# Evaluating the combined effect of climate and anthropogenic stressors on marine coastal ecosystems: insights from a systematic review of cumulative impact assessment approaches

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## Abstract

Cumulative impacts increasingly threaten marine and coastal ecosystems. To address this issue, the research community has invested efforts on designing and testing different methodological approaches and tools that apply cumulative impact appraisal schemes for a sound evaluation of the complex interactions and dynamics among multiple pressures affecting marine and coastal ecosystems.

Through an iterative scientometric and systematic literature review, this paper provides the state of the art of cumulative impact assessment approaches and applications. It gives a specific attention to cutting-edge approaches that explore and model inter-relations among climatic and anthropogenic pressures, vulnerability and resilience of marine and coastal ecosystems to these pressures, and the resulting changes in ecosystem services flow. Despite recent advances in computer sciences and the rising availability of big data for environmental monitoring and management, this literature review evidenced that the implementation of advanced complex system methods for cumulative risk assessment remains limited. Moreover, experts have only recently started integrating ecosystem services flow into cumulative impact appraisal frameworks, but more as a general assessment endpoint within the overall evaluation process (e.g. changes in the bundle of ecosystem services against cumulative impacts). The review also highlights a lack of integrated approaches and complex tools able to frame, explain, and model spatio-temporal dynamics of marine and coastal ecosystems' response to multiple pressures, as required under relevant EU legislation (e.g., Water Framework and Marine Strategy Framework Directives). Progress in understanding cumulative impacts, exploiting the functionalities of more sophisticated machine learning-based approaches (e.g., big data integration), will support decision-makers in the achievement of environmental and sustainability objectives.

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# Introduction

Marine and coastal ecosystems (MCEs) play a crucial role for society by regulating climate, providing food resources and contributing to well-being (Albert et al., 2020; EEA, 2019). However, most of these ecosystems (e.g., seagrass meadows, coral reefs and maërl beds) across the globe have been significantly altered by multiple human-related drivers (e.g., overexploitation of fish, shellfish and other organisms, land- and sea-based pollution, aquaculture) (IPBES, 2020). In addition, the complex interplay between anthropogenic and climate-related pressures (e.g., rising sea temperature sometimes resulting in marine heatwaves, increased occurrence of climate and weather extremes, ocean acidification, etc.) is increasingly exacerbating the cumulative impacts across all MCEs, undermining their resilience to consecutive perturbations and their capacity to provide ecosystem services (EEA, 2019; IPBES, 2019; IPCC, 2019). Specifically, cumulative impacts cause a reduction in the health and resilience of MCEs (Beusen et al., 2022; IPBES, 2019), and consequently increase their overall vulnerability to additional external pressures (Berrouet et al., 2018; Salomidi et al., 2012).

In that context, in the early 2000s, the research community started developing methodological approaches and tools for the assessment of cumulative impacts and multi-risk scenarios (hereafter CIA methods). These arised from the complex interaction between human activities (e.g., shipping traffic, fishing) and climate change (e.g., sea surface temperature , ocean acidification) affecting MCEs, and aimed to support decision-makers in the identification of sustainable management strategies (Halpern et al., 2008; Hayes & Landis, 2004). Policies at the international and EU level (UN-SDGs, EU Water Framework Directive, EU Maritime Spatial Planning, Green Deal initiative, Biodiversity Strategy for 2030), and the related definition of environmental targets, requires a comprehensive review to identify suitable existing methodological approaches and tools for managing cumulative impacts and risk to support their implementation and achievement of goals.

The objective of this paper is to provide an in-depth review of CIA and multi-risk assessment (MRA) approaches and applications, jointly applying a Scientometric and systematic literature review of publications identified during the 2000-2022 period (March 2022). The integration of both review approaches allows descriptive analysis and network extraction of the conceptual structure (and terminologies) underpinning this research field, while mapping and systematically analysing its theoretical/methodological trends, as well as gaps and challenges ahead. This review is the first done at this scale, comparing studies against multidisciplinary research questions and related comparison criteria (e.g., ecosystem services component, integration of the ecological tipping point concept), embracing both environmental, ecological, technical/methodological and policy perspectives. Particularly, it tries to respond to 2 main research questions*: i) Which are the key methodologies and scientific information/tools that the research community can apply to evaluate the effects of human activities and climate change on MCEs? ii) How has the complexity of stressors on MCEs (e.g., synergism, antagonism) been integrated into CIA/MRA frameworks to identify tipping points and the resilience of ecosystems?* Other recent global reviews have mainly focused on identifying methodological similarities among analysed studies (Blakley & Russell, 2022; Gissi et al., 2021; Halpern et al., 2019; Halpern & Fujita, 2013; Jones, 2016; Korpinen & Andersen, 2016; Stelzenmüller et al., 2018), as well as exploring some specific aspects into CIA and MRA frameworks and tools for MCEs (e.g., investigation of tipping points, shift changes, Decision Support Systems supporting CIA) (McClenachan et al., 2020; Menegon, Depellegrin, Farella, Sarretta, et al., 2018a; Thrush et al., 2021). This investigation extends the abovementioned perspectives, and merges them together to frame and drive the review process and identify key challenges and gaps, as well as research horizons ahead. The paper gives elements of comparison for scientists and policy makers who aim to use CIA and MRA methods and tools to evaluate and monitor environmental targets in MCEs, while highlighting the best available knowledge and data.

The paper is structured in 3 sections. A preliminary overview on the methodological approaches and the related data acquisition process underpinning the literature review is given in Section 1. The main results obtained from the review are presented in Section 2, while a discussion, in Section 3, highlights the main findings and key relevant challenges and proposes some pathways for improvement.

# 1. Data acquisition and review methods

A multi-phase systematic literature review was performed to get an overall picture of the current state-of-the-art regarding scientific studies and applications focused on CIA and multi-risk appraisal in MCEs. Specifically, as shown in Figure 1, the methodological approach is comprised of three main steps, including i) data collection, ii) Scientometric analyses; and iii) Systematic analyses (based on the PRISMA - Preferred Reporting Items for Systematic Reviews and Meta-Analyses - approach), as described in the following paragraphs 1.1-1.2 and 1.3, respectively.

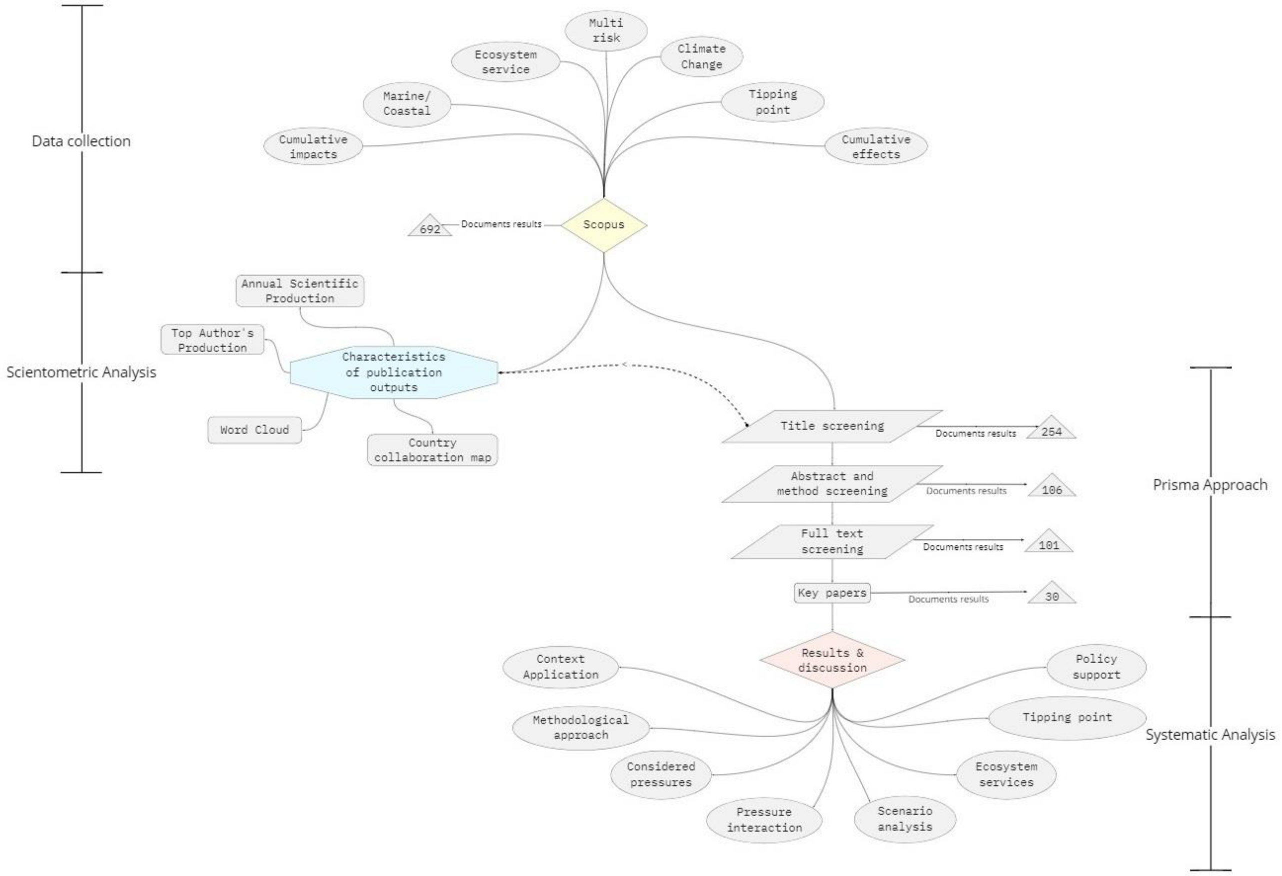

*Figure 1: Methodological approach for the evaluation of existing studies and applications dealing with cumulative impact assessment in marine and coastal ecosystems.*

## 1.1 Data collection

Peer-reviewed literature dealing with cumulative impact and multi-risk appraisal in MCEs was systematically searched using Scopus, a source-neutral abstract and citation database developed by independent subject matter experts. The Scopus database is considered the largest curated bibliographic abstract and citation database (Baas et al., 2020), and it was selected as the main source of information for this review. Specifically, building on the objectives of this paper, we performed a search query combining the following keywords in Scopus: '*cumulative impact, cumulative effect, marine coastal ecosystem, marine coastal environment, ecosystem service, multi risk, climate change, ecological tipping point*' through appropriate Boolean operators ("AND", "OR", "NOT"). This set of keywords allows to define the scope of the search and, therefore, identify a comprehensive list of relevant applications integrating methodological approaches for cumulative and multi-risk appraisal in MCEs (the query string is detailed in Supplementary Material SM1, whereas Supplementary Material SM5 provides updated definitions (and related References) of the introduced keywords). More precisely, the first part of the query string – *(("cumulative impact*" OR "cumulative effect*") AND ("marine" OR "coastal" AND "ecosystem*" OR "environment"))* - allows to already select all those publications including at least "cumulative impact/effect" keywords and, therefore, also those papers reporting "cumulative impact/effect assessment" keywords. Moreover, as detailed through the research questions included in the Introduction, the final query contains the keyword "multi-risk" (and not "risk-based assessment/approach") since the key objectives of this review is to give specific attention to novel frameworks and tools allowing to explore and model inter-relations among multiple pressures, and the diverse responses of ecosystems to the latter. The resulting list of papers published between the 2000-2022 timeframe (the search was limited to this period because this research topic started getting attention from the early 2000s) and their connected records (e.g., information including title, author and author keywords, affiliations, etc.) were exported as a Bibtex file for a qualitative and quantitative analysis through the Bibliometrix R Package (Aria & Cuccurullo, 2017; Mingers & Leydesdorff, 2015), and subsequently, the systematic literature review (Section 1.3).

## 1.2 Scientometric analysis

The Scientometric analysis explores, evaluates and monitors the state of a particular field of research, meta-analytically evaluating the development of a predefined research area to identify its key components and underlying theoretical frameworks (Geissdoerfer et al., 2017). This quantitative analysis takes advantage of the main metadata related to each paper: citation information (such as the author's name, document title, year, and citation count), bibliographical information (e.g., affiliations, publisher, and editor), abstract and keywords (e.g., the authors' keywords and the index keywords). The information exported from Scopus was processed by applying the open-source *Bibliometrix* Package, designed for the statistical R software (Aria & Cuccurullo, 2017). *Bibliometrix* is a web-based application for bibliometric and co-citation analysis able to achieve comprehensive science mapping analysis of scientific literature (Aria & Cuccurullo, 2017) (http://bibliometrix.org/biblioshiny), thus supporting an overarching understanding and interpretation of network patterns, as well as recognising gaps across research fields.

Building on the workflow shown in Figure 1, a preliminary screening of papers, based on the title's pertinence to the review topic of concern allowed to better focus the bibliometric analysis on a restricted list of relevant papers that were then analytically processed through this R-based tool. In particular, this kind of review allows the identification of major focal topics, trends and gaps, while discovering and visualizing the evolution of the topic through the 2000 – 2022 period (Section 2). All the analysis and graphs (i.e., annual scientific production, top authors' production over time, word-cloud, country collaboration map) are presented and discussed within Supplementary Material SM3.

## 1.3 Systematic literature review - selection of 'key papers'

Following a preliminary identification of major focal topics made through the Scientometric analysis, a systematic literature review was then applied. This review process consists of a rigorous methodological examination of the identified scientific literature (as detailed in Section 1.1), allowing to separate the insignificant, unsound, or redundant publications from the salient and critical ones that are worthy of further investigation (Mulrow, 1994). Specifically, the systematic literature review has been performed based on the PRISMA approach (Moher et al., 2009), consisting of a pyramidal analysis composed of an iterative stepwise process following a predefined checklist that ensures a transparent and complete analysis and reporting from each review phase.

This process reduced the list of papers (692 publications) initially selected through the keywords' query applied in the Scopus database (Section 1.1) through different phases, including i) publications' screening based on the title's pertinence to the topic of concern and review objectives (resulting in selected 254 publications); ii) Screening based on reading the abstracts and methodological sections of publications remaining from the original list (106 documents were selected); iii) Further screening through the reading of the full papers. During this process, 5 papers were removed from the final statistics as they were not in line with the objective of this review. The table with the full list of 101 papers resulting from the review stage 2 is reported in the Supplementary material SM4; iv) Selection of the most relevant publications (30 "key papers") on the topic of concern based on an in-depth reading of the whole papers (including sections devoted to results' analysis and discussion); v) Comparison and discussion of the final list of "key papers" against a set of comparison criteria.

The comparison criteria aim to clarify the main features of the reviewed CIA-related methodological approaches, specifying the: a) case study area, providing details on the scale of the analysis; b) name of the method assigned by authors, together with the specific type of analytical approach applied (e.g., mapping, indicator/index, machine learning, Bayesian network); c) components analysed through the CIA and MRA-related methods, including specification on pressures (with their interactions), exposed environmental targets and vulnerability factors (or indicators) integrated in the study; d) presence/absence of climate change/management scenario analysis; e) ecosystem services component, as a part of CIA/MRA frameworks, including the type of ecosystem service considered (i.e., provisioning, regulation & maintenance, and cultural services); f) integration of the ecological tipping point concept into the CIA/MRA analysis; g) evidence for use of CIA approaches for integrated management of MCEs.

This iterative process (including the selection of specific comparison criteria) was applied under tight cooperation among 14 MaCoBioS (H2020, https://macobios.eu/) partners, jointly collaborating under this review. Participants, covering multifaceted fields of environmental/marine sciences and chemistry, risk assessment, ecological and physical modelling and maritime spatial planning and management, enabled an interdisciplinary knowledge exchange to systematically review selected papers against different perspectives, as well as identify key challenges that need to be addressed in future CIA and MRA frameworks.

More details on the comparison criteria co-selected by MaCoBioS partners are reported in the Supplementary material SM3.

# 2. Results of the review

## 2.1 Characteristics of publication outputs: insights from the Scientometric review

The Scientometric methodological approach, as described in Section 1.1, allowed extracting and processing bibliometric data from the initial set of 692 papers selected as input data by applying the open-source bibliometrix R Package under the 2000-2022 timeframe. Moreover, the same Scientometric analysis was repeated by considering only the 254 papers obtained against the title-screening phase, as implemented under the systematic literature review (Section 1.3). This further evaluation allowed for a more robust review, focusing only on a restricted number of preselected papers, thus avoiding non-significant documents (e.g., reviews papers or publications not focusing on the topic of concern of this review) for the scope of this study (a detailed description of the Scientometric analysis is available within Supplementary Material SM3).

Analysis of annual scientific production (number of papers per year) allowed the recognition of 2008 as a turning point in this particular research field (Figure 2), mostly due to the global-scale study carried out by Halpern et al. (2008). After this relevant CIA application, yearly production displays a positive rising trend overall, although the abrupt increase in 2014 may be associated with the first period of the initial assessment of marine environmental status under the MSFD. Overall, the number of studies applied in MCEs continuously increased during the last decade, with around 60 articles published per year on average during the last 3 years.

Focusing on the most influential authors (Supplementary material SM3), through the analysis of the author's production overtime, the pioneer of these applications, Halpern B.S., also emerged as the most productive author (with an overall number of 23 publications on this topic, under the 2000-2022 timeframe).

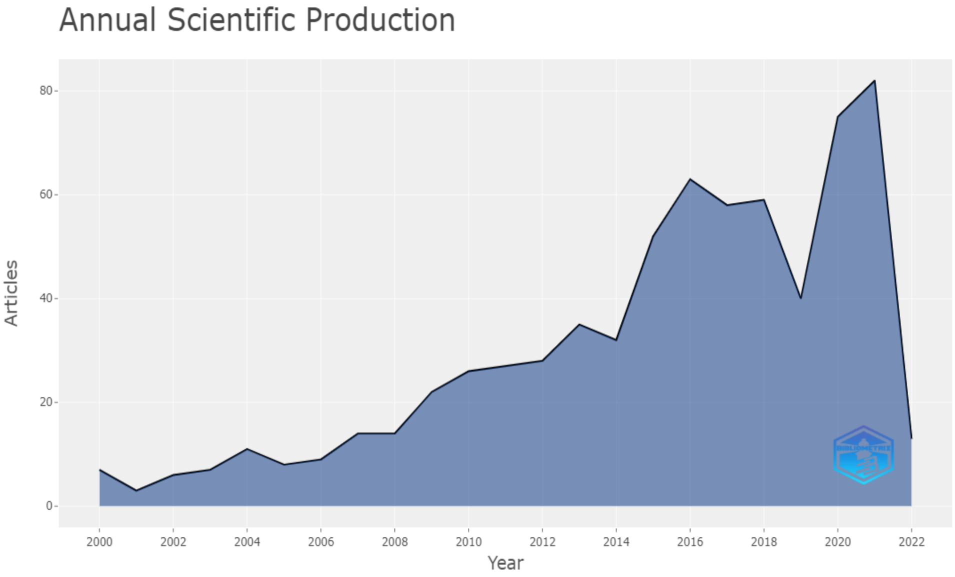

*Figure 2: Number of publications (n=692) applying cumulative impact assessment in marine and coastal ecosystems during the 2000–2022 timeframe*

Further, word cloud analysis of the most frequent 50 author's keywords, together with those contained in the query string, reveals "ecosystem-based management", "marine spatial planning" and "climate change" to be the most frequently used keywords (Supplementary material SM3). This is unsurprising given many CIA methods have been developed to support decision-makers and planners in the design of spatial plans for MCEs management and conservation/restoration under the ecosystem-based management approach (Menegon, Depellegrin, Farella, Sarretta, et al., 2018b), as promoted by the Maritime Spatial Planning (MSP), Marine Strategy Framework Directive and Convention on Biological Diversity regulatory frameworks (Andersen et al., 2015; Domínguez-Tejo et al., 2016; Manea et al., 2020). Recently, climate change threats have also started to be considered across many regulatory frameworks (e.g., MSP), and methodological approaches have recently started integrating this concept to assess and model future environmental conditions of MCEs, and foresee potential alteration of biological, chemical and physical processes (Furlan et al., 2020; Gissi et al., 2019). Finally, analysing scientific collaborations among countries applying CIA methods in MCEs, it was observed that the USA, Canada, UK and China emerged as the first countries approaching this specific topic, with collaborations among countries increasing in the last decade according to the related rise in publications.

## 2.2 Cumulative Impacts Assessment in marine and coastal socio-ecological systems: key output from the systematic literature review

101 articles (as reported in the Supplementary Material SM4) were systematically reviewed by all MaCoBioS partners, focusing on the type of methodological approaches, as well as the main components employed across these methods (e.g., ecosystem services and tipping point evaluation). The following Sections report the resulting output of this review process, comparing CIA applications exploring and modelling the vulnerability and resilience of MCEs under future scenarios, as well as the assessment of ecological tipping points and changes in the ecosystem service flow (Sections 2.2.1-2.2.4). Finally, Section 2.2.5 discusses the integration of CIA approaches, and their results, in the planning and management processes of MCEs (hence, it clarifies the relevance of this review in terms of policy support against key regulatory frameworks, agreements and strategies dealing with MCEs management). 30 selected ‘key papers’, part of this set of publications is reported in Table 1, presenting up-to-date methods and integrating most of the concepts previously reported (e.g., ecosystem services and tipping point evaluation).

*Table 1: Results from the systematic literature review in terms of ‘key papers’ dealing with the application of cumulative impact assessment in marine and coastal ecosystems.*

| Article detail | | CIA conceptual frameworks and methodological approaches | | | Healthy MCEs under a changing climate – Scenario analysis | | Ecosystem Services evaluation | | Tipping point evaluation | Policy support for MCEs management |
|---|---|---|---|---|---|---|---|---|---|---|
| **Authors** | **Location** | **Type of method** | **Components** | **Interactions (Y/N)** | **Y/ N** | **Type of scenario** | **Y/N** | **Considered ES: Provisioning (P), Regulating and Maintenance (R), Culture (C), functioning (F)** | **Considering tipping point Y / N** | **Considering policy (management actions) Y / N** |
| (Jonsson et al., 2021) | Balti Sea | Indicator /index; Mapping | Pressure; Exposure; Sensitivity; Cumulative impact | N | Y | Different MSP scenarios. | N | | N | Y |
| (Furlan et al., 2020) | Adriatic Sea | Bayesian Network | Pressure; Hazard; Vulnerability; Risk; Cumulative impact | Y | Y | 4 “what if” scenarios: i) new MPAs; ii) increasing SST within anthropogenic chemical hazards; rising nutrient input; management measures and adaptation strategies. | N | | N | N |
| (Halpern et al., 2019) | Global | Mapping; Indicator/index | Stressor; Exposure; Vulnerability; Cumulative impact | N | N | | N | | N | N |
| (Furlan et al., 2019) | Adriatic Sea | Mapping; Indicator/index | Hazard; Exposure; Vulnerability; Risk; Pressure; Cumulative impact | Y | Y | Rising temperatures for the 2035-2050 scenario under the RCP 8.5: exogenic variable (SST); endogenic variables (Chl-a variations; chemical and biological impact) | N | | N | N |
| (Stock et al., 2018a) | California Coast | Mapping; Machine Learning; Indicator/index; Statistics | Stressor; Exposure | N | N | | N | | N | N |
| (Muñoz et al., 2018) | Spanish contiguous zone | Indicator/index; Mapping; Modelling; | Driver; Pressure; Sensitivity; Vulnerability; Exposure; Risk | N | Y | Future conflicts among activities (were estimated by applying a conflict matrix) | Y | (P) Nursery area, Habitat. (R) Nursery area maintenance; (F) Resistance; resilience; sensitivity | N | Y |
| (Menegon, et al., 2018b) | North-Adriatic Sea | Mapping; Indicator/index; Ranking; Statistics | Pressure; Exposure; Sensitivity; Risk; Cumulative impact | N | N | | Y | (P) Food provisioning; Raw materials; (R) Air and water quality; disturbance protection; Photosynthesis; Nutrient cycling; Nursery; Biodiversity; (C) Cognitive benefits; Leisure; Feel good/warm glove; | N | N |
| (Menegon, et al., 2018a) | Adriatic Sea | Mapping; Indicator/index; Monte Carlo Simulation | Pressure; Exposure; Sensitivity; Cumulative impact | Y | N | | N | | N | N |
| (Battista et al., 2017) | Karimunjawa (Indonesia); | Indicator/index; Ranking | Stressor; Vulnerability; Exposure; Risk | Y | N | | Y | (R) Coastal protection; Erosion control; Water purification; Maintenance of fisheries and wildlife; Nutrient cycling; Carbon sequestration; Biodiversity; (C) | N | N |

|  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|
|  | Cantilan (Philippines) |  |  |  |  |  |  | Tourism, recreation, education, and research; (F) System recovery potential; connectivity; resistance to impact; functional redundancy and diversity. |  |  |
| (Uusitalo et al., 2016) | Baltic Sea | Bayesian Network; Mapping; Expert-based scoring | Pressure; Exposure; Vulnerability; Cumulative impact | N | Y | 3 scenarios: (1) business-as-usual scenario (current or recent nutrient loading and fishing mortality levels are maintained, but no further restrictions are implemented); (2) a 30% cut in the pressures (nutrient inputs and fishing mortality); (3) 60% cuts in the pressures. | N |  | N | N |
| (Hayes & Landis, 2004) | Point Roberts; Drayton Harbor; Birch and Lummi Bays; Cherry Point | Ranking; Mapping; Monte Carlo Simulation | Stressor; Exposure; Risk; Effect | N | N |  | N |  | N | N |
| (Halpern et al., 2008) | Global | Mapping | Driver; Vulnerability; Exposure; Cumulative impact | N | N |  | N |  | N | N |
| (Singh et al., 2020) | The coast of British Columbia, Canada | Modelling; Mapping; Expert-based scoring; Ranking | Driver; Ecosystem service | N | Y | 3˚C SST increase and 0.3 pH decrease for 2100: exogenic variable (temperature, ocean pH); endogenic variables (oil-spill) | Y | (P) Commercial Demersal/pelagic Fishing; Energy; Finfish/Shellfish aquaculture; (R) Coastal Protection; (C) Coastal Aesthetics and recreation (kayak, boating, camping, dive sites) | N | N |
| (Fu et al., 2020) | British Columbia, Canada | Modelling; | Driver; Pressure; Risk; Cumulative impact; | Y | Y | High & low fish population biomasses; halving fishing mortality rate; doubling plankton biomass and halving marine mammal biomass; Unfavourable (from fish perspective); fishing mortality doubled; halved plankton biomass; and marine mammal biomass doubled. | Y | (P) Total fish biomass of all-trophic-level species; the biomass of higher-trophic-level fish species | Y | Y |
| (Hammar et al., 2020) | Swede | Mapping; Indicator/ index; Expert-based scoring | Pressure; Exposure; Cumulative impact; Sensitivity | N | Y | MSP scenarios 2020-2030: i) MSP proposals developed after extensive stakeholder dialogue; ii) Eco-alternative plans safeguarding ecological functions to achieve GES status; compared to no implemented MSP simple projection from current industry trends; | N |  | N | Y |
| (Turschwell et al., 2020) | Global Mangrove | Bayesian Network; Modelling; Mapping | Driver; Pressure; Impact; State; Response | Y | N |  | N |  | N | Y |
| (Tulloch et al., 2020) | Global | Mapping; Indicator/ index | Stressor; Exposure; Vulnerability; Cumulative impact | N | Y |  | N |  | N | Y |
| (Fang et al., 2020) | Xincun Lagoon, Hainan, (China) | Indicator/ index; Mapping; Modelling | Activity; Pressure; Vulnerability; Cumulative Impact | Y | Y | Different vulnerability (μ value) from mangroves, seagrass beds and other areas | N |  | N | Y |
| (Hansen & Bonnevie, 2020) | Baltic Sea | Mapping; Indicator/index | Pressure; Exposure; sensitivity; Cumulative impact | Y | Y | Scenarios where ecosystems might become endangered, areas where competition/ conflict might arise, and areas where synergies might cause potential for co-location | N |  | N | Y |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| (Stock et al., 2018) | Global ocean | Modelling; Monte Carlo uncertainty analysis | Stressor | N | N | | N | | Y | |
| (Corrales et al., 2018) | Israeli Med. continental shelf | Modelling; Monte Carlo uncertainty analysis | Pressure; Cumulative impact | Y | Y | 2010-2060. Warming - RCP2.6 (Scn5), RCP4.5 (Scn6) and RCP8.5 (Scn7); Endogenic: Fishing effort - Kept at 2010 levels or New Israeli regulations; Trophic groups biomass; Alien species: biomass Forced or not | | (P) Total biomass; Forage fish/ Invertebrate/ Predatory biomass; Kempton's index; Total catch; (F) Mean Trophic Level of the catch; and of the community; Total System Throughput; Finn's Cycling Index; Path length | Y | Y |
| (Weijerman et al., 2018) | Maui Nui (an islands complex), Hawai'i | Modelling; Mapping | Hazard; Exposure; State; Cumulative Impact | Y | Y | RCP 8.5 with High/low sediment mitigation; existence adding random MPAs; high/low bleaching events | Y | (P) Fisheries production (potential provisioning service); (R) State of the reef; Trophic integrity of the reef (supporting service) | N | Y |
| (Ihde & Townsend, 2017) | Chesapeake Bay (USA) | Modelling; Indicator/index | Stressor; Exposure | Y | Y | 50-year projections: a 1.5 ◦C increase in water temperature, removal of 50% of Marsh biomass), removal of 50% of SAV biomass, a 25% reduction in nitrogen and a 20% reduction in sediment inputs | Y | (F) Modelisation of change of 3 species important for fisheries in the area | N | Y |
| (Clark et al., 2016) | Tauranga Harbour estuary (New Zealand) | Mapping; Indicator/index; Expert judgment | Stressor; Vulnerability; Exposure; Cumulative impact | N | N | | N | | N | N |
| (Teichert et al., 2016) | North-East Atlantic | Statistical analyses; Machine Learning | Stressor; State | Y | N | Simulation of Ecological quality ratio (EQR) restoration benefits | N | | Y | Y |
| (Lasram et al., 2016) | Tunisia's EEZ | Mapping; Indicator/index; Expert-based ranking | Threats; Pressure; Exposure; Vulnerability; Cumulative impact | N | N | | Y | (F) Functional biodiversity | N | Y |
| (Marzloff et al., 2016) | South-eastern Australia | Modelling | Impact; Exposure; State | Y | Y | Qualitative predictions under alternative scenarios about species poleward redistributions and/or management interventions. Exogenic variables: range shifts, species relocation | N | | N | Y |
| (Clarke Murray et al., 2015) | Marine waters of British Columbia (Canada) | Mapping; Indicator/index | Stressor; Vulnerability; Exposure; Cumulative impact | N | Y | Four scenarios: (1) Current, (2) Climate change, (3) Planned developments, and (4) Combined Current + Climate + Planned. | N | | N | N |
| (Harris et al., 2015) | South Africa | Mapping; Indicator/index | Threats | N | N | | N | | Y | N |
| (Okey et al., 2015) | Canada's Pacific marine areas | Mapping; Expert-based scoring | Pressure; Vulnerability; Exposure; Sensitivity; Impact | Y | N | | N | | N | N |

### 2.2.1 Conceptual frameworks and methodological approaches

The multiplicity of risk-based and CIA approaches applied by the research community to evaluate the effects of human activities (such as fishing, seabed extraction, transport, etc.) and climate change on MCEs (as detailed in the Supplementary Material SM4) is remarkable. GIS-based mapping, indicator/index (through the integration of several indicators representing pressures and the presence and state of MCEs), numerical and ecological models, Machine Learning (ML), or expert-based ranking, are some of the most applied methods to analyse and modelling environmental impacts from local to global stressors, while providing support for sustainable management and adaptation pathways.

As summarised in Figure 3, most of the analysed approaches build on the methodological framework developed by Halpern et al. (2008), mapping the spatial distribution and intensity of human activities, at the global scale, over several ecological components and ecosystems (e.g., coral reefs, seagrass beds, mangroves, rocky reefs). Specifically, in this reference approach, final predicted cumulative impact scores are calculated by multiplying the normalised value of pressures' intensity with expert-based weights, representing each ecosystem type's sensitivity to these pressures. Similarly, always drawing on the Halpern et al. (2008) study, most of the reviewed applications (55 out of 101 relevant papers – as reported in the Supplementary material SM3) build on an indicator/index-based approach (Bonnevie et al., 2020; Halpern et al., 2019), sometimes integrated into ML-based methods (Furlan et al., 2020; A. Stock et al., 2018b; Teichert et al., 2016; Turschwell et al., 2020). The wide application of both mapping and indicator/index-based methodologies is also due to the requirements posed by both the EU and international regulatory frameworks (e.g., MSFD and MSP directives, UNCLOS), which require analysing and locating human activities and their drivers to reduce spatial conflicts and trade-off among multiple uses, while supporting the sustainable use and conservation of marine coastal resources. Expert-based ranking (28 publications out of the selected 101 relevant papers – as reported in Supplementary material SM4) is also frequently applied for several purposes, including i) to consider experts' perception in the evaluation of the risk linked to human and climate-induced impacts (Armstrong et al., 2019; Brodersen et al., 2018)); ii) to estimate ecological vulnerabilities to pressures (Clark et al., 2016; A. R. Jones et al., 2018; Mach et al., 2017; Singh et al., 2017; Uusitalo et al., 2016b); and iii) to analyse interactions among multiple pressures (Cook et al., 2014; Furlan et al., 2019). On the other hand, differently from these studies mainly based on expert judgments, a step-wise risk-based approach is proposed by Piet et al. (2021) for a fully quantitative CIA integrating information for different sectoral human activities, pressures and ecosystem components.

Within CIA approaches, quite a large set of applications are also carried out using ecological (Cornwall & Eddy, 2015; Ihde & Townsend, 2017) and conceptual models (Cook et al., 2014) to evaluate cumulative impacts of human activity at the ecosystem level. Among these, Cornwall & Eddy (2015) applied Ecopath with Ecosim (EwE) ecological/ecosystem model, a food web model that considers energy flows between functional groups of species. Similarly, Fu et al. (2020) evaluated how stressors cumulatively affect modelled species using the *Object-oriented Simulator of Marine Ecosystems* (OSMOSE) model. Finally, ML-based methods emerging among methodologies being applied across marine coastal realms, thanks to the recent increase in data availability for environmental monitoring and management (i.e., 'Big data'[1]). In this context, Stock et al. (2018) compared the predictive performance of ten statistical and ML algorithms (e.g., Classification and Regression Trees, Random Forests and Boosted regression trees) to understand whether these models could make accurate predictions of ecological indicators representing MCEs' condition (i.e., kelp biodiversity, fish biomass, and rocky intertidal biodiversity) of California coast. Similarly, Teichert et al. (2016) operationalised a Random Forest model to explore the complex structure of non-linear inter-relations between multiple stressors (both anthropogenic and climate change), and the ecological response of biological systems to these stressors. In particular, this model has been used to investigate the effect of stressors interactions on fish ecological status in European estuaries, as well as to evaluate the ecological benefits arising from the implementation of restoration actions.

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[1] Big data, defined as '*high volume, high velocity, and/or high variety data that require new processing paradigms to enable insight discovery, improved decision making, and process optimisation*' (Beyer and Laney, 2012)

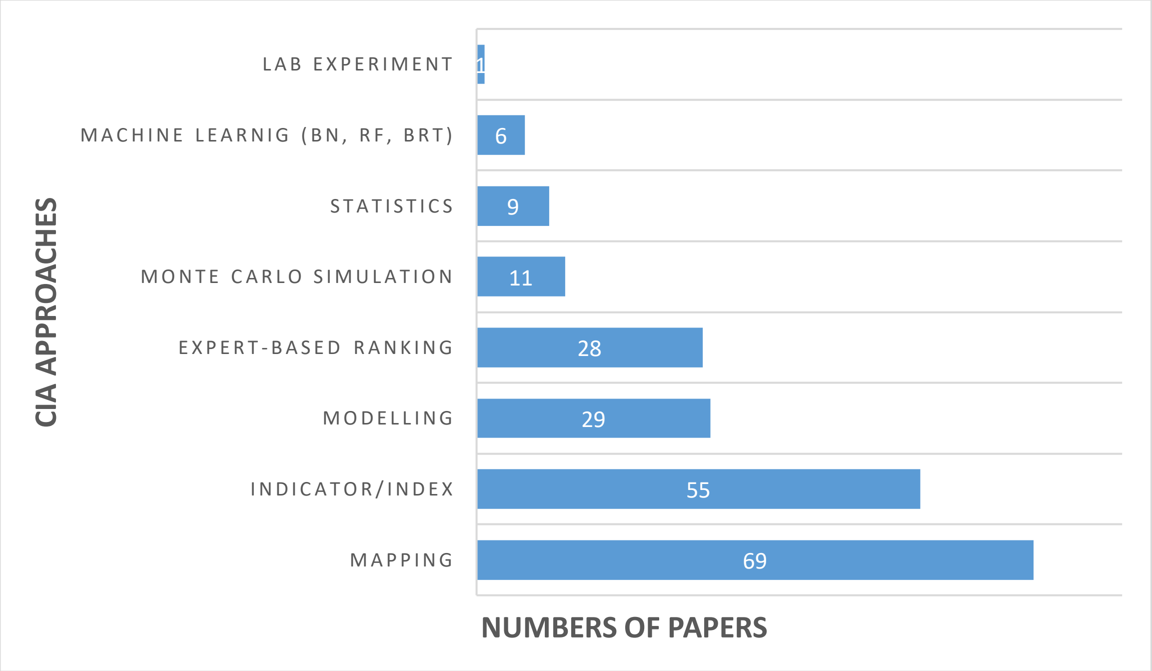

*Figure 3: Summary of risk-based and cumulative impact assessment approaches and tools applied within the selected 101 relevant papers.*

Another ML-based application was developed by Furlan et al. (2020), coupling Bayesian Network approaches (BN[2]) with a GIS tool, to evaluate cumulative impacts under different idealised scenarios. In this study, BNs allowed the consideration of multiple variables (e.g., stressors, assessment end-points) and types of data (e.g., quantitative and qualitative) from heterogeneous data sources and disciplines (e.g., probabilistic quantities elicited from expert knowledge, empirical data, mathematical representations) within the same analytical framework.

Across these studies, some authors also integrate statistics and mathematical techniques to better detect uncertainties associated with several factors (e.g., incomplete and inaccurate data availability, linearity, aggregation of different factors, etc.), providing more robust analysis and, in turn, reducing the possibility of unsustainable management decisions. For instance, Piet et al. (2021) carried out a confidence assessment, providing an overview of the quality and adequacy of the available data and information underpinning CIA application. In particular, this assessment was based on a hierarchy confidence classification, structured with

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[2] Bayesian Network: a family of ML-based algorithms providing an intuitive graphical structure by combining principles of Graph theory and Probability theory; (Pearl & Russell, 2011; Pollino et al., 2007)

different levels and criteria applied to different methodological aspects (e.g., data processing, spatio-temporal resolution and coverage, etc.), and elements integrated in each phase i.e., activities, pressure and ecosystem component, including their relations.  Whereas, Stock et al. (2018) implemented uncertainty analysis, using Monte Carlo simulations, to identify robust high- and low-impact areas on the global oceans (considering the effects of 7 factors of uncertainties simultaneously, including their interactions). Similarly, using Monte Carlo simulations with 1000 runs, Andersen et al. (2020) evaluated the robustness of the impact index and stressor ranking for Danish marine waters, considering the possible weaknesses in data quality and the effects of model assumptions. More precisely, they ranked 35 stressors according to their contribution to the cumulative impact score, aggregated for the North Sea-Baltic Sea transition zone. This methodology, i.e., identifying and ranking the most influential stressors contributing to the overall cumulative impacts, provides useful information to support the identification of conservation priorities, as required by marine coastal laws.

Regardless of the applied methodological approach, the operationalisation of risk-based and CIA methodologies requires a strong linkage between all components and processes underpinning impacts and changes in MCEs’ state and ecosystem services flow. Specifically, looking at the key elements integrated into CIA methodologies, the review has identified different and fragmented components (better described in the Supplementary Material SM5) across the publications (as illustrated in Figure 4). This is due to the specific terminologies applied by different research communities (e.g., risk, ecology, chemistry-related communities), making it difficult to identify mainstream components. Still, most of the key components considered overall are in line with those integrated by Halpern et al. (2008) in his index, as a direct consequence of the methodological framework applied, i.e., the predicted cumulative impact scores are calculated as a function of the intensity of the selected “drivers”, the presence/absence of marine ecosystems (“exposure”) and their “vulnerability” to pressures. Exposure and vulnerability are among the most cited concepts being integrated across different methodological approaches for CIA applying risk-based frameworks (IPCC, 2014). Among the risk-based studies, Piet et al. (2021) introduced the concept of “risk of impact” as assessment endpoint of their step-wise approach. Finally, another set of terminologies, such as “state” and “response”, is linked to the other conceptual framework of greatest interest for CIA and risk assessment works, i.e., the DPSIR (Driver-Pressures-State-Impact-Response) framework (EEA, 1999), together with its more recent modifications (e.g., DPSWIR, Driving Force-Pressure-State-Impact-Well-being-Response; (Cooper, 2013)). In general, these terminologies, and especially those representing triggering factors (i.e., variables that explain the occurrence of the analysed phenomena/effect), are often applied by authors for explaining the same (or similar) concepts (e.g., pressure, driver, stressor, and threat). This amplifies the redundancy of components integrated into the same analytical method, and creates general confusion and misunderstandings due to the different use of the same terminologies (see 3. Discussion for further details).

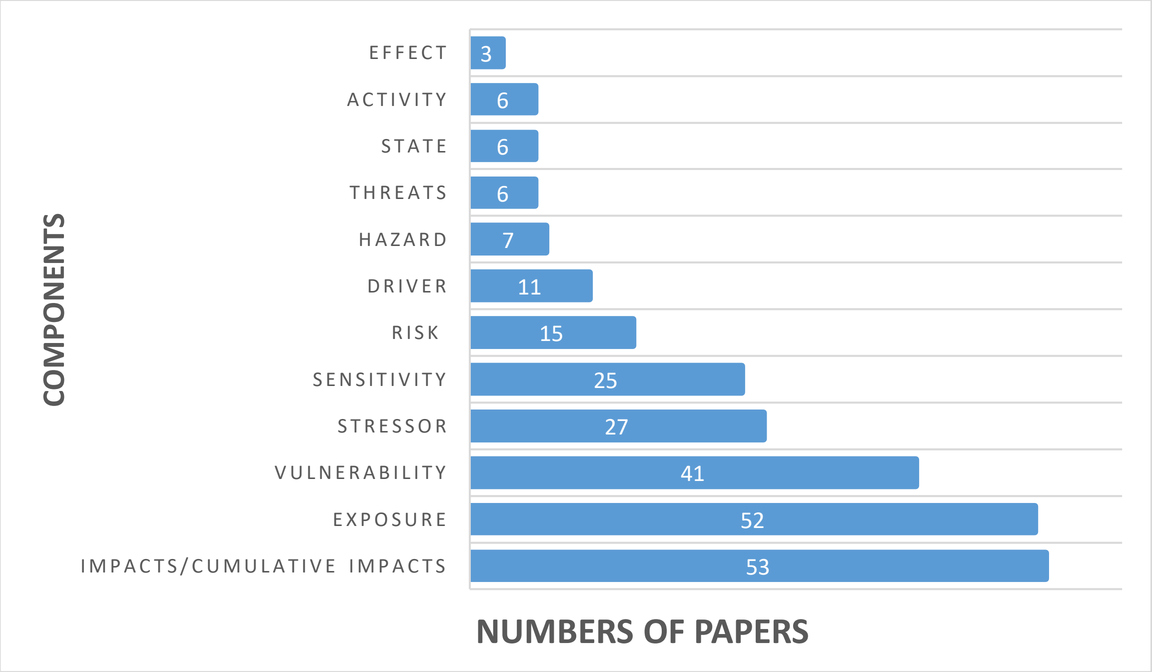

*Figure 4: Summary of key components applied within cumulative impact assessment and risk-based methodological frameworks in the 101 selected papers*

### 2.2.2 Scenario analysis for healthy marine and coastal ecosystems

Exploring changes in cumulative impacts against different climate conditions before they happen can be a crucial task to provide support to policy makers and planners involved in the design of sustainable marine spatial plans and climate adaptation strategies (Corrales et al., 2018; Furlan et al., 2019; Jonsson et al., 2021;

Magris et al., 2021). Consequently, researchers have begun applying different tools (e.g., Bayesian network models) integrating scenario analysis into CIA-related studies to understand ecosystems' responses to a changing future. The majority of CIA methodologies applied across the 101 selected papers (see the full list in Supplementary material SM4) focus on a snapshot in time based on recent/current conditions. Only 23 papers evaluated changes in cumulative impacts against different climate or management scenarios.

Within these 23 papers, it is possible to identify two main research streams: i) studies exploring variations in cumulative impacts against different climate scenarios (e.g. temperature variation) usually based on projections from numerical models (IPCC, 2014); ii) applications integrating "what if" scenarios (i.e. idealised scenarios based on narratives) to evaluate cumulative impacts changes under the effects of different environmental patterns and socio-economic pathways (e.g., simulating the potential consequences of different management measures).

Focusing on the first research stream, only 4 studies referred to the IPCC[3] Representative Concentration Pathways (RCP) describing four different 21st-century GHG emissions trajectories (i.e., RCP2.6, RCP4.5, RCP6, and RCP8.5), based on a possible range of raising radiative forcing pathways (IPCC, 2014). Among these, Otto et al. (2020) focused on the intermediate GHG emission scenarios (i.e., RCP4.5 and RCP6), whereas Furlan et al. (2019) and Weijerman et al. (2018) on the worst one (i.e., RCP8.5). Corrales et al. (2018) tested the impact of a continued increase in sea temperatures on the Israeli Mediterranean continental shelf over 50 years (2010 - 2060), taking into account three GHG emission scenarios (i.e., RCP 2.6, 4.5, and 8.5). Moreover, future scenarios accounting for a new set of fishing regulations currently being implemented, and a continued increase in alien species biomass were tested to assess potential futures of marine resources and ecosystem conditions within the analysed case study area. As described in Section 3.2.4., the resulting output of this analysis showed collapsed conditions for different species (a sign of potential tipping points) according to the investigated scenarios.

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[3] Intergovernmental Panel on Climate Change

Of those publications exploring “what-if” scenarios, most evaluated potential changes in cumulative impacts under the implementation of several management measures (as already tested in Corrales et al., 2018) to compare the expected environmental effects of different plan alternatives. For instance, Stelzenmüller et al. (2010) operationalised a Bayesian Belief Network–GIS framework to evaluate cumulative impacts under three different spatial planning objectives and related solutions (e.g., relocation of fishing pressure). Similarly, Hammar et al. (2020) evaluated the environmental effects of two different set of idealized MSP scenarios for 2030, namely (i) negotiated plans (i.e., MSP proposals developed after extensive stakeholder dialogue) and (ii) eco-alternative plans (i.e., a scenario more in accordance with the target posed by MSFD 2008/56/EC). The comparison between a Business As Usual scenario and different planning options (and scenarios) detected some alterations in the final cumulative impact score, making it possible to evaluate how these impacts could be amplified or reduced under different management measures. With a focus on the Hawaiian Islands of Maui, Molokai, and Lānaʻi, Weijerman et al. (2018) developed fifteen scenarios, combining different settings in land- and marine-based management and climate-related stressors (under the RCP8.5), to better understand future variation in the coral reef ecosystem services provision. Similarly, Furlan et al. (2020) applied a GIS-based Bayesian network approach to evaluate the probability of cumulative impacts under four *“what-if”* scenarios representing different marine management options (i.e., how impacts change due to the establishment of new MPAs) and climate conditions (i.e., potential rising sea temperature) envisioned for the Adriatic Sea. The results of the simulated scenarios provided some insights on the management programs/measures required to achieve Good Environmental Status targets, as required under relevant EU legislation (e.g., an integrated approach in MSP emerged as the most effective way to substantially reduce cumulative impacts on the Adriatic Sea).

Finally, looking at the overall picture of papers applying scenario analysis, a wide range of both endogenic (i.e., managed pressures or those emanating within the system) and exogenic pressures (i.e., unmanaged pressures are those emanating from outside the system) have been investigated by authors under the simulation of future changes. S*ea surface temperature* emerged as the most considered exogenic variable (Furlan et al., 2019; Ihde & Townsend, 2017; Singh et al., 2020b), followed by *precipitation* (Uusitalo et al., 2016), *ocean acidification* (Ainsworth et al., 2011; Fulton et al., 2009; Singh et al., 2020b), and *salinity* (Otto et al., 2020). A wide range of endogenic variables representing biological disturbance (e.g., shipping traffic as the main vector of non-indigenous species introduction; Fu et al., 2020; Weijerman et al., 2018) and chemical pollution (e.g., oil-spill, eutrophication; Fulton et al., 2009; Furlan et al., 2020; Singh et al., 2020b) have been integrated into CIA-related scenario analysis to simulate how changes in their range can contribute to increase the vulnerability of MCEs.

### 2.2.3 Incorporating the ecosystem services perspective into CIA frameworks

Ecosystem services are the benefits people obtain from ecosystems and are essential to people's well-being (MA, 2005). The magnitude and sustainability of the use of these services depend on the functioning of the ecosystem. Changes to ecosystem conditions or ecosystem processes such as the ones that generally result from cumulative impacts will naturally lead to changes in the capacity to deliver ecosystem services, although human culture and ingenuity may buffer adverse effects for a limited amount of time. Therefore, CIA of various human activities and stressors on ecosystem services is crucial to understand supply (i.e., biophysical means) and service (i.e., delivery to people) provision.

CIA methodological approaches generally evaluate how human activities affect species and habitats, neglecting how multiple activities affect the capacity of the whole ecosystem to provide direct and indirect benefits to human well-being (Depellegrin et al., 2017; Singh et al., 2020b). This is even more true in the marine environment. Indeed, less than a quarter of the reviewed articles (n=21) incorporate the ecosystem services perspective. Since the term 'ecosystem services' is relatively new, increasing in popularity since the Millennium Ecosystem Assessment (MA, 2005), the integration of ecosystem services into the CIA framework only started with one of the most straightforward marine ecosystem services, i.e., fisheries yield, in 2007 (e.g., Sutherland et al., 2007). It was only in 2014 that a bundle of ecosystem services (provisioning, regulating and maintenance, and cultural – considering the Common International Classification of Ecosystem Services classification or 'CICES' v5.1, Haines-Young & Potschin-Young, (2018)) were included in a CIA framework by

Cook et al. (2014). However, the trend has changed over the past few years. Based on the frequency of marine ecosystem services considered in the investigated studies under the three above-mentioned ES categories, '*regulating and maintenance*' resulted as the most analysed marine ecosystem services category (i.e., 50%), followed by provisioning and cultural services, respectively (Figure 5).

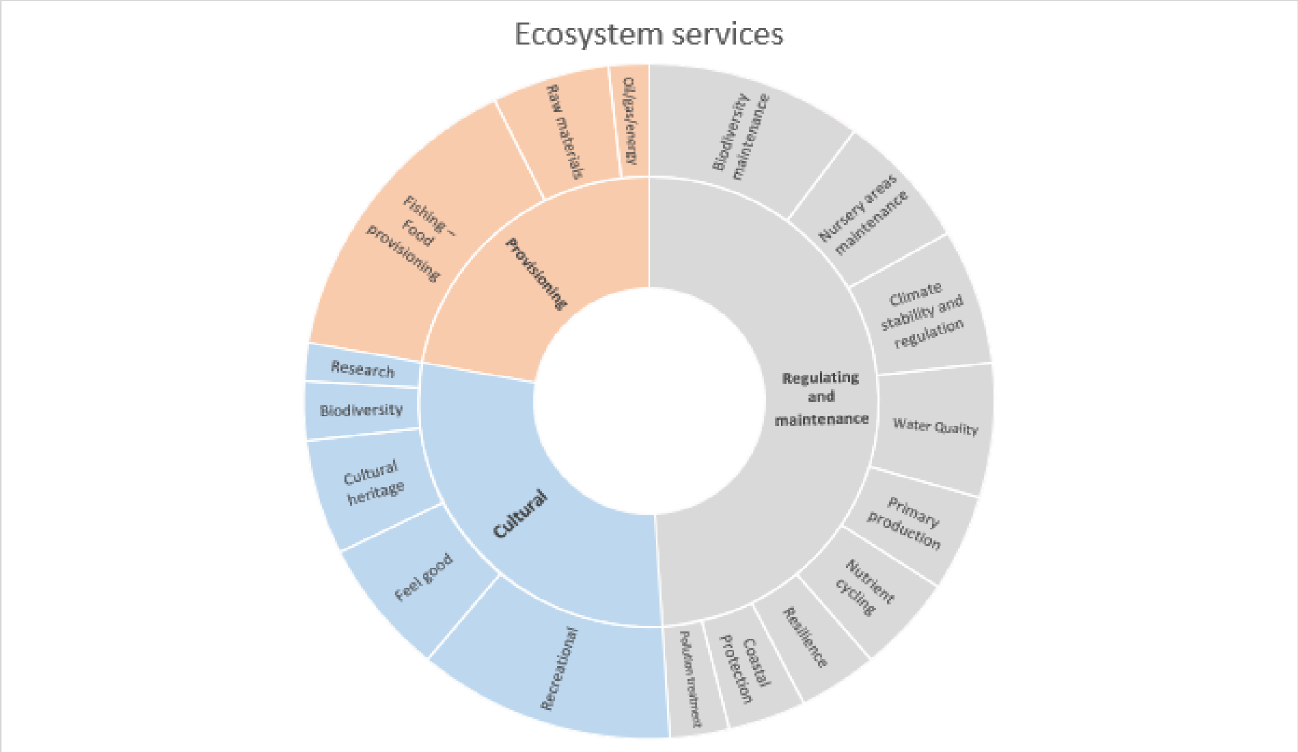

*Figure 5: Marine ecosystem services frequency applied for integrating and modelling ecosystem services within cumulative impact assessment methodologies in the marine environment. The nineteen marine ecosystem services extracted from the reviewed publications were divided according to the CICES v5.1* (Haines-Young & Potschin-Young, 2018)

The assessment method of ecosystem functions and services, varies greatly from subjective evaluation to expert judgement to quantitative assessments; however, most are qualitative or semi-quantitative at best, considering that data availability is often a problem. Therefore, most recent methods based their appraisal on expert judgement, considering that areas covered by determined EUNIS habitat may contribute to enrich the ecosystem services capacity of MCEs (Depellegrin et al., 2017; Farella et al., 2020; Menegon et al., 2018b). The spatial coverage of data available for relevant stressors may also limit the inclusion of stressors that are likely to have a significant impact on a studied MCE. For example, Allan et al. (2013) were able to include 34 of 50 anthropogenic stressors identified. Although including 34 anthropogenic stressors is already a great achievement, having to put aside 16 of them is concerning. They also focused on the spatial distribution of the stressors and not on the distribution of their impacts because assessment of impacts of stressors at the ecosystem level was not feasible. Another challenge for CIA is the type of relationship between stressors and impacts. Generally, only linear responses are considered, probably due to a lack of data. Thus, twice as much stressor is assumed to double the impact. Additionally, interactions between stressors are mostly not assessed or, at best, assumed to be additive. To summarise, there appears to be a significant lack of knowledge with respect to the impacts of and interactions between multiple stressors acting simultaneously within an ecosystem.

In addition, stressor and condition maps usually consider only one snapshot in time. However, the policy question is not only about the presence or absence of a stressor or habitat, but about the changes in the pressure, state, and, more importantly, the benefits to people such as fishing, recreation, or coastal protection that may be more meaningful to decision-makers and the public (Bockstael et al., 2000; Yee et al., 2014). This is where scenario analysis is useful to identify the best actions that will reverse, mitigate, or prevent ecosystem degradation and sustain benefit to society. Few studies applied scenario analysis whilst accounting for ecosystem services into a CIA framework. Weijerman et al. (2018) used a spatially-explicit biophysical ecosystem model – the Hawai'i Reef dynamics Simulator (HIReefSim) based on the Coral Reef Scenario Evaluation Tool (CORSET) – to evaluate socio-ecological trade-offs of land-based vs. marine-based management scenarios, and local- vs. global-scale stressors and their cumulative impacts on coral reefs. Fu et al. (2020) used an individual-based spatially explicit ecosystem modelling platform OSMOSE (Object-oriented Simulator of Marine Ecosystems) to investigate the cumulative effects of fishing, plankton biomass change, and marine mammal consumption on the dynamics of some commercially important fish species and the whole British Columbia marine ecosystem. The authors calibrated the model based on data acquired from 1940 to 2018 and applied scenario simulations for the past 20 years (1998-2018). Recently, Corrales et al. (2018) used the Ecosim foodweb model and analysed future scenarios (2010-2060) considering multiple pressures. The authors provided robust modelling that takes interactions between pressures into account. While Ecopath with Ecosim (EwE) has been widely used since its first use in 1984 (Polovina, 1984), it requires the collection, compilation and harmonisation of various types of information (Colléter et al., 2015), which might be difficult in data-poor regions. Where data are lacking then, the Comprehensive Assessment of Risk to Ecosystems (CARE) model, developed by Battista et al. (2017), allows the cumulative impact of multiple stressors and interactions that may result in synergistic or antagonistic impacts, on whole-ecosystem productivity, functioning, and ecosystem services.

From all the above results, the incorporation of marine ecosystem services into a CIA approach has been increasing and allows not only to analyse conflicts between cumulative pressures of human activities and marine habitats but also to reveal conflicts and synergies among uses and services, thereby providing meaningful support to decision- and policy makers for MSP (Hansen & Bonnevie, 2020; Muñoz et al., 2018). As such, many software (e.g., InVEST, CORSET, HIReefSim, and Ecosim, EwE) and models (e.g., CARE, marine ecosystem services -Threat, and marine ecosystem services -Capacity) have been developed as Decision-Support Tools. However, methodological approaches published within the investigated timeframe (2000-2022) rarely considered all the three marine ecosystem services categories, and instead focused on single ecosystem services, such as carbon sequestration provided by the seagrass species *Posidonia oceanica* (Gkadolou et al., 2018) or the potential provisioning of fish according to the condition of coral reefs (Weijerman et al., 2018). Yet, looking at a single ecosystem service in a CIA framework could misguide decision-makers. Moreover, across the analysed papers, the ecosystem services component has been integrated into the different CIA frameworks as an additional assessment endpoint without considering the potential influence of specific ecosystem services in reducing/mitigating the effect of both endogenic and exogenic pressures while increasing the resilience of MCEs to further perturbations. Much research is still needed to understand those positive/negative feedbacks between anthropogenic and climate-related pressures, the ecological condition of marine habitats and ecosystem services.

### 2.2.4 When cumulative impacts lead to ecological tipping points

Resilience represents an insurance against potentially adverse changes in the performance of ecosystem functions – and ultimately on the delivery of ecosystem services. Thus, the concepts of ecological resilience in relations to ecosystems services should be intertwined into CIA & risk assessment frameworks, offering insurance against the loss of valued functions (Folke et al., 2004; Thrush et al., 2009). The assessment of resilience, or loss of resilience, of a system subjected to cumulative pressures and risk scenarios requires metrics that forewarn approaching thresholds of change well in advance so that actions can be implemented (de Juan et al., 2018). However, key knowledge gaps remain in terms of defining exactly how close a system is to a threshold of change and what the research community can actually measure in natural ecosystems to better understand resilience and advert of drastic change (de Juan et al., 2013). Van Nes et al. (2016) proposed that the term 'tipping point' should simply be used for any situation where accelerating change caused by positive feedback (although they propose no value is assigned, only a sign) drives the system to a new state. Then, the management of cumulative impacts needs to uptake the information on how close a system is to a tipping point (Thrush et al., 2021), and incorporate this concept into MRA frameworks.

The systematic literature review exposed the slow uptake of ecosystem metrics informing the risk of approaching a tipping point under a MRA framework. Six publications mentioned the topic (i.e., tipping point, threshold, shifting baseline concepts); however, none of these actually implemented or proposed an approach that encompassed the tipping points assessment. Among these, as already mentioned in Section 2.2.1, Fu et al. (2020) applied an ecosystem model (OSMOSE) focused on a set of commercial fish species and their (predatory-prey) interaction with other species. They assessed two temporal scenarios (a favourable and un-favourable one) considering fishing drivers (fishing, change in plankton biomass and change in mammal biomass) in a cumulative fashion (synergistic, antagonistic, etc.), and then evaluated consequences on the commercial species biomass. Therefore, this study takes an ecosystem approach by considering the cumulative effects of three drivers (i.e., fishing, change in plankton and mammal biomasses) and assesses temporal changes in commercial fish biomass (ecosystem service provision) against each scenario;

nevertheless, the OSMOSE model is basically focused on fishery activities, so it fails to adopt an integrative cumulative impact perspective inherent to a CIA. On the other hand, due to the huge amount of data required to represent the trophic interactions and life-history dynamics of the species of interest, this approach does not specifically address tipping points. Similarly, Stock et al. (2018) explored impact maps taking into account cumulative (non-linear) effects, highlighting the need to incorporate uncertainty appraisal into MRA frameworks (considering as baseline Halpern et al., 2008), as there is high uncertainty in evaluating interactive behaviours of multiple stressors over ecosystems. In this work, the authors run 3000 simulations for cumulative human impact maps to identify the frequency of selection of different cells in the "vulnerability" categories. The resulting outputs showed a relatively high standard error in the assignations. They discussed "thresholds" but only related to the robustness of the model vulnerability level assignation. Finally, among the selected papers, Corrales et al., (2018) investigated future changes in marine resources by applying an ECOSIM model. They tested the effects of new fishing regulations with predictions on invasive species under IPCC scenarios (RCPs 2.6, 4.5 and 8.5), addressing the effects of stressors both separately and in a cumulative fashion. They addressed the effects of stressors separately but also in a cumulative way, exploring temporal changes in the predicted biomass of fish species. Even though they did not specifically explore thresholds of change, these thresholds could be approximated from the predicted biomass curves.

Other studies, selected in the Scopus search but discarded after applying the selection criteria (basically because these papers address an ecological problem – regime shifts – but do not incorporate the problem into management) were successful in identifying environmental limits or ecosystem tipping points. However, these studies have in common the availability of long temporal series (some starting in the 1950s) of very large gradient experiments. Both scenarios are not feasible for an operational assessment protocol as they are limited to highly rich data case studies. Among these, Oguz & Gilbert (2007) analysed long-term data (1960-2007) of the pelagic system in the Black Sea to detect regime shifts under fishery exploitation and nutrient enrichment scenarios. Similarly, other long temporal series (starting in the 1950s) have been detected by Miller et al. (2016) to explore the causes of anguillid eel populations' decline under cumulative stressors (damp construction, overfishing, pollution, etc) and by Wang et al., (2015) to address threshold of change in estuary systems. Other studies detected regime shifts of marine rockpool communities in a mesocosm experiment (White et al., 2018), changes in Cystoseira populations linked to increased anthropogenic pressures in the northwest Mediterranean (Blanfuné et al., 2019) and environmental limits for the communities (regarding sedimentation and nutrient input) through a large-scale experiment (experimental impact conditions in 15 estuaries) (Thrush et al., 2021).

To our knowledge, there is no published study that effectively incorporates the assessment of ecosystem thresholds of change or tipping points into CIA-MRA frameworks. Despite the importance of identifying approaching thresholds in ecological science, the complexity of empirically defining threshold levels for multiple interacting stressors (Thrush et al., 2014) hampers the selection of metrics that can be systematically incorporated into regular ecosystem assessments. In order to manage ecosystems to avoid the loss of functions (and therefore services), CIA and MRA frameworks need to understand (and embrace) the mechanism linking stressors to ecosystem consequences – with special attention on tipping points (Hodgson & Halpern, 2019; Stelzenmüller et al., 2020). After all, one of the main objectives is to avoid reaching regime shifts, or thresholds of change, where ecological and societal values are gradually degraded until the properties of ecosystems are no longer recognised.

### 2.2.5 Policy support for risk management and climate adaptation in marine and coastal socio-ecological systems

There is increasing recognition of CIA methods' relevance in supporting policy and management of MCEs. CIA can theoretically support policy and management in several ways. First, by providing a spatial perspective on the major pressures and threats which impact a specific area over time, CIA may improve the capacity of decision-makers to prioritise appropriate management strategies, such as marine spatial planning, protected area establishment, restoration, etc. (e.g.,  Jones et al., 2018; Tulloch et al., 2020). Second, by evaluating overtime how CIA changes according to variations of data on multiple pressures (e.g., temperature, nutrient input, etc.) (Furlan et al., 2020), CIA may support the assessment of the effectiveness of different strategies and drive future research and effective ecosystem-based management (Marzloff et al., 2016). By incorporating scenario methodologies, CIA could support long term planning by showing how different strategies could improve the provision of marine ecosystem services (e.g., using scenario methodologies) (Farella et al., 2020; Weijerman et al., 2018). Lastly, CIA may increase transparency in planning decisions. CIA also enables policy makers to better balance the benefits and consequences of marine coastal plans and policies prior to implementation (Hammar et al., 2020). Moreover, it can be used as a tool to support policy makers to communicate scientific evidence (for instance through maps) on which management strategies and decisions are based, thus providing a larger degree of transparency before and during stakeholder consultations (McQuatters-Gollop et al., 2019).

Despite the potential holistic application of CIA methods in policy and management, the current review reveals that most of the literature concerning CIA in coastal and marine ecosystems do not consider policy or management actions. Of the 101 papers reviewed, the majority (about 70%) do not consider policy or management actions, while only 30% mention this.

Out of the 30% of studies that consider policy and management actions, most of those evaluating the environmental status of the European seas refer to the MSFD (2008/56/EC) as a relevant policy and MSP as a process of analysing and allocating the spatial and temporal distribution of anthropogenic activities (Brodersen et al., 2018; Fernandes et al., 2017; Gkadolou et al., 2018; Hammar et al., 2020; Hansen & Bonnevie, 2020; Jonsson et al., 2021; Korpinen et al., 2021; Manea et al., 2020; Willsteed et al., 2018). Similarly, authors that operationalised these assessment frameworks in other marine coastal areas worldwide (e.g., Xiamen and British Columbia, respectively in China and Canada), referred to other national/local policies. For instance, Ihde & Townsend, (2017) developed scenarios considering both reductions in Nitrogen and sediments inputs to reflect the nutrient and sediment goals required under the US EPA specifications for the Total Maximum Daily Load Regulations (USA EPA, 2010). On the other hand, Xue et al. (2004) presented the assessment of cumulative environmental impacts and the implementation of integrated coastal management (implemented as part of the Regional Programme for the Prevention and

Management of Marine Pollution in the East Asian Seas) within the harbour of Xiamen, China. In this study, authors combined policy and planning, including legislative and enforcement mechanisms, with scientific knowledge support.

The literature review also reveals a lack of empirical evidence on how or if CIA methodologies or approaches have influenced management processes of MCEs. The reviewed papers mainly highlight the theoretical contributions of CIAs to guide policies and decision making for the management of MCEs, while a few engaged with providing nuance on interventions based on the CIA application. For example, Hammar et al. (2020) mention one clear example where CIA has been integrated into marine spatial planning in practice. In this case, a national marine spatial planning strategy in Sweden has been developed using a CIA-based GIS application to evaluate the expected effectiveness of precautionary measures in marine planning and for comparing different locations of new activities. Some other papers assessed alternative interventions (such as marine protected areas or fishing management alternatives) within their CIA methodology to understand what kind of strategies are necessary to effectively manage impacts within their study scope (Fu et al., 2020; Jones et al., 2018; Marzloff et al., 2016). MCEs are complex adaptive systems that translate into management and policy challenges (Willsteed et al., 2018).

CIA in marine spatial planning may improve the capacity of planners to address environmental impacts. However, integrating CIA into ecosystem-based management requires a structured and transparent approach with common terminology, methods and the setting of baselines (Andersen et al., 2020). This review found that, at present, there are a variety of principles and definitions underpinning CIAs which have inconsistent language, interpretation and parametrisation which limits the effective use of CIA to effectively support management and policy making (Judd et al., 2015; Lonsdale et al., 2017; Willsteed et al., 2018). To enable more effective decision making, there is a need for comprehensive CIA methodologies that not only focus on the impacts of human activities on ecosystems, but that assess how different human impacts interact with each other and contribute to environmental change. The latter can provide a more realistic base line to enable management decisions (Hansen & Bonnevie, 2020).

# 3. Discussion

The results of this review have provided insights into the CIA and MRA approaches and applications developed in literature. This section provides a reflection on different aspects of this specific research field. In particular, building on the information extracted from the 101 selected papers (papers reported in the SM3 of Supplementary Material), this section discusses the potentials, limitations and barriers of the analysed frameworks and related applications, providing recommendation for future research and improvements.

## 3.1 Diving into a sea of terminologies

Over the last decades, numerous and diverse issues leading to ecological implications have challenged both environmental scientists and decision-makers in understanding the relationships between social/economic interests and associated environmental issues, requiring practical evaluation techniques building on interdisciplinary approaches. Environmental risk and impact assessments are rather complex procedures that can help to analyse and manage a wide range of environmental issues, including those related to climate change. Different assessment approaches and frameworks have been developed so far in order to understand the processes underpinning MCEs deterioration. As observed in this review, most of these methods apply a stepwise (and cyclic) approach, starting from the definition of the problem, toward the impact/risk identification, analysis, and evaluation. Particularly, the definition of the issue of concern, including the identification of all relevant stressors (sources of risk), the potential exposure pathways, and the harm (losses) that might result from exposure to hazard (impacts), is the first step for an effective evaluation process. However, the definition of “risk” may vary across different research fields. Many disciplines dealing with risk assessment showed different perspectives about its definition, as well as on components to be included in the process of its calculation. This review also highlighted substantial discrepancies in the risk and cumulative impact-related literature, fragmented into many disciplinary streams, with different definitions evolving within each research community. In this setting, at least two distinct conceptual frameworks for environmental risk and impact analysis have been recognised: the DPSIR and the risk-based framework (building on the IPCC definitions, where risk results from the interaction among hazard-exposure-vulnerability), with related assessment components. Terminologies vary within the reviewed studies which apply diverse conceptual frameworks but essentially refer to the same assessment procedure: i.e., an additive approach to map and analyse the potential effects of multiple human pressures on marine species, habitat and ecosystems. Moreover, a lack of clarity in the use of some terms has been identified with e.g., “stressors”, “threats”, “drivers”, and “pressures” terms considered sometimes interchangeably.

Recently, some authors tried to manage this ‘sea of terminologies’ by framing exhaustive glossaries and conceptual frameworks bridging concepts from several research streams (M. Elliott et al., 2017; Judd et al., 2015; Piet et al., 2021; Stelzenmüller et al., 2018). Joint efforts and tight cooperation between the research community and the European Commission could lift the main uncertainties, as well as better understand how to achieve a standard and consensus framework (ensuring collaboration across geographic boundaries, disciplines and sectors) that incorporates cross-border multi-risk management.

## 3.2 AI for complex marine and coastal ecosystems

Assessing and managing multi-risks posed by interactive anthropogenic and natural drivers is one of the major challenges that the research community is currently facing. The inherent complexity of MCEs and the limited knowledge on spatio-temporal dynamics underpinning their functioning, health and resilience, represent major obstacles to precisely identify hot-spot risk areas requiring targeted interventions. Within the investigated publications, non-linear relationships and interactive effects induced by multiple activities/pressures are poorly explored (Battista et al., 2017; Corrales et al., 2018; Furlan et al., 2019; authors usually applied additive models to evaluate synergies among pressures, as proposed by Halpern et al., 2008), due to the limited capability of traditional approaches (e.g. indicators and index-based method, multi-criteria decision analysis) to capture and mapping these complex dynamics and the resulting MCEs response. To overcome these limitations, the research community has started to apply new methodological approaches and tools leveraging the most recent advances in hardware and computer science, including the application of techniques exploiting capabilities offered by Artificial Intelligence (AI, e.g., machine and deep learning models) to solve a wide range of complex environmental issues (Bui et al., 2020; Peterson et al., 2020). Thanks to the current digitisation of European and international society and the consequent availability of a huge amount of data for environmental observation and monitoring (e.g., remote sensing data from Copernicus Sentinels, USGS Earth Explorer, among others), AI-based models represent an alternative approach to investigate complex environmental systems. Moreover, by providing all the information necessary for achieving Trustworthy AI (e.g., inform SHs regarding the system's capabilities and limitations, as well as provide an exhaustive description of the data is being integrated in the model and the ways in which it is being used) (EC, 2019; Felzmann et al., 2020), these methods support the evaluation of complex (and even unknown) interactions between interacting climate-driven and local/global anthropogenic factors affecting MCEs (Teichert et al., 2016), needed to provide a sound quantification of cumulative impacts. In particular, as emerged from the reviewed studies, these models can be used to i) identify the most influential pressures driving severe changes in MCEs condition (Teichert et al., 2016); ii) model and predict a wide range of individual and combined effects among different pressures, including the analysis of antagonistic/additive/synergistic behaviours (Furlan et al., 2019); iii) model and evaluate multiple scenarios accounting for diverse climate patterns (e.g. changes in the precipitation regime, rising sea temperatures) (Furlan et al., 2020), use of MCEs resources and services, management measures (e.g. restoration activities, implementation of artificial protections) (Stelzenmüller et al., 2010; Teichert et al., 2016; Uusitalo et al., 2016b) and governance pathways.

### 3.3 Dealing with a shifting baseline

In the current context of global warming and ecological crisis, there is an increasing demand for approaches that can forecast future cumulative impacts of multiple stressors (Fu et al., 2020; Hammar et al., 2020; Muñoz et al., 2018). This study highlighted that the current CIA application is mainly focused on the present condition of MCEs. This is due to the complexity and variability of these environments, as well as to the lack of detailed information on their responses to multi-risk scenarios. In highly variable marine and coastal environments, this is made even more challenging due to 'shifting baselines' in any ecosystem components (e.g., species shifts, changes in hydrographic patterns and human activities), making it difficult to detect the long-term effects of such changes and identify cumulative impacts-prone areas requiring adaptation and restoration measures (Duarte et al., 2009; Elliott et al., 2015).

This is a key scientific challenge that must be considered when setting targets for the evaluation of Good Environmental Status (GES) as required by the MSFD (EC, 2008), since improved scenario analyses, integrating these shifting baselines, are relevant to drive the formulation of possible mitigation measures for reaching the objective of GES (Elliott et al., 2015).

In the context of predicting the future, as also emerged in Zennaro et al. (2021), the current digital transformation is showing high predictive potential to evaluate and manage short-, medium- and long-term multi-risk and cumulative impacts scenarios under climate change. Specifically, long-range planning, informed by climate and "*what if*" scenarios analysis, enables marine managers to predict and explore a range of potential alternative futures to identify appropriate measures, while avoiding actions that could lead to further alterations of MCEs. As a consequence, the design of advanced models able to accommodate 'shifting baselines' due to climate change, as well as a wide range of potential short-term societal responses (e.g., including monitoring and measures; Swaney et al., 2012), will represent key tools for addressing integrated adaptation pathways, providing a more holistic view of the management of current global warming and ecological crisis.

## 3.4 A broader perspective on Good Environmental Status

This section discusses how authors dealing with CIA and MRA in European marine coastal ecosystems framed their approaches (including key indicators integrated) under these regulatory frameworks, as well as identifies challenges that need to be addressed in future CIA frameworks to better support EU support the implementation and achievement of the relevant EU acquis (e.g. MSFD and MSP directives). In particular, the main goal of the MSFD is to achieve GES of EU marine waters. GES is described through 11 descriptors (i.e., state descriptors that characterise marine biodiversity and pressures descriptors that relate to human-induced pressures), the level of achievement of which determines whether GES is achieved or not. Measures of those descriptors could feed CIA frameworks, which in return could pave the way toward disentangling the effect of single and multiple pressures on the state of MCEs and their contribution to people. Pressures on the marine environment act in various ways, changing the state of the environment, which subsequently modify or impact the ecosystem goods and services provided and the well-being of humans. Policy makers at local, regional and national levels can decide to respond by acting on the Driving Forces, Pressures, State and Welfare (see Cooper 2012) by implementing policy tools, for instance, economic incentives supporting environmental stewardship and less impactful use. These policies, however, require qualitative and/or quantitative evidence to justify them and to monitor their effects on the ecosystem. This requires a lot of data, starting with ecological data on the state of marine ecosystems. However, to understand the state of an ecosystem, baselines need to be established, a critical step for the sound assessment of ecological status (Borja et al., 2012). Indeed, one ecosystem may present different states whilst being “healthy”, depending on natural environmental conditions (e.g., wave exposure, sedimentation load, current, temperature). Long-term monitoring allows the detection of changes or phase shifts, as long as the selected indicators are sensitive enough to disturbances. However, the selection of the right indicators is still under debate for many coastal ecosystems. Moreover, in addition to state indicators, other indicators are required to assess the functions and the provision of ecosystem services and it is only recently that the assessment of ecosystem services started to include the ecological condition to adjust the production function (Culhane et al., 2019; Failler et al., 2015; Trégarot et al., 2017) or to assess the risk or vulnerability to ecosystem services supply

(Culhane et al., 2019; Trégarot et al., 2021). The relationships between ecological condition and the delivery of ecosystem services are complex (Grizzetti et al., 2019) in such a way that a well-preserved ecosystem does not necessarily coincide with a high level of ecosystem services delivery. For instance, a degraded coral reef will see its service of water purification increase substantially due to the overgrowth of macroalgae that have a much higher nutrient uptake rate than coral species (Den Haan et al., 2016). However, other services will decrease (recreational activities, coastal protection, provision for food etc.). Understanding the thresholds at which ecological phase shifts are observed, and understanding the implication of these phase shifts, is crucial to link changes in the ecological condition and delivery of services, and incorporate these links into CIA and work towards integrated approaches to avoid reaching ecological tipping points (Hodgson & Halpern, 2019; Stelzenmüller et al., 2020). Accordingly, considering a broad bundle of ecosystem services within CIA and MRA frameworks is essential to avoid misguiding outcomes.

## 3.5 Obstacles for CIA implementation into policy

Despite the increasing and wide application of CIA and MRA methods in research, their use and application are still limited and there is little empirical evidence that the results of their application are integrated into policy discourse. For CIA to be of practical use, it needs to account for the complexity of socio-ecological systems and the transboundary character of many MCEs within which human activities take place, as well as the different responses across multiple administrative jurisdictions. This requires more coherence between methodologies over time, agreement on terminologies and principles (Willsteed et al., 2018), but also finding tools to account for and address transboundary pressures (for instance, climate change, ocean acidification, pollution).

For better integration of CIA into policy, more empirical studies are also required to test data needs and usefulness of CIA at delivering the desired spatial and temporal resolution relative to identified indicators and management goals (Willsteed et al., 2018). CIA methodologies have a better chance to be implemented if they are embedded in already existing decision-making and planning processes for climate change adaptation and management of MCEs (Hammar et al., 2020). However, there seem to be a few persisting obstacles that prevent decision-makers from making full use of methodologies and tools developed by academia (Kirchhoff et al., 2013). To help overcome this gap between knowledge production and its use, researchers might need to improve communication and engagement with policy actors and develop approaches able to better integrate institutional, economic and cultural constraints (Bednarek et al., 2015). In this sense, for CIA methodologies to be applied in practice, it is important that evaluation pathways are conducted through a process that ensures coordination and synergies among different actors, policies, and programs at different scales and layers.

# 4. Conclusions

In this study, a theoretical review of the state of the art of methodological approaches and frameworks already developed by the scientific community for cumulative and multi-risk appraisal in MCEs was performed. Specifically, an iterative scientometric and systematic literature review of relevant studies was carried out to recognise trends and gaps in this specific research field, providing a comprehensive analysis and discussion of the existing literature over the past 20 years. More than 700 articles were initially identified, which were carefully screened to finally select a comprehensive set of 101 papers, representative of the most relevant CIA-related studies and applications for MCEs.

As the first remark, the performed review showed a meaningful increase in publications from 2008, when Halpern B.S. analysed for the first time the relationships and cumulative effects of multiple pressures affecting MCEs. Afterwards, building on this milestone approach, authors started integrating into their study an increasing number of pressures (frequently in line with the list of pressures listed within the MSFD) using indicator/index-based methods, while ranking the pressures-ecosystem nexus through expert-based judgement (as proposed in the Halpern B.S. approach). In the last decade, with the progressive digital transformation, new methods (data-driven approaches including, e.g., Bayesian Networks and Random

Forest models) have been developed and tested to evaluate the effect of multiple pressures affecting MCEs. Moreover, following recent EU policy and international agreements (e.g., EU 2030 Biodiversity strategy, Sustainable Development Goals), the ecosystem services perspective started to be integrated into CIA frameworks as a further assessment endpoint within the overall evaluation process.

Drawing on these outputs, this review identified key challenges that need to be addressed in future CIA frameworks to provide more accurate guidance to policy makers for sustainable coastal ecosystem management. The first challenge for the research community is to develop and test cutting-edge approaches (e.g., ML-based models) able to capture/evaluate the complex and non-linear inter-relationships among multiple pressures affecting MCEs, which increase the level of complexity and uncertainties underpinning the design of integrated plans. Dynamics are neglected in most of the reviewed studies, where the combined effect of different pressures was modelled “just” under an additive fashion, thus without considering potential synergistic or antagonistic interactions. Solving these limitations depends on the research progress of multi-source monitoring techniques needed to characterise and monitor the quality of the environment. Indeed, spatio-temporal data for marine and coastal environmental monitoring (e.g., satellites, drones) are becoming increasingly available. Consequently, authors now have the possibility to design and train more sophisticated data-driven models that allow integrating heterogeneous data to disentangle complex (and even unknown) interactions between human activities, the climate system, the ecosystems and the services they provide. In addition, this would also support the implementation of multivariate scenario analysis, useful to estimate the potential ecosystems’ response to the effect of different environmental and social patterns.

Similarly, this review also revealed a lack of consideration of the potential influence of specific ecosystem services in reducing/mitigating the effect of both endogenic and exogenic pressures while increasing the resilience of MCEs to further perturbations. In particular, some authors only recently started integrating into CIA frameworks the ecosystem services flow component, but only as an additional assessment endpoint within the overall assessment process (i.e., potential ecosystem services losses or degradation against cumulative impacts scenarios). The reason behind this limited and latest integration can be traced back to the recent international definition of marine ecosystem services under the CICES classification supporting ecosystem service mapping and capital ecosystem accounting.

Importantly, the current review revealed a reduced consideration of policy or management actions and their potential empirical evidence on how these CIA methodologies have influenced management processes of MCEs. Most of the studies just mentioned the theoretical contributions of CIAs to guide policies and decision-makers within the management of the analysed ecosystems. Greater effort should be made to improve synergies between the research community and stakeholders (including policy makers) from local to national and international levels.

Finally, progress in understanding cumulative impacts, particularly through ML models which can help improve the overall understanding of environmental systems behaviour, might help to identify some relevant trends potentially representing ecosystem thresholds of change or approaching tipping points. Overall, these advances would reinforce, on one side, the current systemic knowledge and, on the other, provide more accurate CIA future scenarios allowing to drive more robust adaptation planning in MCEs.

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