applied in general to key conservation features to assess if candidate OECMs will provide conservation benefits to those features in the future under CC.

Question 9

Level 1: How to assess the transboundary ecological coherence of the MPA network?

Advice about how to use the guidance to answer the question: The guidance provides a method to consider connectivity in designing or assessing a climate smart MPA network (chapter 6, step 5).

7.3 Indirectly CC related questions (Type 3)

Question 1

Level 1: How to incorporate social and economic criteria in MPAs identification/ designation?

Advice about how to use the guidance to answer the question: i) Clarify the key conservation features (i.e., species, habitats and ecosystem) that are of priority for conservation (chapter 2); ii) Analyze sensitivity and adaptability to CC of the key conservation features (chapter 3.3); iii) Identify potential trade-off with economic and social preferences (section 6.2).

Question 2

Level 1: How to increase the stakeholder knowledge and awareness on MPAs and MSP?

Advice about how to use the guidance to answer the question: Not the main purpose of 3.2. However, leveraging knowledge and information about CC effects and consequences among stakeholders is a key aspect of the CC guidance.

Question 3

Level 1: How to include/ better include the evaluation of stakeholders' satisfaction level (e.g., alignment expectations) in the MSP/MPA Processes?

Level 2: How can we better demonstrate the effectiveness of conservation measures to stakeholders?

Advice about how to use the guidance to answer the question: The CC guidance provides a robust and transparent method to support the integration of CC consideration in MPA network design. This will help the interaction with stakeholders along the planning process by transparently communicating exposure, sensitivity and vulnerability of key species and habitats.

Question 4

Level 1: How should the reliability/accuracy of the spatial data for MPAs identification be improved?

Advice about how to use the guidance to answer the question: The D3.3 guidance mentions a feasibility analysis to assess data availability in chapter 3.4; uncertainties are assessed in chapter 4.3.1.

This set of questions presents different ways in which guidance can be used.

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Link to the Sharepoint :

https://sustainableprojects921.sharepoint.com/:x:/r/sites/MSP4BIO/Freigegebene%20Dokumente/WP3_Systemic%20approach/T2.1_WP3DataRequests.xlsx?d=we9144656eb954daf99726fd5a0ae5eb6&csf=1&web=1&e=wKI9la , sheet "Ecological traits", for list of traits databases provided to T3.1 for the preparation of D3.2

https://sustainableprojects921.sharepoint.com/:x:/r/sites/MSP4BIO/Freigegebene%20Dokumente/WP3_Systemic%20approach/T2.1_WP3DataRequests.xlsx?d=we9144656eb954daf99726fd5a0ae5eb6&csf=1&web=1&e=2xMAre sheet "Ecological traits (cluster)"

https://sustainableprojects921.sharepoint.com/:x:/r/sites/MSP4BIO/Freigegebene%20Dokumente/WP3_Systemic%20approach/T2.1_WP3DataRequests.xlsx?d=we9144656eb954daf99726fd5a0ae5eb6&csf=1&web=1&e=XP2clu sheet "Species population trends"

9. Appendices

Supplementary 1 – Theoretical ranking of climatic and anthropic stressors on marine taxa based on the vulnerability score (modified from Butt et al., 2022).

From *Butt et al., 2022*

Theorical ranking per taxa

Seabirds
Biomass removal (0.74)
Bycatch (0.66)
Invasive species (0.55)
Sea Level Rise (0.53)
Light pollution (0.51)
Wildlife strike (0.50)
Habitat loss - degradation (0.44)
Storm disturbance (0.42)
Entanglement macroplastic (0.40) /Noise pollution (0.40)
Organic pollution (0.30)
Sedimentation (0.23)
Air T° (0.21)
Inorganic pollution (0.20)
Water T° (0.10)
Autrophication nutrient pollution (0.08)
Ocean acidification (0.06) / Plastic pollution microplastic (0.06)
Poisons/Toxins (0.04)
Oceanographic processes (0) / Salinity (0)/ UV (0)

Marine mammals
Biomass removal (0.79) / Bycatch (0.79)
Wildlife strike (0.65)
Entanglement macroplastic (0.63)
Habitat loss - Degradation (0.43)
Sea Level Rise (0.38)
Noise pollution (0.36)
Organic pollution (0.34)
Storm disturbance (0.22)
Inorganic pollution (0.18)
Invasive species (0.17)
Light pollution (0.16)
Water T° (0.15)
Air T° (0.11) / Eutrophication nutrient pollution (0.11) / Ocean acidification (0.11)
Sedimentation (0.10)
Plastic pollution microplastic (0.07)
Poisons - toxins (0.05) / Oceanographic process (0.05)
Salinity (0.04)
UV (0.0)

Bony fish
Biomass removal (0.64)
Salinity (0.38)
Inorganic pollution (0.36) / Organic pollution (0.36) / Poisons - toxins (0.36)
Bycatch (0.35) / Water T° (0.35)
Eutrophication nutrient pollution (0.34)
Plastic pollution microplastic (0.33) / Sedimentation (0.33)
Habitat loss – degradation (0.32)
Ocean acidification (0.30)
Oceanic processes (0.27)
Entanglement macroplastic (0.13) / Light pollution (0.13)
Storm disturbance (0.11)
UV (0.10)
Noise pollution (0.05) / Sea Level Rise (0.05)
Wildlife strike (0.02)
Air T° (0.01)
Invasive species (0.00)

Marine Reptiles
Biomass removal (0.75)
Bycatch (0.74)
Wildlife strike (0.59)
Entanglement macroplastic (0.58)
Habitat Loss – degradation (0.43)
Sea Level Rise (0.34)
Storm disturbance (0.29)
Organic pollution (0.28)
Sedimentation (0.25)
Inorganic pollution (0.21)
Invasive species (0.16)
Water T°(0.14)
Eutrophication nutrient pollution (0.11) / Light pollution (0.11)
Air T° (0.07) / Plastic pollution microplastic (0.07)
Poisons – toxins (0.05)
Ocean acidification (0.04)
Noise Pollution (0.0) / Oceanographic processes (0.0) / Salinity (0.0) / UV (0.0)

Elasmobranchs
Biomass removal (0.87)
Bycatch (0.59)
Habitat Loss – degradation (0.39)
Organic pollution (0.36)
Entanglement macroplastic (0.29)
Oceanographic processes (0.27) / Poisons – toxins (0.27)
Inorganic pollution (0.23) / Plastic pollution microplastic (0.23)
Eutrophication nutrient pollution (0.21)
Sedimentation (0.20)
Salinity (0.19)
Sea Level Rise (0.09) / Water T° (0.09)
Storm disturbance (0.08)
Noise pollution (0.04) / Ocean acidification (0.04)
Wildlife strike (0.02)
Air T° (0.0) / Invasive species (0.0) / Light pollution (0.0) / UV (0.0)

Molluscs
Biomass removal (0.70)
Eutrophication nutrient pollution (0.52)
Organic pollution (0.48) / Poisons – toxins (0.48)
Bycatch (0.47)
Plastic pollution microplastic (0.46)
Inorganic pollution (0.44) / Ocean acidification (0.44) / Salinity (0.44)
Sedimentation (0.43)
Water T° (0.38)
Sea Level Rise (0.27)
Air T° (0.23) / Habitat loss – degradation (0.23)
Light pollution (0.22)
Entanglement macroplastic (0.19)
Storm disturbance (0.18)
UV (0.14)
Oceanographic processes (0.12)
Invasive species (0.0) / Noise pollution (0.0) / Wildlife strike (0.0)

Corals
Biomass removals (0.68)
Habitat loss – degradation (0.61)
Salinity (0.60)
Eutrophication nutrient pollution (0.57) / UV (0.57)
Water T° (0.54)
Oceanographic processes (0.45)
Ocean acidification (0.43)
Organic pollution (0.39) / Sea Level Rise (0.39)
Inorganic pollution (0.38)
Sedimentation (0.32)
Poisons – toxins (0.31)
Light pollution (0.22)
Storm disturbance (0.20)
Bycatch (0.13) / Plastic pollution microplastic (0.13)
Air T° (0.0) / Entanglement macroplastic (0.0) / Invasive species (0.0) / Noise pollution (0.0) / Wildlife strike (0.0)

Echinoderms
Biomass removals (0.71)
Water T° (0.53)
Eutrophication nutrient pollution (0.49)
Oceanographic processes (0.45) / Salinity (0.45)
Inorganic pollution (0.44)
Poisons – toxins (0.43)
Ocean acidification (0.40)
Habitat loss – degradation (0.39) / Organic pollution (0.39)
Sedimentation (0.38)
Bycatch (0.29)
Plastic pollution microplastic (0.27)
Storm disturbance (0.26)
Light pollution (0.16)
UV (0.12)
Sea Level Rise (0.08)
Entanglement macroplastic (0.07)
Air T° (0.04)
Noise pollution (0.01)
Invasive species (0.0) / Wildlife strike (0.0)

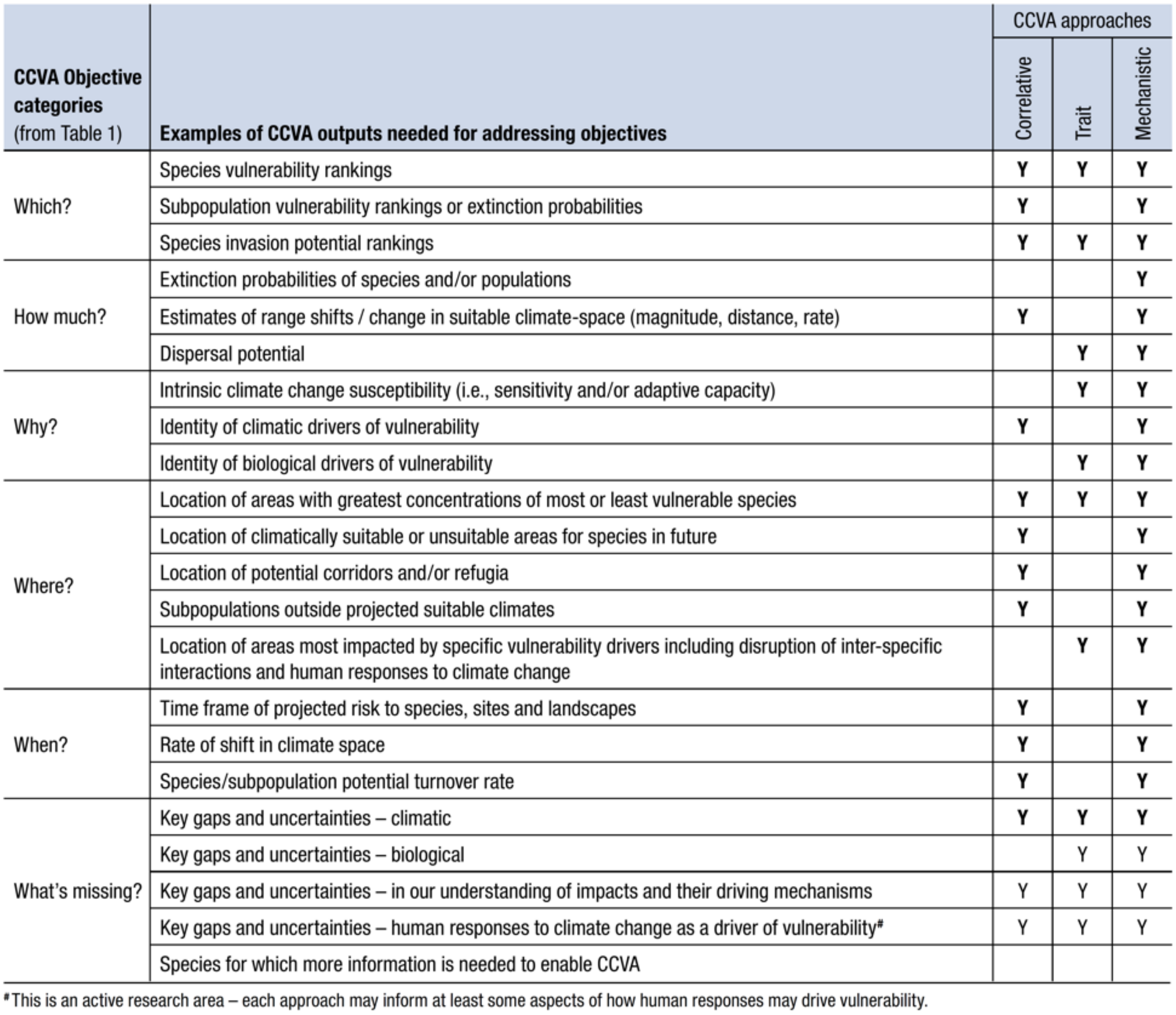
Cephalopods
Biomass removals (0.71)
Eutrophication nutrient pollution (0.48)
Salinity (0.43)
Inorganic pollution (0.42)
Organic pollution (0.40)
Bycatch (0.39)
Ocean acidification (0.38)
Oceanographic processes (0.37)
Poisons – toxins (0.36) / Sedimentation (0.36) / Water T° (0.36)
Habitat loss – degradation (0.35)
Plastic pollution microplastic (0.29)
Noise pollution (0.23)
Entanglement macroplastic (0.14)
Light pollution (0.10) / Storm disturbance (0.10)
Sea Level Rise (0.09)
UV (0.07) / Wildlife strike (0.07)
Air T° (0.0) / Invasive species (0.0)

Marine Arthropods
Biomass removals (0.81)
Water T° (0.40)
Plastic pollution microplastic (0.38)
Organic pollution (0.37)
Bycatch (0.36) / Salinity (0.36) / Sedimentation (0.36)
Inorganic pollution (0.32)
Eutrophication nutrient pollution (0.31) / Poisons – toxines (0.31)
Light pollution (0.28) / Ocean acidification (0.28)
Habitat loss – degradation (0.24) / Sea Level Rise (0.24)
Air T° (0.21)
UV (0.19)
Storm disturbance (0.15)
Entanglement macroplastic (0.14) / Oceanographic processes (0.14)
Noise pollution (0.01)
Invasive species (0.0) / Wildlife strike (0.0)

Polychaetes
Biomass removals (0.84)
Plastic pollution microplastic (0.55)
Poisons – toxines (0.41)
Sedimentation (0.40)
Organic pollution (0.39)
Oceanographic processes (0.28) / Salinity (0.28)
Inorganic pollution (0.26) / Water T° (0.26)
Light pollution (0.25)
Eutrophication nutrient pollution (0.18)
UV (0.17)
Air T° (0.15) / Storm disturbance (0.15)
Sea Level Rise (0.11)
Ocean acidification (0.07)
Bycatch (0.0) / Entanglement macroplastic (0.0) / Habitat loss-degradation (0.0) / Invasive species (0.0) / Noise pollution (0.0) / Wildlife strike (0.0)

Sponges
Biomass removals (0.79)
Sedimentation (0.46)
Plastic pollution microplastic (0.43)
Organic pollution (0.41)
Poisons – toxins (0.36)
Water T° (0.34)
Inorganic pollution (0.33)
Bycatch (0.32)
Storm disturbance (0.29)
Light pollution (0.26)
Eutrophication nutrient polution (0.22)
UV (0.15)
Ocean Acidification (0.14)
Habitat loss – degradation (0.08)
Entanglement macroplastic (0.07)
Salinity (0.06)
Air T° (0.0) / Invasive species (0.0) / Noise pollution (0.0) / Oceanographic processes (0.0) / Sea Level Rise (0.0) / Wildlife strike (0.0)

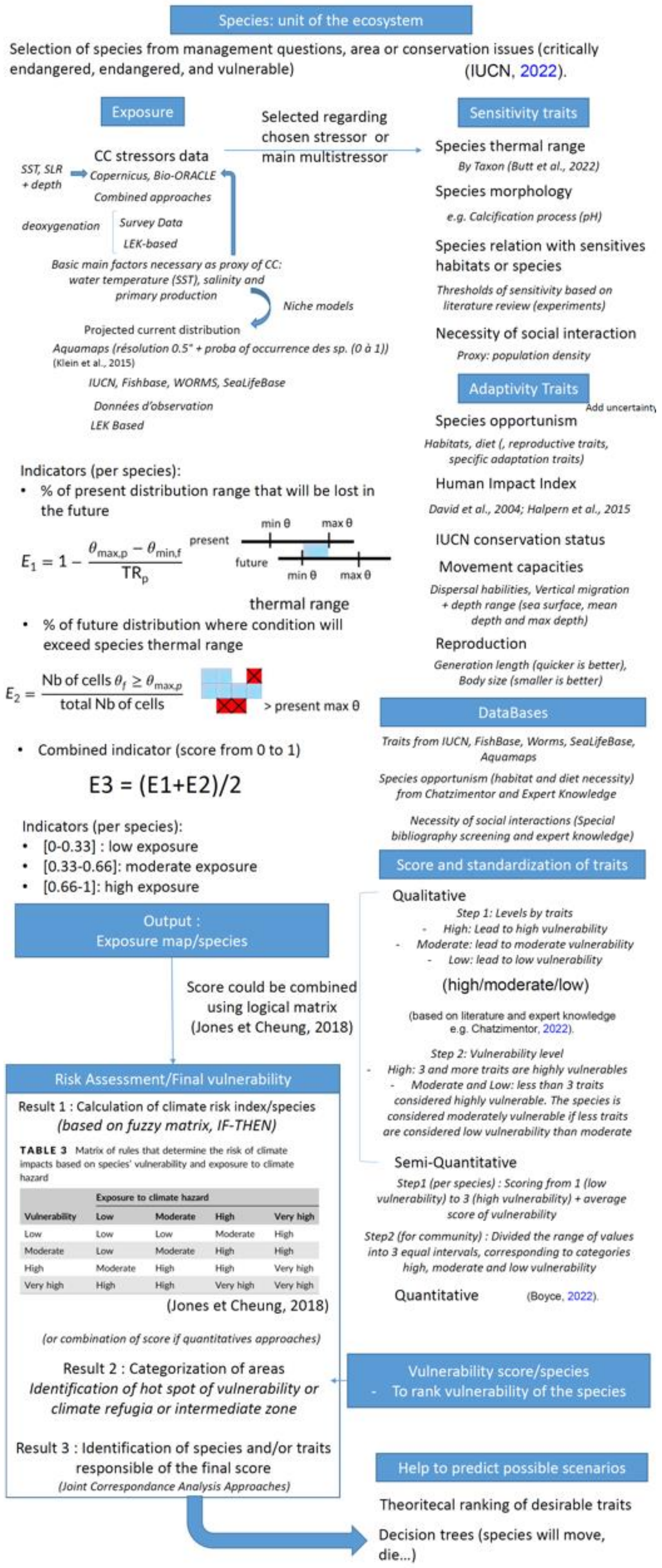
Supplementary 2 – Table of objectives of Climate Change Vulnerability Assessment and methodologies adapted to answer it (from Foden et al., 2016) (Foden, 2016)



CCVA Objective categories (from Table 1)	**Examples of CCVA outputs needed for addressing objectives**	CCVA approaches		
		Correlative	Trait	Mechanistic
Which?	Species vulnerability rankings	**Y**	**Y**	**Y**
	Subpopulation vulnerability rankings or extinction probabilities	**Y**		**Y**
	Species invasion potential rankings	**Y**	**Y**	**Y**
How much?	Extinction probabilities of species and/or populations			**Y**
	Estimates of range shifts / change in suitable climate-space (magnitude, distance, rate)	**Y**		**Y**
	Dispersal potential		**Y**	**Y**
Why?	Intrinsic climate change susceptibility (i.e., sensitivity and/or adaptive capacity)		**Y**	**Y**
	Identity of climatic drivers of vulnerability	**Y**		**Y**
	Identity of biological drivers of vulnerability		**Y**	**Y**
Where?	Location of areas with greatest concentrations of most or least vulnerable species	**Y**	**Y**	**Y**
	Location of climatically suitable or unsuitable areas for species in future	**Y**		**Y**
	Location of potential corridors and/or refugia	**Y**		**Y**
	Subpopulations outside projected suitable climates	**Y**		**Y**
	Location of areas most impacted by specific vulnerability drivers including disruption of inter-specific interactions and human responses to climate change		**Y**	**Y**
When?	Time frame of projected risk to species, sites and landscapes	**Y**		**Y**
	Rate of shift in climate space	**Y**		**Y**
	Species/subpopulation potential turnover rate	**Y**		**Y**
What's missing?	Key gaps and uncertainties – climatic	**Y**	**Y**	**Y**
	Key gaps and uncertainties – biological		Y	Y
	Key gaps and uncertainties – in our understanding of impacts and their driving mechanisms	Y	Y	Y
	Key gaps and uncertainties – human responses to climate change as a driver of vulnerability[#]	Y	Y	Y
	Species for which more information is needed to enable CCVA			

[#] This is an active research area – each approach may inform at least some aspects of how human responses may drive vulnerability.

This project has received funding from the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.



Species: unit of the ecosystem

Selection of species from management questions, area or conservation issues (critically endangered, endangered, and vulnerable) (IUCN, 2022).

Exposure

Selected regarding chosen stressor or main multistressor

CC stressors data

SST, SLR + depth → *Copernicus, Bio-ORACLE*

Combined approaches

deoxygenation *Survey Data* *LEK-based*

Basic main factors necessary as proxy of CC: water temperature (SST), salinity and primary production

Niche models

Projected current distribution

Aquamaps (résolution 0.5° + proba of occurrence des sp. (0 à 1)) (Klein et al., 2015)

IUCN, Fishbase, WORMS, SeaLifeBase

Données d'observation

LEK Based

Indicators (per species):

- % of present distribution range that will be lost in the future

$$E_1 = 1 - \frac{\theta_{\max,p} - \theta_{\min,f}}{\mathrm{TR}_p}$$

thermal range

- % of future distribution where condition will exceed species thermal range

$$E_2 = \frac{\text{Nb of cells } \theta_f \geq \theta_{\max,p}}{\text{total Nb of cells}}$$

- Combined indicator (score from 0 to 1)

$$E3 = (E1+E2)/2$$

Indicators (per species):

- [0-0.33] : low exposure
- [0.33-0.66]: moderate exposure
- [0.66-1]: high exposure

Output :
Exposure map/species

Score could be combined using logical matrix (Jones et Cheung, 2018)

Risk Assessment/Final vulnerability

Result 1 : Calculation of climate risk index/species *(based on fuzzy matrix, IF-THEN)*

TABLE 3 Matrix of rules that determine the risk of climate impacts based on species' vulnerability and exposure to climate hazard

	Exposure to climate hazard			
Vulnerability	**Low**	**Moderate**	**High**	**Very high**
Low	Low	Low	Moderate	High
Moderate	Low	Moderate	High	High
High	Moderate	High	High	Very high
Very high	High	High	Very high	Very high

(Jones et Cheung, 2018)

(or combination of score if quantitatives approaches)

Result 2 : Categorization of areas
Identification of hot spot of vulnerability or climate refugia or intermediate zone

Result 3 : Identification of species and/or traits responsible of the final score
(Joint Correspondance Analysis Approaches)

Sensitivity traits

Species thermal range
By Taxon (Butt et al., 2022)

Species morphology
e.g. Calcification process (pH)

Species relation with sensitives habitats or species
Thresholds of sensitivity based on literature review (experiments)

Necessity of social interaction
Proxy: population density

Adaptivity Traits

Add uncertainty

Species opportunism
Habitats, diet (, reproductive traits, specific adaptation traits)

Human Impact Index
David et al., 2004; Halpern et al., 2015

IUCN conservation status

Movement capacities
Dispersal habilities, Vertical migration + depth range (sea surface, mean depth and max depth)

Reproduction
Generation length (quicker is better), Body size (smaller is better)

DataBases

Traits from IUCN, FishBase, Worms, SeaLifeBase, Aquamaps

Species opportunism (habitat and diet necessity) from Chatzimentor and Expert Knowledge

Necessity of social interactions (Special bibliography screening and expert knowledge)

Score and standardization of traits

Qualitative

Step 1: Levels by traits
- *High: Lead to high vulnerability*
- *Moderate: lead to moderate vulnerability*
- *Low: lead to low vulnerability*

(high/moderate/low)

(based on literature and expert knowledge e.g. Chatzimentor, 2022).

Step 2: Vulnerability level
- *High: 3 and more traits are highly vulnerables*
- *Moderate and Low: less than 3 traits considered highly vulnerable. The species is considered moderately vulnerable if less traits are considered low vulnerability than moderate*

Semi-Quantitative

Step1 (per species) : Scoring from 1 (low vulnerability) to 3 (high vulnerability) + average score of vulnerability

Step2 (for community) : Divided the range of values into 3 equal intervals, corresponding to categories high, moderate and low vulnerability

Quantitative (Boyce, 2022).

Vulnerability score/species
- To rank vulnerability of the species

Help to predict possible scenarios

Theoritecal ranking of desirable traits

Decision trees (species will move, die…)