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Cumulative impacts assessment in marine areas.
A multi-disciplinary approach setting the scene for the adaptive management of the Adriatic sea

SETTORE SCIENTIFICO DISCIPLINARE DI AFFERENZA: CHIM/12
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TABLE OF CONTENTS:

A Filippo,
per averci sempre creduto..

SUMMARY

In the last few decades the health of coastal and marine ecosystems has been progressively endangered by the anthropogenic presence. Multiple natural and human-made pressures, as well as climate change effects, are posing increasing pressures on coastal and marine areas, triggering alteration of biological, chemical and physical processes, thus jeopardizing the future use of marine ecosystems' goods and services. As a consequence marine managers and policy makers are increasingly calling for new approaches and tools able to account for changing conditions over time due to natural processes and different management options. Improving our capacity to model and evaluate the combined effects of interactive stressors (e.g. temperature variation, shipping traffic, aquaculture, ports and harbors activities), in decisional contexts where data are limited and uncertainty is high, is therefore essential to address the future planning and management of our seas.

Starting from an initial review cumulative impacts assessment methodologies already applied in marine areas by the International research community, the main aim of this thesis was to develop and apply a multidisciplinary assessment approach, supporting a sound evaluation and communication of the cumulative impacts posed by climate drivers in combination with local to regional anthropogenic pressures affecting marine ecosystems and activities.

By considering different climate scenarios (i.e. baseline 2000-2015 and future 2035-2050) and management options, a holistic multi-risk approach was developed to evaluate the cumulative impacts induced by natural and anthropogenic pressures on key marine targets (e.g. seagrasses, maërl and coral beds, marine protected areas). The analysis is composed of five operative steps (i.e. hazard, exposure, vulnerability, risk and cumulative impact assessment), implemented through integrated tools and methods (i.e. GIS-based maps, Multi Criteria Decision Analysis –MCDA-, environmental indicators), including the application of Bayesian Belief Networks (BBNs) to visualize and compare the impact of potential alternative scenarios. Applied together, these tools act as a decision support tool able to assimilate different data and expertise in a unique model able to effectively inform marine spatial planning and the related decision making processes.

A first testing of the designed methodology was applied in the Adriatic sea case study, producing a set of GIS-based multi-hazard, exposure, vulnerability, risk and cumulative impacts maps and tabular results summarizing key risk metrics useful to define the progress toward the implementation of the Marine Strategy Framework Directive (MSFD) as well as to support adaptive management able to account for uncertainties and unexpected scenarios within marine areas.

The results of the analysis showed basically low and moderate cumulative impact scores mostly focused in the Italian Exclusive Economic Zones (EEZ), mainly due to the massive shipping traffic, the trawling fishing activities taking place seawards from the Italian coast, and the location of benthic infrastructures leading to severe physical impacts on the seabed. More specifically, higher cumulative impacts scores can be detected in the Nord Adriatic sea in both the analyzed timeframe scenarios, especially in areas located around the Po delta river and the ports of Trieste and Venice due to the intense shipping traffic and the high nutrient input in the area.

Moreover, the simulated scenarios through the application of BBNs showed a low reduction of the overall cumulative impact score under the effect of the implementation of adaptation strategies (i.e. enhancement of the network of marine protected areas). This result in mainly due to the higher influence of the anthropogenic pressures (e.g. trawling fishing, dredging activities) in the final estimate of the cumulative impact score, requiring a more sustainable and integrated management of marine space and resources

In conclusion, the proposed cumulative impact assessment methodology, represents a step forward compared to methodologies developed so far, mostly assuming an additive behavior of pressures in marine areas. Even if relative, it provides a more comprehensive assessment of the cumulative impacts potentially affecting the same marine region, trying to shape interactive relationships in dynamic systems such as marine environments. Moreover, by considering in the assessment future climate scenarios and management measures, the proposed methodology represents a valuable decision support tool to drive a more adaptive management of marine areas under changing environmental conditions.

The approach is flexible to be applied in different marine regions and for multiple scenarios since it can be easily up-scaled to evaluate the consequences of multiple pressures at a broader regional scale (e.g. Mediterranean scale) as well as down-scaled by improving the assessment with more detailed dataset. It can be enhanced by fine-tuning the hazards' spatial modelling according to metrics and thresholds updated by the EU member states for the step-by-step implementation of the MSFD requirement, as well as by including other and more detailed targets and vulnerability factors as more research on environmental and anthropogenic data is available. Finally, developed methodology can be applied adopting a bottom-up approach in order to tailor the assigned scores and weights as well as the simulated alternative scenarios according to stakeholders' needs and perspectives.

LIST OF CONTRIBUTIONS

Published papers:

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Manuscripts in preparation:

Furlan E., Torresan S., Critto E., Lovato T., Marcomini A. Spatially explicit risk approach for multi-hazard assessment and management in marine environment: the case study of the Adriatic sea. *In preparation.*

Furlan E., Torresan S., Ronco P., Critto A., Boteler B., Breil M., Kontogianni A., Kruger I., Le Tellier J., Garmendia M., Pascual M., Roeleveld G., Sauzade D., Skourtos M., Marcomini A. Tools and methods supporting adaptive policy making in marine areas: a review and implementation of the Adaptive Marine Policy Toolbox. *In preparation.*

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Furlan E., Slanzi D., Torresan S., Critto E., Marcomini A. Multi-scenarios' evaluation in the Adriatic sea: implementation of a GIS-based Bayesian Belief Network comparing baseline with future climate and management scenarios. *In preparation.*

Proceedings of national and international conferences (extended abstracts):

Furlan E., Torresan S., Critto E., Marcomini A. Multi-hazard assessment of natural and anthropogenic stressors in marine areas: the case study of the Adriatic sea. Proceedings of the 41st CIESM Congress, 12- 16 September 2016, Kiel, Germany.

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MOTIVATIONS AND OBJECTIVES

According to the recent integrated assessment of the European environment's state (EEA, 2015), Europe's seas are facing increasing threats and degradation due to a wide range of human activities, impairing marine ecosystems and their goods and services for human wellbeing. The growth of maritime activities is taking place without the full understanding of the complex interactions between natural and human-induced changes (Ehler and Douvere, 2009). Due to this overexploitation, happening across all of Europe's regional seas, marine biodiversity is declining, jeopardizing the conservation status of ecosystems and compromising the achievement of the Good Environmental Status by 2020, as required by Marine Strategy Framework Directive (EC, 2008). A further complication is determined by climate change which is posing additional pressures on marine ecosystems through rising sea levels, increased sea temperatures and ocean acidification. Climate change is already affecting the marine environment and will continue triggering changes on biological, chemical and physical processes (IPCC, 2014), with stronger and more numerous impacts projected for the future, leading to exacerbate others existing anthropogenic pressures (e.g. temperature-induced changes are expected to interact with existing nutrient inputs) with resulting more severe cumulative impacts (Brown et al., 2014). Even if the international awareness about cumulative impacts affecting marine environments, has increased over the last years, the assessment of the integrated effect of over-exploitation of resources, climate change and loss of biodiversity remain persistent issues of concern (EEA, 2014).

Several European and International projects were funded so far for developing and implementing methodological approaches aimed at evaluating cumulative impacts and risks produced by both natural and anthropogenic pressures on marine areas (PERSEUS[1], HARMONY[2], PEGASO[3], COCONET[4], Massachusetts Ocean Management Plan[5]). However, despite the understanding of the interactive and complex nature of pressures in dynamic ecosystems, such as marine areas, documented by numerous empirical and correlational studies (Crain et al., 2008; Sundbäck et al., 2007; Torquemada et al., 2005; Nordemar et al., 2003), most of the methodologies developed so far have assumed an additive accumulation of impacts associated with single stressors (Halpern et al., 2008a; Breton et al., 2014; Andersen et al., 2013; Micheli et al., 2013; Kappel et al., 2012;

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[1] Policy-oriented marine Environmental Research for the Southern European Seas.

[2] ‘Development and demonstration of Marine Strategy Framework Directive tools for harmonization of the initial assessment in the eastern parts of the Greater North Sea sub-region.

[3] People for Ecosystem Based Governance in Assessing Sustainable Development of Ocean and Coast.

[4] Towards COast to COastNETworks of marine protected areas (from the shore to the high and deep sea), coupled with sea-based wind energy potential.

[5] http://www.seaplan.org/

Korpinen et al. 2012; Parravicini et al., 2012; Ban et al., 2010; Stelzenmüller et al., 2009). This hiring tends to neglect more complex cause-effect relationships among natural and anthropogenic pressures, acting in concert on the same targets and inevitably leading to interactive impacts (i.e. additive, antagonistic or synergic) (Crain et al., 2008). Moreover, the cumulative impacts induced by potential alternative climate and management scenarios have been rarely explored (Berry et al., 2015; Brown et al., 2014; Stelzenmüller et al., 2010), limiting the assessment to a snapshot in time based recent/current conditions. These limitations are reflected, in turn, in the traditional (and current) marine management and planning, applying sectorial and uncoordinated approaches, not considering the effects and consequences induced by the overlap of multiple human activities, often in conflict with each other, or with the environmental status of the affected areas. This highlights the importance to model and evaluate the combined effects of interactive stressors under different potential scenarios, in order to approximate their dependencies and resulting impacts and, finally, provide marine planners ad managers a useful overview of the overall cumulative impacts threatening the marine environments and its valuable ecosystems.

In light of this background, the main objective of this thesis is to develop and implement a multidisciplinary assessment approach, supporting a comprehensive evaluation of the cumulative impacts affecting marine ecosystem and its relevant environmental targets (e.g. seagrasses meadows, marine protected areas, coral and maërl beds). More specifically, it aims at spatially represent and analyze the interactive effects induced by climate drivers (e.g. sea surface temperature variation) in combination with local to regional anthropogenic pressures (i.e. shipping traffic, aquaculture activities, chemical pollution by oil-spill), also considering changes under alternative climate and management scenarios.

The overall approach was developed with the aim to be flexible to be applied to different marine regions and for multiple scenarios, supporting to evaluate both the progress toward the achievement of GES (EC, 2008) and the potential effects of long-term changes. Moving beyond the traditional cumulative impacts assessment methodologies, the proposed approach integrates different metrics and scenarios of climate, ocean, bio-geochemical and anthropic pressures in an interactive impacts perspective, allowing to identify marine areas where management actions and adaptation strategies would be best targeted. Its operative steps (i.e. multi-hazard, exposure, vulnerability, risk and cumulative impact assessment), are implemented through integrated tools and methods (i.e. GIS-based maps, Multi Criteria Decision Analysis -MCDA-) including the application of Bayesian Belief Networks (BBNs) to evaluate the likelihood of cumulative impacts under potential simulated scenarios. Applied together, these tools act as a decision support system providing analysis' output able to facilitate and inform maritime spatial planning and management and aids science-based decision-making (Cormier et al., 2010).

The methodology was developed within the European project PERSEUS (Policy-oriented marine Environmental Research in the Southern EUropean Seas, http://www.perseus-net.eu) carried out in collaboration with the Foundation Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC, http://www.cmcc.it). The Adriatic sea was selected as case study to test the developed assessment approach and the main findings of the analysis are presented and discussed in this thesis.

THESIS STRUCTURE

This thesis is structured in three main sections: Section A illustrates the theoretical background; Section B describes the multi-disciplinary cumulative impact assessment methodology developed within the thesis; finally, Section C presents the results of the application of the methodology to the case study area of the Adriatic sea.

Section A, after a short introduction to the regulatory frameworks applied within marine management and assessment, it presents the state of the art of current methods and approaches for cumulative impact assessment in marine areas, focusing on the modelling methods applied across the operative steps (i.e. pressures, vulnerability and impact assessment). Finally it illustrates the main challenges and issues related to the assessment of cumulative impacts, mainly related to the analysis of the interactive fashion between pressures as well as the evaluation of multiple climate and planning scenarios able to inform the adaptive management of marine areas.

Section B describes the multi-risk assessment approach designed for the cumulative impact assessment of natural and anthropogenic hazards in the Adriatic sea, as well as the GIS-based Bayesian Belief Network (GIS-BBN) developed for scenarios analysis under different set conditions. After a brief presentation of the case study area, the risk-based methodological framework, including the evaluation of multiple hazards and impacts, is presented. Then, each phase of the multi-risk methodology (i.e. multi-hazard, exposure, vulnerability, risk and cumulative impact assessment) are described by stating the related GIS-based input data, selected for the Adriatic Sea, and the applied MCDA (Multi Criteria Decision Analysis) aggregation functions. Then, the conceptual model of the GIS-BBN is described, followed by the presentation of the step-by-step procedure applied for the network parametrization, including the evaluation, simulation and analysis of multiple climate and management scenarios in the case study.

Finally, **Section C** describes the results of the cumulative impact assessment methodology applied in the Adriatic sea case study, including a wide range of risk maps and tabular results summarizing key metrics useful for science-based maritime spatial planning. The results of each step of the methodology, including the application GIS-BBN, are presented and critically analyzed.
Conclusions are aimed at providing a summary of the main findings get during the implementation of the proposed approach, including possible further investigations and recommendations for the improvement of the proposed overall methodology.

SECTION A: THEORETICAL BACKGROUND

1. Regulatory frameworks for coastal and marine management

In the last few decades the health of coastal and marine ecosystems has been increasingly compromised by the anthropogenic presence (Airoldi et al., 2007). Multiple pressures (i.e. pollutants, coastal development, climate change, overfishing) are highly threatening the capability of these environments to sustain and support all the ecosystems' goods and services people want and need (Foley et al., 2010).

The recent integrated assessment of the European environment's state (EEA, 2015), as well as others global and regional assessments of the marine environment, confirm that biodiversity in the world's oceans and coastal areas continues to decline as a consequence of uncoordinated and unsustainable management of human activities. This underlines the limits of the traditional management and planning strategies which apply sectorial and not coordinated approaches, not considering the effects, and related consequences, induced by the overlap of multiple human activities, often in conflict with each other, or with the environmental status of the affected areas.

In this context, over the course of the last 30 years, several agreements, directives, communications and guidelines have been developed by International and European organizations with the main aim of better regulate the multiple uses of marine and coastal areas which inevitably lead to the depletion of these resources. Figure 1.1 summarizes the most relevant regulatory frameworks developed so far within the International and European context for the assessment and management of coastal and marine areas. They have been adopted at the national level, leading to the development of further local laws and regulations.

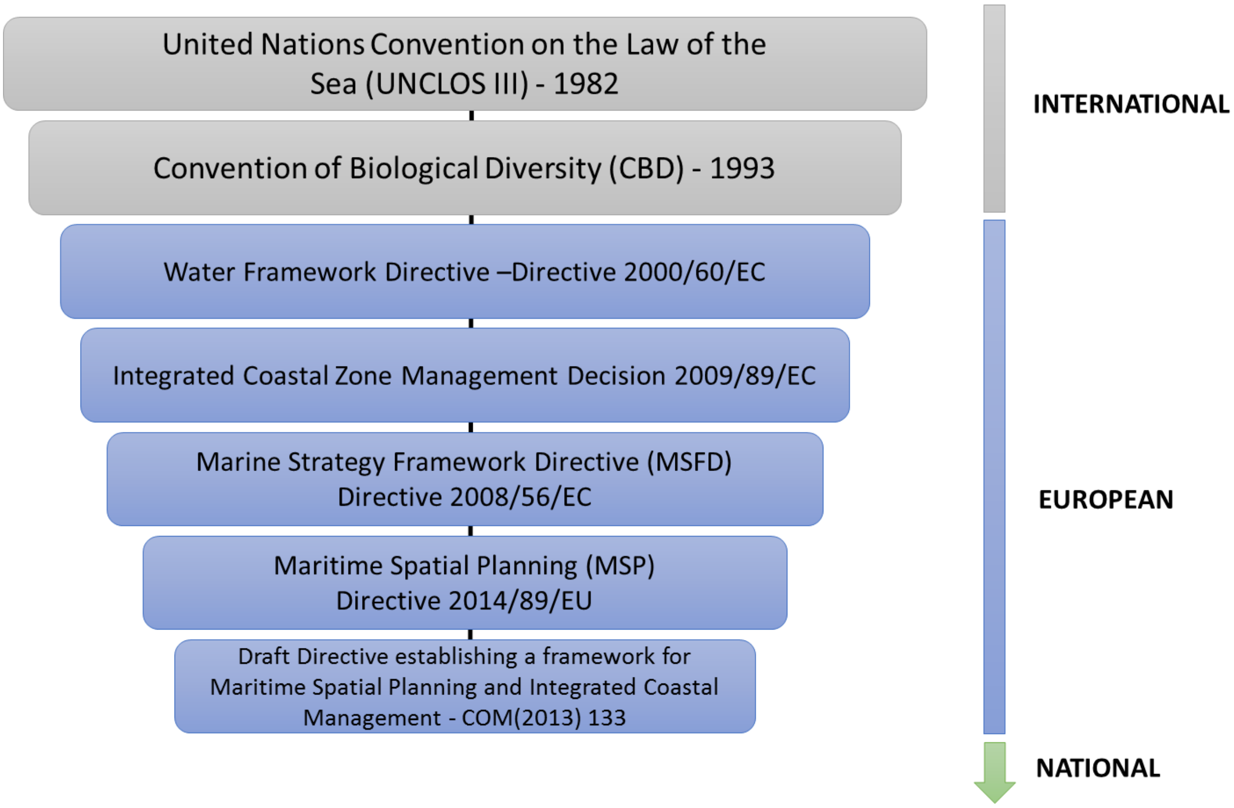

Fig 1.1: Relevant regulatory frameworks concerning the assessment and management of marine areas within the International and European context

This Chapter addresses the in force regulatory frameworks by focusing first on the International context (Paragraph 1.1), and then on the European one (Paragraph 1.2). Finally, paragraph 1.3 summarizes the main findings resulting from the critical analysis of the selected regulatory frameworks, highlighting main cross-cutting issues and challenges to be faced for a more comprehensive and effective planning and management of marine areas.

1.1 The International regulatory framework

The ability of any nation to exercise regulatory controls, management and planning activities over their claimed territorial seas is founded upon specific laws ad agreements. Accordingly, a first step toward an integrated and coordinated management scheme of marine systems, is to define clear spatial references recognized by all countries and specific objectives for the balanced planning and exploitation of marine resources. In this context, this paragraph focuses on the main agreements and conventions signed at the International level to support international cooperation between states in the management and protection of marine environments. More specifically, the United Convention of the Law of the Sea (UNCLOS; UN, 1994) (Paragraph 1.1.1) and the Convention on Biological Diversity (CBD; (UN, 1992) (Paragraph 1.1.2) are here presented in order to provide the spatial references identified by all Member States for the management and exploitation of global oceans as well as the approaches and assessment tools aimed at maintaining marine biodiversity and resilient systems for future generations.

1.1.1 The United Convention of the Law of the Sea (UNCLOS)

Within the International regulatory context the United Convention on the Law of the Sea (UN, 1994) is the international agreement that officially ratifies the transition from an unregulated to a regulated use of the sea. It represents the most relevant agreement for the delineation and codification of maritime rights and responsibilities of sovereign nations as well as the basis for the declaration of the maritime zones, introducing the concept of the Exclusive Economic Zones (EEZ). The UNCLOS resulted from the third United Nations Conference on the Law of the Sea, which took place from 1973 through 1982. It was the natural evolution of the previous one held in Geneva in 1958 aimed at solving the remaining unresolved issues, face the new requirements emerged in the context of the exploitation of marine resources and, finally, define, in a more structured way, the division of seas and oceans in specific jurisdictional zones. It came into force in 1994 and, to date, 162 countries, included the European Community, have joined in it.

This Convention provides an important legal reference to improve sea governance arrangements, as it allows nations to impose their own jurisdiction on well-defined oceans and seas' spatial zones, establishing rights and obligations to be respected by other nations. More specifically, by means of 320 articles and nine annexes, it regulates all aspects related to ocean management and assessment, such as its spatial delimitation, environmental control, marine scientific research projects, economic and commercial activities (including fisheries), transfer of technology and the settlement of disputes concerning ocean matters.

The UNCLOS represents the first regulatory tool setting boundaries and legal zones into the sea, where coastal states may exercise their sovereignty and rights on living resources. These zones are divided by means of a reference line, known as 'baseline' (Article 5) and defined by the Convention as "*the low-water line along the coast as marked on charts officially recognized by the coastal state, used for measuring the breadth of the territorial sea*". Accordingly, these baselines allow to identify two separate geographical areas: waters on the landward side belonging to the states' internal waters and under coastal states' jurisdiction and, on the other side, the high seas freely accessible to all nations.

As represented in figure 1.2, the UNCLOS defines 5 major marine zones where different standards, rights and rules are applicable. These areas are divided as following:

- Territorial seas.

It extends seawards to a limit not exceeding 12 nautical miles (about 22km) from the baseline. States are allowed to exercise their sovereignty, fully managing this area. As for inland waters, within the territorial sea, a nation has exclusive sovereignty over the water, seabed, and airspace over. The agreement also establishes that all nations have the right of innocent passage through the territorial sea of another nation and that, outside certain conditions, the nation laying claim to the territorial sea cannot hamper innocent passage of a foreign vessel.

- Contiguous zone.

This region of the sea extends beyond the territorial sea to a distance of 24 nautical miles from the baseline. In this area the prerogatives of the sovereign state are mainly related to all the necessary controls aimed at preventing the infringement of its customs, fiscal, immigration or sanitary laws and regulations within its territory or territorial sea, and punish infringement of those laws and regulations committed within its territory or territorial sea.

- Continental shelf.

Within the UNCLOS this term acquires a legal meaning not coinciding with that related with the geological formation. It includes seabed and subsoil of marine areas to the limit of 200 nautical miles from the baseline. The portion of the continental shelf beyond the 200 nautical mile limit is known as the extended continental shelf. The coastal states has the right to explore and exploit natural resources within this zone but no limits may be imposed to third countries on the exploitation of water masses and surface.

- Exclusive Economic Zone (EEZ).

This area extends for no more than 200 nautical miles seawards from the territorial sea baseline and is next to the 12 nautical mile territorial sea. It must be explicitly established by coastal states and shall include, in addition to the seabed and subsoil, the water column, stretching for 200 nautical miles seawards from the baseline. Unlike the internal waters and the territorial sea, the EEZ is not part of the national territory. Within these areas coastal states have specific rights over the management, exploration and exploitation of marine resources, including activities linked with the offshore energy production from water and wind. As the term ‘Exclusive Economic Zone’ suggests, only coastal states can build and use infrastructures such as oil platforms and wind turbines or engage in fishing in this area: third countries are excluded from such activities. This is highly important from an economic perspective considering, for instance, that around the 90% of all the commercially relevant fish species occurs in the coastal states’ EEZs.

- High seas.

This term refers to the open ocean, to all parts of the sea not included in the territorial sea, the EEZ and the internal waters of a coastal state. These waters are freely accessible to all nations, including those have not physical access to the sea, and are not subject to the sovereignty of any nation. The freedom of the high seas includes: freedom of navigation, fishing, overflight and freedom to lay submarine cables and pipelines.

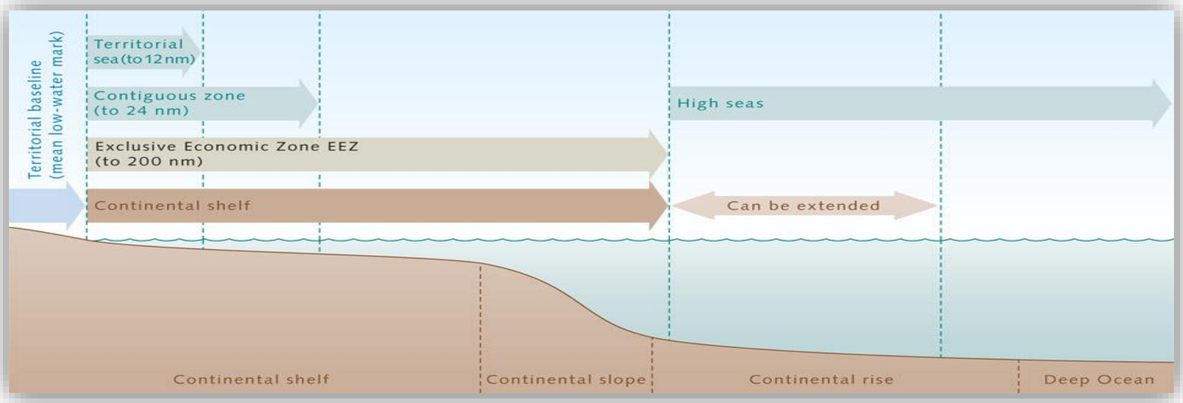

Fig 1.2 Representation of the legal zones into the sea defined in the frame of the UNCLOS (UN, 1984)

It is important to notice that, aside from defining jurisdictional boundaries on oceans and seas, the UNCLOS establishes a framework for conduct, especially in relation to economic interests and ecosystems' protection. In this context it regulates and controls several human activities like fishing, navigation, oil and gas extraction, exploitation of resources of the deep seabed and keeps under surveillance their effects which may cause substantial pollution or significant and harmful changes to the marine environment.

1.1.2 The Convention on Biological Diversity (CBD)

As emerged in the previous paragraph, marine and coastal resources are vital to humanity's economic and social development. This explains the growing recognition that biological diversity is a global asset of enormous value that must be preserved both for present and future generations. However the exploitation of natural resources shows no sign of reduction and, considering the continuous increase of human population, further changes of the marine environment will be expected. It is widely recognized as marine ecosystems are suffering the most important decline in biodiversity and the irreversible alteration of the ecosystem structure and functions is highly threatening the future use of marine ecosystem goods and services (EEA, 2015; Airoldi L., 2007; Douvere & Ehler, 2009). Indeed, the loss of marine biodiversity is irremediably compromising the ability of oceans to produce food, contrast diseases, filter pollutants, maintain water quality and react to external pressures such as climate change and overfishing, suggesting a decrease of their resilience to survive under the influence of pressures and changes (Meiner, 2009). The resulting scenario makes clear the need to better reflect on the management approach to be applied in marine areas, in order to achieve the balanced sustainable development and protection of these fragile ecosystems.

In this context, one of the most relevant regulatory framework developed with the main aim to preserve, protect and restore the ecosystems' health is the Convention of Biological Diversity (CBD, UN, 1992) opened for signature at the Earth Summit in Rio the Janeiro on 5th June 1992, and entered into force on 29th December 1993. Even though the Convention has an international dimension, the responsibility for the implementation of its principles and action plans is assigned to the Contracting parties through the application of measures taken at national and local level.

Main objectives, and pillars, of the Convention are:

- The sustainable use of biodiversity's components.
- Fair and equitable sharing of benefits arising out of the utilization of genetic resources.
- Conservation of biological diversity.

In order to achieve these ambitious goals, the Convention identifies the Ecosystem-Based Approach (EBA) as the strategic tool to promote both the protection and restoration of marine and coastal areas, supporting the development of a network between Marine Protected Areas (MPA) (Maes, 2008). The EBA represents a strategy for the integrated management of land, water and living resources, promoting its conservation and sustainable use in an equitable way. It is based on the application of appropriate scientific methodologies focused on levels of the biological organization which encompass the essential processes, functions and interactions among organisms and their environment (Farmer et al., 2012). Main aim of this approach is to maintain ecosystem in a healthy, productive and resilient condition, able to meet human needs and demands. This approach is different from previous ones that usually focus on a single species, sector or activity since the EBA allows to analyze ecological dynamics rather than individual problems (Douvere & Ehler, 2011). In this context, the EBA appears, therefore, to be the key tool to be applied within the development of integrated plans and policies potentially producing relevant impacts on the marine environment., supporting a balanced marine management, based on the concept of sustainability, reversibility, flexibility and ability to follow and apply natural processes.

The Convention also encourages member States to use the Strategic Environmental Assessment (SEA) (EP, 2001) to evaluate, as soon as possible during the decision making process, not only the impacts of individual projects but also the cumulative effects produced by multiple anthropogenic and natural pressures on marine ecosystem. Indeed, within the CBD the environmental impact assessment process is enriched by two new concepts: the cumulative nature of impacts and the strategic value of detect and analyze impacts since the early stage of the planning process.

1.2 The European regulatory framework

European approach to marine protection and management outside the domain of sea fisheries has been piecemeal until relatively recently. Over the past four decades the EU has regulated marine basic activities by means of a number of sectoral policies (e.g. common transport policy and the common fisheries policy) representing ‘stand-alone policies’, leaving to Member States a degree of independence in influencing the conservation decisions taken by the International organizations with responsibility on the protection of the marine environment. In this context, in October 2007 the European Commission adopted the *Blue Book* which introduced the Integrated Maritime Policy (IMP), aimed at setting out a common framework for EU policies concerning maritime issues. It does not replace previous sectorial policies but rather ensures that these policies are coherent and mutually reinforced by each others. More specifically it aims “*to enhance Europe's capacity to face challenges imposed by i.e. globalization, climate change, degradation of the marine environment, maritime safety and security, and energy security and sustainability*” (EC, 2007). In the European Union, the IMP envisages the Maritime Spatial Planning (MSP) as a tool for developing and implementing maritime policy, however, it was not binding for States until few years ago with the entering in force of the MSP Directive (EC, 2014). As a consequence the EU required to Member States to set up processes of marine spatial planning and highlights the role of the Community in identifying the parameters, the geographical extent of the regions involved and items that are of common interest.

In this context plays also a fundamental role the Directive 2008/56/EC - Strategy Framework Directive to the Marine Environment (MFSD; EC, 2008)- establishing a framework for Community action in the field of policy for the marine Environment (Douvere & Ehler, 2009). The MSFD has a direct relevance for MSP in Europe, introducing the concept of ecosystems-based approach to the management of human activities affecting the marine environment and the ecological system, thus promoting the integrated management of human uses while maintaining ecosystems goods and services (Leslie & McLeod, 2007; Ruckelshaus et al., 2008). The implementation of the MSFD has consistently benefited of the experience gained through the implementation of the Water Framework Directive (EC, 2000) establishing a framework for Community action in the field of water policy. The WFD introduces an integrated approach to water management based on the concept of river basin planning and its provisions cover all inland surface waters, groundwater, transitional and coastal waters. Many of the concepts developed within the WFD have been recovered and reprocessed in the MSFD, in particular in the context of setting the Good environmental status criteria and ensuring their comparability across the regional European seas (Borja et al., 2010).

This paragraph addresses the main European regulatory frameworks supporting the assessment and management of coastal and marine environments. More specifically according to the objectives of this Ph.D. thesis, next paragraphs focus on the Marine Strategy Framework Directive (MSFD), considered the pillar for the implementation of the IMP (Douvere & Ehler, 2009) (Paragraph 1.2.1), the recent MSP Directive (Paragraph 1.2.2) and the draft Directive establishing a framework for MSP and Integrated Cpastal Zone Management (Paragraph 1.2.3).

1.2.1 The Marine Strategy Framework Directive (MSFD)

Within the European context the growing interest on the development and protection of marine ecosystems is highlighted by the Marine Strategy Framework Directive (EC, 2008) providing a legislative framework to:

- sustainably manage human activities at all scales, from national to regional/local seas;
- setting environmental targets for healthy and clean marine ecosystems;
- promoting the application of the Ecosystem-Based and integrated Approach (EBA) to reach the Good Environmental Status (GES) by the Member States by 2020.

The MSFD marks an important milestone in the progress of the EU’s marine environmental policy in so far as it is the first legal framework specifically aimed at protecting and preserving the marine environment, preventing its deterioration and, where practicable, restoring marine ecosystems in areas where they have been adversely affected (Long, 2011). Moreover, from a normative perspective, the MSFD also represents the first European concerted attempt to apply the Ecosystem-Based approach in the management of human activities affecting marine environments and ecological systems, ensuring that they are not irreversibly damaged by the effects produced by natural and anthropogenic pressures (Long, 2011).The conceptual approach proposed by the MSFD, for the protection and management of the marine environment and its natural resources, reflects several important principles that already belong to environmental policies. These include the precautionary principle, the belief that environmental damage should be a priority to be ratified at the polluter-pays’ principle.

From a geographical point of view the MSFD sets specific provisions on the area of application. More specifically, it has to be applied to marine waters which, as explained in article 3 of the Directive, include “*the waters, the seabed, and subsoil on the seaward side of the baseline from which the extent of territorial waters is measured extending to the outmost reach of the area where*

Member States have and/or exercise jurisdictional rights, in accordance with the 1982 United Nations Law of the Sea Convention".

The directive is structured in five chapters, and the first of these is focused on setting out the subject matter, scope, definitions, marine region and sub-regions, marine strategies, rules for coordination and cooperation between Member States and competent authorities. It also introduces some new concepts linked with the definition of 'marine region' and 'marine sub-region', one of the most relevant change brought about the EU law by the MSFD. As represented in figure 1.3 the four marine regions identified by the directive (article 4) are as follow:

- the Baltic Sea.
- The North-east Atlantic Ocean.
- The Mediterranean Sea.
- The Black Sea.

The second chapter deals with the development of marine strategies and includes provisions on the assessment, the definition of GES and related environmental targets. More specifically, in this section the MSFD explicitly requires to member states the analysis of the main pressures and impacts on the environmental status of marine ecosystems, taking into account both cumulative and synergic effects and their transboundary features. The third chapter focuses on the establishment and implementation of coordinated monitoring programmes for the ongoing assessment of the environmental status, whereas the last two address the development of the interim reports describing progress in the implementation of programme of measures and the transposition of the directive into the EU national regulatory frameworks.

Six technical annexes are also included at the end of the directive addressing issues such as the list of the qualitative descriptors for determining GES (Annex I), competent authorities in the Member States for its implementation (Annex II), the indicative list of characteristics, pressures and impacts to be considered within the initial assessment for setting environmental targets (Annex III and IV) and the guideline for defining monitoring programmes and measures (Annex V and VI).

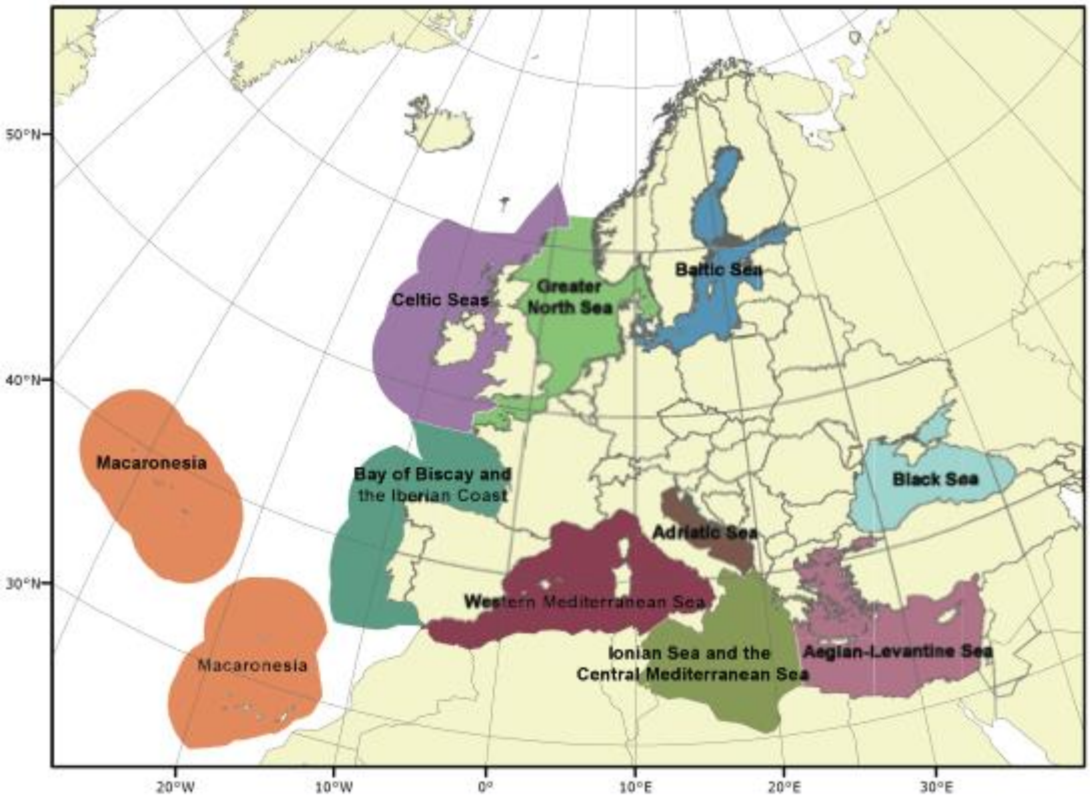

Figure 1.3: Marine regions and sub-regions as established in the first chapter of the MSFD (EC, 2008)

The regulatory structure established by the MSFD is intended to leave each EU Member States to put in place and implement its own 'Marine Strategy' by applying, where possible, existing Regional Seas Programmes (i.e. Regional Sea Conventions such as HELCOM[6], OSPAR[7]). Moreover, the Directive recognized the need for Member States to cooperate and coordinate their actions in designing and implementing their Marine Strategies, in order to strength cross-border cooperation among themselves and with neighboring countries. The development and implementation of marine strategies follows procedural and administrative steps set down by the Directive and this process is reviewed and updated by the Member States in consultation with the EU Commission every six years after its initial development.

1.2.1.1 Methodological steps for the implementation of the marine strategy

Once the Directive has been implemented within national regulatory frameworks, each Member State can develop a marine strategy for its marine waters according to the action plan set down by the Directive itself (Article 5). As represented in figure 1.4, a common approach to all Member

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[6] The Baltic Marine Environment Protection Commission (HELCOM), also known as Helsinki Commission, is an intergovernmental organization governing the Convention on the Protection of the Marine Environment of the Baltic Sea Area (Helsinki Convention).

[7] The Convention for the protection of the Marine Environment of the North East Atlantic (OSPAR Convention) is the current legislative instrument regulating international cooperation on environmental protection in the North-East Atlantic.

States is establishes by the Directive to develop and implement marine strategies, by mean of an iterative process including 5 methodological steps described by related objectives and deadlines.

Figure 1.4: MSFD's implementation cycle for achieving the GES by European Member States by 2020

The first step of the implementation cycle concerns the 'Preparation phase', which includes:

- By 15 July 2012: initial assessment of the current environmental situation of European marine waters and the environmental impacts induced by human activities on these areas. This phase also includes the determination of the GES and the identification of a set of environmental targets and associated indicators to guide progress towards achieving GES in the marine environment by 2020 (Art. 8, 9, 10).
- By 15 July 2014: establishment and implementation of monitoring programmes for ongoing assessment of the environmental status of marine areas and regular updating of targets (Art.11).

The second step is the 'Programme of measures', requiring:

- By 2015: development of a programme of measures designed to achieve or maintain GES (Art. 13);
- By 2016: implementation of the Marine Strategy.

This process has to be reviewed and updated by the Member States, in consultation with the European Commission, every six years after its initial establishment (article 17).

1.2.1.2 GES and related environmental descriptors

As explained in the previous paragraph, the overall objective sets down by the MSFD is achieving and maintaining the GES within EU's marine waters by 2020. The GES is one of the new concepts introduced by the Directive into the EU law and is broadly defined in Article 3 as: *"the* *environmental status of marine waters where these provide ecologically diverse and dynamic oceans and seas which are clean, healthy and productive within their intrinsic conditions, and the use of the marine environment is at a level that is sustainable, thus safeguarding the potential for uses and activities by current and future generations.*" According to this definition, the GES is achieved when the structure, functions and processes of marine ecosystems are fully considered, marine species and habitats are protected and human-induced decline of biodiversity is prevented (Long, 2011).

To define the GES in a marine region and sub-region, Member States have to analyze a set of eleven qualitative descriptors of environmental status, pointed out by the directive in the Annex I. Table 1.1 reports the whole list of these descriptors also including a short description.

Table 1.1. Qualitative descriptors established in the frame of the MSFD for the determination of the GES within the European marine regions and sub-regions (Annex I, MSFD)

QUALITATIVE DESCRIPTORS	DESCRIPTION
Biological diversity	Biological diversity is maintained. The quality and occurrence of habitats and the distribution and abundance of species are in line with prevailing physiographic, geographic and climatic conditions.
Non- indigenous species	Non-indigenous species, introduced by human activities, are at levels that do not adversely alter the ecosystems.
Commercially exploited fish and shellfish	Populations of all commercially exploited fish and shellfish are within safe biological limits, showing a population age, size and distribution that is indicative of a healthy stock.
Marine food webs	All elements of the marine food webs (to the extent that they are known) occur at normal abundance, diversity and levels able to ensure the long-term abundance of the species and the retention of their full reproductive capacity.
Eutrophication	Human-induced eutrophication is minimized, especially adverse effects thereof, such as losses in biodiversity, ecosystem degradation, harmful algae blooms and oxygen deficiency in sea bottom waters.
Sea-floor integrity	Sea-floor integrity is at a level that ensures that the structure and functions of the ecosystems are safeguarded and benthic ecosystems, in particular, are not adversely affected.
Hydrographical conditions	Permanent alteration of hydrographical conditions does not adversely affect marine ecosystems.
Concentration of contaminants	Concentration of contaminants are at levels not giving rise to pollution effects.
Contaminants in seafood	Contaminants in fish and other seafood for human consumption do not exceed levels established by the EC legislation or other relevant standards.
Marine litter	Properties and qualities of marine litter do not cause harms to the coastal and marine environment.
Energy	Introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment.

In defining their GES, Member States shall also take into account an indicative list of elements concerning physical, chemical and biological features, habitat types, hydro-morphology, as well as identify pressures and impacts of human activities on marine ecosystems (Annex III). In this setting, in order to support and coordinate all Member States in the assessment of the environmental status, the European Commission in 2010 adopted a Decision setting down criteria and methodological standards to be applied for determining GES. This Decision (2010/477/EU) (EC, 2010) was developed with the contribution of scientific and technical experts from the Member States, the supports of the European Joint Research Center (JRC) and the International Council from the Exploration of the Sea (ICES). It includes a list of 56 indicators, classified by means of 29 criteria (e.g. species distribution, population conditions, habitat extent, nutrient levels, effects of contaminants), to be considered across the analysis of the environmental descriptors pointed out by the MSFD. These criteria may require further refinement considering the development of new scientific knowledge and, accordingly, the determination of GES will have to be adapted over time, taking into account the dynamic nature of marine ecosystems as well as the variability of pressures and impacts that can change due to the evolution of different patterns of human activity and the impact of climate change (EC, 2010).

1.2.2 The Maritime Spatial Planning Directive (MSP)

The high and rapidly increasing demand and competition of maritime space for new activities (e.g. renewable energy equipment, aquaculture), as well as the multiple natural and anthropogenic pressures on marine ecosystems, highlighted the need for an integrated and coherent planning and management approach allowing to prevent potential conflicts and create synergies between different sectors.

In this setting, following up multiple communications, roadmaps (Roadmap to MSP COM(2008)791, Communication n. 771 of 2010) and talks among member states, in 2014 the European Parliament and the Council of the European Union adopted the Directive 2014/89/EU (EC, 2014), establishing a common framework for maritime spatial planning. It represents one of the main pillars of the Commission's Blue Growth strategy and the EU Integrated Maritime Policy, contributing to a more effective implementation of the EU environmental legislation in marine waters as well as a valuable support for Member States to reach GES, as required by the MSFD (EC, 2008).

Main aims of the Directive is to define when and where human activities should be planned, rationalizing and coordinating competing activities taking place at sea while preserving its quality. More specifically, according to the Directive, ''*maritime spatial planning' means a process by* *which the relevant Member State's authorities analyze and organize human activities in marine areas to achieve ecological, economic and social objectives*' (Art. 3). In this way the MSP Directive supports an efficient use and exploitation of marine space and its resources, creating a stable environment attractive to investors, thus contributing to sustainable blue growth.

The Directive commits all Member States to define and implement maritime spatial plan by 2021 setting minimum requirements for its drawing up. Indeed EU coastal countries are free to define the content of the plan and measures to their specific economic, social and environmental purposes as well as national sectorial policy, but they must respect the minimum requirements posed by the Directive.

By promoting the sustainable growth of maritime economies and use of marine resources, the MSP Directive supports the application of the EBA (Art. 5), as also required by the MSFD Directive (EC, 2008), with the main aim of ensuring that the collective pressure of all activities is kept within levels compatible with the achievement of GES, and that the resilience of marine ecosystems to face human-induced changes is not compromised. In this setting, trans-boundary cooperation between Member States and neighboring third countries is encouraged (Art. 11), always in accordance with the relevant UNCLOS provisions (UN, 1982).

Moreover, since marine and coastal activities are often closely linked, in order to promote the sustainable use of maritime space, the Directive highlights the need to consider the land-sea interactions (Art. 7), integrating the maritime dimension of some coastal activities (and their impacts) in a more integrated and strategic vision as well as promoting coherence between marine plans and ICZM or equivalent formal or informal practices (Art. 6).

Finally, a specific focus is posed by the Directive to climate change issues, requiring to member states to take into consideration long-term changes due to climate change and natural hazard which can lead to severe impacts on marine ecosystems and coastal economic development and growth, leading to deterioration of environmental status, loss of biodiversity and degradation of ecosystem services.

1.2.3 Proposal for a European Directive for Maritime Spatial Planning (MSP) and Integrated Coastal Zone Management (ICZM)

Within the European context, although several legislative tools ask for a close cooperation and coordination between MSP and ICZM, there is no yet a regulatory framework specifically devoted at coordinating their integrated implementation. Both of these approaches have been listed among the strategic initiatives for the implementation of the 'Action Plan' inside of the Blue Paper in 2007 (Meiner, 2009). In this context, the "*Proposal for a directive of the European Parliament and the*

Council establishing a framework for maritime spatial planning and integrated coastal management", enacted in March 2013 with the form of a draft Directive, can be seen as the first attempt to establish a common regulatory framework aimed at supporting the land-sea connectivity by requiring coherence between MSP and ICZM decisions (EC, 2013). This draft Directive asks for the complementary application of these two planning tools, since their geographical and strategic scope overlaps in the coastal and territorial waters of the Member States. More specifically, maritime spatial plans will allow to map existing human activities and identify their future spatial development, whereas integrated coastal management strategies will ensure the integrated management of these human activities (Figure 5) (EC, 2013).

It is clear, in fact, the close link between coastal and marine environment, since many activities developed in terrestrial or coastal environments (i.e. agriculture, industry, urban settlements) inevitably lead to severe impact on the marine environment. According to this Proposal each Member State should establish and implement a maritime spatial plan and an integrated coastal management strategy (Art. 4), allowing to pursue the following objectives (Art. 5):

- promoting the development of new and renewable forms of energy, and maritime transport;
- fostering the sustainable development and growth of the fishery and aquaculture sectors;
- ensuring the preservation, protection and improvement of the environment;
- guaranteeing the rational use of natural resources while making coastal and marine areas more resilience to climate related impacts.

In order to achieve the objectives, maritime spatial plans and integrated coastal management strategies should be coordinated with each other, for ensuring effective cross-border cooperation between Member States, and contain at least a spatial map of marine waters identifying the distribution of all relevant maritime activities (i.e. oil and gas extraction sites and infrastructures, maritime transport routes, submarine cable, pipeline routes, fishing areas, sea farming sites, nature conservation sites)(Art. 6, 7 and 8).

Finally, strategies should consider interactions between terrestrial and maritime activities and in doing so they should have to consider activities such as: exploitation of specific natural resources including infrastructures for the extraction of resources and the production of renewable energy, shipping transport, ports activities, agriculture and industry, fishing and aquaculture, conservation, restoration and management of coastal ecosystems, mitigation and adaptation to climate change (EC, 2013). By means of an integrated perspective to land-sea planning and management, this proposal also conveys a holistic consideration of impacts (including cumulative ones) induced by multiple human activities, to be considered since an early stage of the planning process.

Figure 1.5: Framework for integrated MSP and ICZM highlighting the close link between coastal and marine environment

1.3 Cross cutting issues and challenges

The review of the regulatory frameworks showed that, both in the International and European context, the environmental impact assessment is widely recognized as the suitable approach to pursue a policy of protection, conservation and sustainable development of marine areas. Moreover, most of them gave great prominence to the assessment and management of cumulative impacts also taking into account their synergic behavior and transboundary feature (UN, 1992; EC, 2008).

However, despite this regulatory background, the combined effect between interactive natural and anthropogenic stressors still remains largely unknown, due to the single-sector nature of current management and planning approaches. Moreover, decision-makers usually end up to react to specific events when it is already too late, rather than having the choice to plan and shape actions that could lead to a more desirable ad sustainable future of the marine environment.

This situation has led public authorities and policy makers to realize that the traditional sectoral approach to the management, but also assessment of marine ecosystem, requires a shift toward a more holistic approach, calling for a comprehensive look to all the dimensions of environmental issues (Laffoley et al., 2004). In this context, the EBA has been widely recognized as the key approach for delivering the sustainable development in both terrestrial, coastal and marine environments, recognizing the role of humans as part of these complex ecosystems and allowing to integrate their desires and needs with the conservation of a healthy and productive environment. Despite its broad acceptance and the wide range of principles, definitions and guidelines developed for its application, the EBA is still a concept, widely discussed by the scientific community but with few examples of actual practice (Douvere & Ehler, 2009).

As recognized within the CBD and the MSFD the implementation of the EBA to coastal and ocean management is a complex and demanding process which requires the development of practical tools in order to make this process more tangible. These tools should also consider the land-sea interaction with the aim of integrating the maritime dimension with some coastal uses (and related impacts) to ultimately allow an integrated and strategic vision (EC, 2013). Moreover, to implement an EBA to the marine management, effective analysis of the environmental impacts of activities on ecosystem products and services should be made, and the cumulative and synergic consequences of different activities on them assessed.

2. Cumulative Impacts Assessment (CIA) in the marine environment: a review and some perspective for future management

Efforts to achieve the Good Environmental Status in the European marine regions (EC, 2008) require appropriate planning options and decisions which cannot be designed without the comprehensive knowledge of the impacts induced by different natural and anthropogenic drivers (Parravicini et al., 2012). New advanced methodologies are required in order to effectively model cumulative impacts produced by multiple and interactive pressures and thus provide to planners and decision makers science-based information and impacts' scenarios to address efforts in marine management. This need is also underlined by the several directives, laws, communications and guidelines developed by International and European organizations over the course of the last 30 years, requiring to evaluate not only the effects produced by individual projects, but also cumulative and synergic impacts produced by multiple the uses of marine ecosystem (EC, 2008; (UN, 1992). While ecological research has begun to document the combined effects of various pressures on species and ecosystems, research into the cumulative and interactive impacts of multiple stressors is less frequent (Crain et al., 2008). However, in the last decade some more efforts have been done to estimate and map in a transparent and systematic way the cumulative impacts on marine ecosystem. Applying a method eliciting expert judgments on the vulnerability of ecosystems to anthropogenic threats, Halpern et al. (2008) has given one of the first spatial visualization of cumulative impacts from land-sea at global level. This approach has been followed by other papers and case studies where the same methodology has been applied with smaller spatial scale of analysis and more refined data (Micheli et al., 2013; Korpinen et al., 2012; Breton et al., 2014), or expanded by analyzing other environmental impacts (Andersen et al., 2013) to respond to specific directives' requirements (EC, 2008).

The following paragraphs describe the review of the state of the art of the methodologies and approaches developed so far by the research community to evaluate cumulative impacts in marine areas (Paragraph 2.1), highlighting the applied modelling methods and assumptions across the impact, pressures and vulnerability assessment phases (Paragraphs 2.1.1-2.1.3), as well as the main strengths and weakness of the analyzed approaches (Paragraph 2.2).

2.1 State of the art of current methodologies and approaches

The recent paper by Korpinen & Andersen (2016) highlighted how most of the methodologies developed so far for cumulative pressures and impacts assessment in marine areas show similar analytical and procedural structure. More specifically, from this review paper emerged that the 50% of the reviewed studies were based on the methodological approach designed by Halpern et al. (2008), thus focusing on its three main assessment steps: analysis of the intensity of pressures, vulnerability assessment including the identification of marine ecosystems occurrence and their vulnerability to pressures and, finally, the integration of all previously calculated information into the CIA. Drawing on these findings, the comparative approach proposed in this review focuses on these three methodological steps, providing a more in-depth analysis of each methodological phase.

The research of the publications was performed by using the database of peer-reviewed literature 'Scopus' (https://www.scopus.com) and setting as constraints of the query the key words 'cumulative/interactive impact assessment in marine environment' 'cumulative pressures in marine environment'. The search was limited to the period of publication 2000-2016 ordering results based on their relevance to the set constraints. The research gets hundreds of matches but only 22 studies were analyzed and included in this review, since well-fitting with the aforementioned research criteria as well as integrating at least two different pressures and spatially implementing the designed operational methods in a real case study area. Moreover, three project reports, developed in the frame of the PERSEUS, PEGASO and Harmony European projects, were also included in the list of reviewed documents, since providing interesting methodological development and application within CIA (Gana S., 2013; Breton et al., 2014; Andersen et al., 2013). As a consequence, a total of 25 studies were deeply analyzed in this review.

In order to facilitate the comparative analysis and discussion, the reviewed methodologies were described in a unique Table (Annex A) against a set of criteria linked with each phase (i.e. cumulative impacts, pressures and vulnerability assessment), aimed at highlighting the modelling methods (and assumptions) applied to mimic natural dynamics naturally occurring in complex marine systems. This table represents the reference point for the discussion of the main strength and weakness of the applied methodologies, paving the way for the identification of the main challenges to be faced by the research community to develop more advanced CIA approaches (Paragraph 2.2).

2.1.1 Cumulative impact assessment

The first evidence reviewing the collected publications is that applied approaches are mostly inspired by the methodology developed by Halpern et al. (2008), adapting at case study level the analyzed pressures (e.g. to respond to specific regulatory frameworks), considered ecosystems and the set of scores/weights to represent vulnerability of site-specific ecosystems to drivers of ecological change.

More specifically, focusing on the modelling methods and assumptions applied within CIA, as already proved by Korpinen & Andersen (2016), of the 25 studies reviewed, 20 assumed cumulative impacts as a result of additive or incremental stressors (80%) (as applied by Halper et al. (2008)), whereas 5 included pathways of interactions between pressures (i.e. synergic and antagonistic) in the evaluation procedures (20%).

Among these, an interesting methodology is outlined by Ban et al. (2014), applying Bayesian Belief Network combining multiple stressors within and outside management, to evaluate cascading effects on water quality and coral cover. The proposed method, besides moving forward the traditional approaches applying additive accumulation between stressors, also provides a good example of multi-scenarios evaluation, representing a valuable decision support system to support adaptive management in the Great Barrier Reef.

A similar approach was applied by Brown et al. (2014) simulating three different scenarios of interactions (i.e. no interactions, antagonistic or synergistic interactions) between local and global stressors, under envisioned management constraints. However, the assessment was limited on considering only pairs of stressors (i.e. nutrient input and ocean warming) and their effect on a single marine ecosystem (i.e. seagrass meadows). A wider assessment, always considering alternative scenarios of interacting pressures (i.e. single, additive, antagonistic, and synergistic, based on different aggregation functions) was applied by Foden et al. (2011) focusing on a broader seabed community characterized based on geological survey sediment types.

By performing a geospatial modelling framework integrating data on spatial distribution and intensity of human activities with related sensitivity of marine landscapes to these pressures (based on the Halpern approach) Stelzenmüller et al. (2009) evaluates the risk of cumulative impacts, under four simulated scenarios in the waters of the United Kingdom (England and Wales). More specifically, a random pairwise comparison of the importance of pressures (e.g. equal importance of pressures, linear decrease of importance of pressures, logistic decrease of importance of pressures) was simulated in order to shape scenarios. Even though the framework doesn't describe the exact mechanisms of interactions between pressures, it revealed a range of variability in the prediction of risk of cumulative impacts that go forward the traditional additivity perspective.

Finally, it has to be underlined, that all the approach allow a relative estimation of the sea water conditions, where lower cumulative impact scores indicate healthier ecosystems whereas higher scores that cumulative impacts are likely occurring. In this setting, field studies measuring different combinations of stressors and their resulting individual and population-level impacts (in quantitative terms) are critical to design effective management strategies.

2.1.2 Pressures assessment

This assessment phase focuses on the on the analysis of the spatial pattern/distribution and intensity of pressures, identifying always more stressors to be considered in the analysis as well as sophisticated modelling methods. Indeed, multiple natural and anthropogenic pressures were evaluated and spatially modelled across different case studies, also taking into account climate-driven pressures. More specifically, of the 25 studies reviewed, 9 (36%) also evaluated climate pressures such as sea temperature variation, ocean acidification and changes in UV radiation (Okey et al., 2015; Cook et al., 2014; Micheli et al., 2013; Maxwell et al., 2013; Halpern et al., 2008). However, climate pressures only focus on recent climate scenario, rather than future projections allowing to get estimates of future exposure. A more advanced assessment of future climate change scenarios (with an associated probability) for different stressors should be implemented with the main aim of providing marine planners and decision makers, valuable information for forward looking and adaptive planning. Moreover, their interaction with chemical, biological and physical pressures should be investigated in order to identify and evaluate potential cascading and triggering effects increasing resulting cumulative impacts.

As far as human-made pressures are concerned, in only one publication the effect of marine debris was evaluated in the Papahānaumokuākea Marine National Monument –Hawaii- (Selkoe et al., 2009), since homogenous and wide scale (e.g. marine region) data on this emerging environmental issue are still lacking.

By focusing on the modelling methods and assumptions applied within pressures assessment, in almost all the reviewed approaches, simple linear functions were used to spatially model the spreading of pressures' intensity from the activity. More specifically, a linear decay of pressures' intensity from their origin was assumed, applying time by time specific distance-based spatial models (i.e. different buffer zones limiting pressure spread) (Andersen et al., 2013). Linear decay assumes that stressors diffuse equally in all directions and depth within the defined buffer zone, when in fact marine currents and river plumes are likely to highly influence the diffusion of stressors. Moreover, considering the time perspective, pressures were considered with long-lasting persistence in the selected timeframe scenario neglecting more complex temporal patterns and dynamics.

Finally, together with the evaluation of future climate scenarios more efforts should be devoted to the integration, in the assessment processes, of real marine planning scenarios designed for the area of concern. In this way, developed pressures assessment procedures would highly contribute to support the implementation of the Strategic Environmental Assessment (EP, 2001) thus ensuring that potential negative effects to the marine environment, from the various planned human activities, are prevented.

2.1.3 Vulnerability assessment

This assessment step focuses on the analysis vulnerability of key marine species and habitats to different natural and anthropogenic pressures.

Most of the reviewed approaches were inspired by the methodology developed by Halpern et al. (2008) applying the expert judgement to quantify the sensitivity of the ecosystem components to the analyzed stressors. More specifically of the 25 studies reviewed, 11 elicited vulnerability scores organizing survey at the case study level, whereas other 4 studies directly implemented in the assessment scores defined by Halpern et al. (2008) for the global oceans. This wide use of expert judgment instead of direct empirical assessments (based on in-situ survey) to calculate impact weights, highly increases the uncertainty of the resulting impact score relying on an arbitrary opinion of a limited number of involved experts. However, empirical quantification of the ecological impacts of a suite of drivers is currently unavailable for wide marine regions (e.g. Mediterranean sea).

Moreover, as already applied by Halpern et al. (2008) ecosystems components were assumed to be homogeneous within their spatial boundaries, thus spatially modelling them as presence absence in the case study of concern. In this setting an interesting approach presenting novel features, is presented by Foden et al. (2011) evaluating seabed habitat sensitivity to different anthropogenic activities by determining recovery rates of the benthic community following cessation of an activity, and based on the activity’s distribution and intensity. In this setting the vulnerability assessment is enriched by a dynamic component allowing to represent the coping capacity of potentially affected marine ecosystems to the considered pressures.

However, more advanced ecosystem models should be implemented within vulnerability assessment procedures, in order to understand the direct and indirect effects of natural and anthropogenic pressures on marine ecosystems and biological communities. Furthermore, the expansion of this assessment phase should consider maps of species distribution and abundances, also incorporating their time-based occurrence (i.e. seasonal changes) based on accurate quantitative knowledge. Complex ecological dynamisms, such as feeding and spawning migrations of marine species, should be explored taking into account the spatial linkages between pressures, which effectively expand the spatial extent of threat impacts.

2.2 Cumulative impacts assessment: strengths and weakness

The review of the state of the art of methodological approaches dealing with CIA in marine areas, has shown the application of different methods in multiple geographical contexts and spatial scales of analysis, responding time by time to specific evaluation and management purposes. One of the main strength, across most the analyzed approaches, stands in the transparency and repeatability of the assessment steps (i.e. cumulative impacts, pressures, vulnerability), simplifying methodology and results' communication and understanding also to a non-expert public. This highly contributes to increase awareness of a wider society (e.g. marine managers, citizens and stakeholders) on cumulative impacts affecting seas as well as to improve planning and management and related decision-making processes, providing a concrete guidance on where conservation measures should be more critical and mitigation on driving stressors is mainly required.

Moreover, great efforts were devoted to collect and integrate a large amount of heterogeneous environmental and socio-economic data, including their related metadata. Their application within assessment processes, often focused on wide marine regions (Halpern et al. 2008; Micheli et al. 2013) thus allowing to develop comprehensive and homogenous dataset characterizing the spatial patterns (with intensity and distribution) of complex impacts, pressures and vulnerabilities. Most of these dataset are available for free on web (https://www.nceas.ucsb.edu/globalmarine/data) thus allowing other people to replicate the assessment, fine-tuning scores and assumptions according to specific needs as well as expanding the assessment by including more refined data available for the case study of concern.

However, some weakness still persist, mainly related to the modelling approaches and methodological assumptions applied during the different assessment steps, simplifying more dynamic interactions between pressures and vulnerabilities naturally occurring in dynamic marine systems.

Table 2.2 summarizes the most relevant identified weakness, describe in the form of consequences and challenges to be faced by the research community to effectively inform future management and planning of marine areas.

Table 2.2 Identified consequence and challenges for future management of marine areas across the main operative steps of CIA

	Consequence and challenges for future management of marine areas
Impact assessment	Evaluate cumulative impacts in their interactive fashion by identifying the most suitable aggregation method.
	Evaluate uncertainty related to the analyzed scenarios.
	Apply semi-quantitative and quantitative approaches.
	Identify a common scale and thresholds of comparison.
Pressures analysis	Improve spatial models for shaping intensity and spatial distribution of pressures.
	Consider pressures sources and propagation in three dimensions.
	Consider pressure persistence in the selected timeframe scenario and on the considered marine targets.
	Assess cascading and triggering effects increasing resulting cumulative impacts.
	Identify and evaluate appropriate climate-driven pressures with an associated probability and uncertainty. Evaluate their interaction with chemical, biological and physical pressures.
	Evaluate multiple planning scenarios with an associated probability and uncertainty.
Vulnerability analysis	Develop more accurate spatial model coupling vulnerability of marine ecosystem to the considered pressures.
	Identify multiple vulnerability factors for the characterization of the exposed marine targets.
	Consider the coping capacity (recovery potential) of the potentially affected marine ecosystems to the considered pressures.
	Consider a changing resilience towards a given impact -may in - or decrease.
	Based on in-situ survey and samples, designs specific vulnerability functions (fragility curves) linking vulnerability of each element at risk to the corresponding pressure.
	Define future scenarios for the vulnerability factors that should be considered as a dynamic element in complex marine systems.
	Provide a common scale and thresholds for the comparison of the vulnerability between different marine regions.

SECTION B: METHODOLOGICAL DEVELOPMENT

3. Description and characterization of the case study area

This chapter introduces the case study area of the Adriatic marine sub-region (Paragraph 3.1) focusing on its administrative, environmental and socio-economic aspects. Moreover, available input data, retrieved for the case study, are described, including all the GIS-based data (i.e. vector and raster maps) and climate model outputs (Paragraph 3.2) used across the different steps of the assessment.

3.1 The Adriatic sea: main features and environmental issues

The case study area selected for the implementation of the cumulative impacts assessment methodology is represented by the marine sub-region of the Adriatic sea located in the wider Mediterranean sea (Figure 3.1).

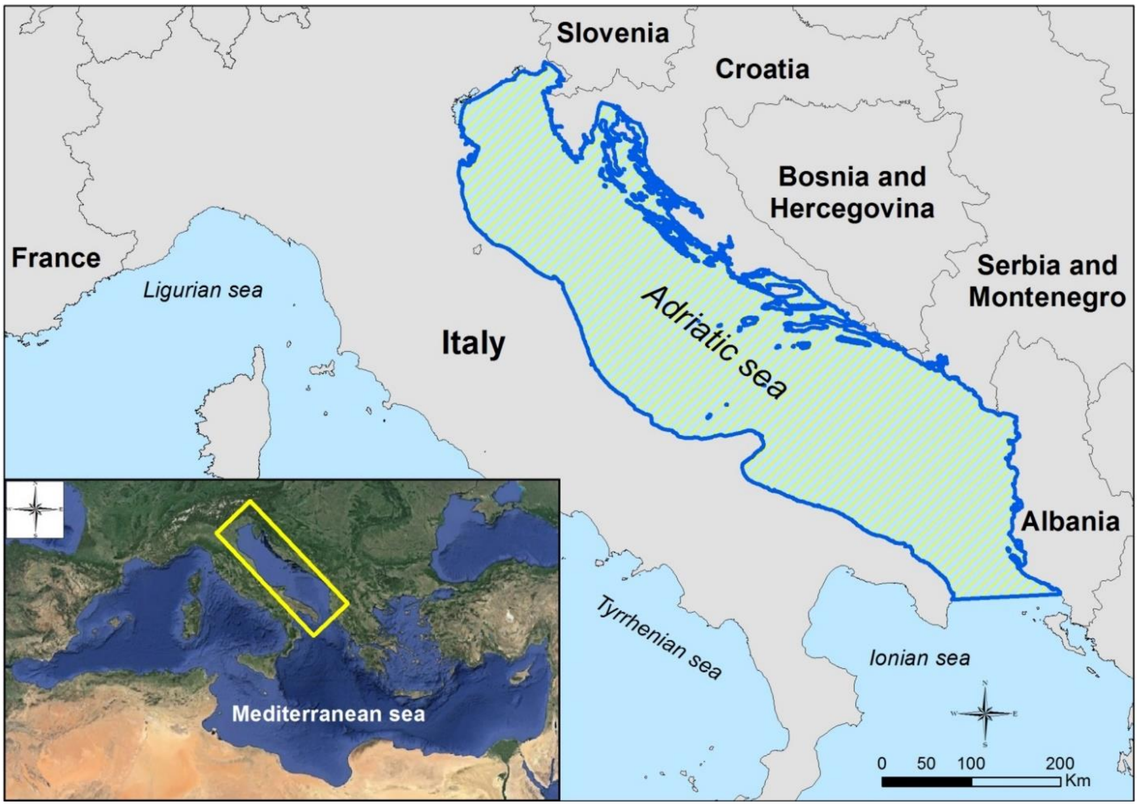


Figure 3.1 Spatial localization of the Adriatic sea case study area within the Mediterranean region

The Adriatic Sea is a semi-enclosed basin with a total surface of about 138,600 km² and a volume of 33,000 km³. Its shape can be approximated to a rectangle extending north-southwest, about 800 km long and 200 km wide (EC, 2011) (Ramieri E., 2014), bounded by the Italian peninsula at west, the Balkan peninsula at east and communicating with the Ionian Sea in the south through the Otranto Strait, which is the narrowest part of this marine area (75 Km wide). It is surrounded by six coastal states: Albania, Bosnia and Herzegovina, Croatia, Italy, Slovenia and Serbia-Montenegro, carrying out different interests for the use and exploitation of its space and marine resources.

The basin is divided into three major geographical parts: Northern, Central and Southern, where the coastal areas correspond to three continental shelves. Overall, the Adriatic sea is featured as a shallow enclosed sea area; however, the southern part of the region is far deeper than the northern one in the areas of the Pomo depression (-260 m) and the Pelagosa sill (-170 m) in the middle Adriatic, the wide abyssal depression (-1200 m) and the Otranto sill (-800 m) in the South Adriatic. The northern and northwestern coastlines are featured by shallow waters and sandy beaches, whereas the eastern part of the basin is deeper, rocky and comprises many islands and islets. The beauty and the high environmental value of the Adriatic Sea makes this region an attractive place to live and work: each year, more tourists spend holidays in the countries surrounding the Adriatic sea where important tourist destinations are located (e.g. Venice, Trieste, Dubrovnik, Rovinj) (Ramieri et al, 2014). However, this massive coastal and marine tourism, as well as multiple economic activities located along the coastline, are leading to increased sea pollution by marine litters, one of the major concern for the global oceans. Indeed, land-based sources (including land-based activities and coastal tourism), rather than ocean-based ones (e.g. shipping transport for touristic and commercial activities), result as the main sources of anthropogenic debris in the Mediterranean Seas (Suaria & Aliani, 2014; Galgani et al., 2013; UNEP, 2009). They represent a relevant environmental and economic threat for the biodiversity of marine ecosystems and the goods and services they provide (Sutherland et al., 2011).

As far as the economic side is concerned, the Adriatic sea is also an important maritime transport route, used by tourist and merchant ships in international and national trade, by yachts, fishing vessels and other non-merchant ships. A significant number of relevant industrial centers are located along the western Adriatic coasts (e.g. industrial area of Porto Marghera - Venice) and several mid-European countries highly depend on the Northern Adriatic ports (e.g. the port of Trieste, Venice, Koper and Rijeka) for importing energy. Moreover, apart from being an important maritime transport route, the Adriatic sea basin is among others a productive area for fishing (including the aquaculture activity). Fishing has traditionally been an important sector for most the Adriatic countries and Italy is by far the largest fishing fleet in the Adriatic (EC, 2011). However, the share of the fisheries sector in the national economies is decreasing. Fish stocks have suffered from overfishing and pollution caused by water discharges of industrial activities, agriculture and urbanized areas, especially in the Italian part of the Northern Adriatic Sea.

In this context of multiple human-made pressures taking place in the same marine space, a further complication is determined by climate change which poses additional exogenic pressures on this environment, through rising sea levels, increased sea temperatures and ocean acidification (IPCC, 2014). Climate change is a prominent issue for the Adriatic sea both considering the vulnerability of important ecosystems such as wetlands, seagrasses meadows and coral beds, and the concentration of relevant cultural and socio-economic values. The basin is known to have a large spatial and temporal variability (both seasonal and interannual) depending on its driving forcing (atmospheric and land-based). In this setting, is therefore quite important to evaluate, at the regional scale, the localization and extent of changes in the Adriatic sea case study, according to both endogenic and exogenic forcing, also considering potentially affected sensitive targets and their vulnerability to multiple and interactive pressures.

3.2 Available dataset for the case study area

Acquiring the necessary data, to inform impact assessment approaches in marine areas, is a difficult task, mainly because detailed data for coastal and marine habitats are far less organized and available than data for terrestrial environments (Grech, Coles, & Marsh, 2011). Accordingly, with the main aim of evaluating the effect of multiple threats on relevant marine habitat in the Adriatic sea case study, an in-depth research and collection of GIS-based dataset was performed, paying specific attention to their spatial resolution and homogeneous coverage for the whole basin. A variety of physical and environmental data, as well as data on main endogenic and exogenic drivers acting on the case study, were retrieved in order to characterize the spatial pattern and distribution of targets (e.g. seagrasses, marine protected areas) and their vulnerability.

The available dataset is summarized in Table 3.1, highlighting the main thematic area (i.e. data on marine physical and environmental features and endogenic/exogenic drivers), spatial domain and resolution, data source and update.

Data concerning the spatial distribution of human activities located in the Adriatic sea (i.e. ports, aquaculture facilities, shipping routes, offshore installations) were basically retrieved from web data portals of the SHAPE project '*Shaping an Holistic Approach to Protect the Adriatic Environment between coast and sea*' (http://www.shape-ipaproject.eu/) and the Adriplan project '*ADRiatic Ionian maritime spatial PLANning'* (http://adriplan.eu/), both focused on developing a multilevel and cross-sectorial governance systems for the Adriatic sea (Ramieri et al., 2014).

Table 3.1 Available GIS-based dataset for the application of the multi-risk approach in the Adriatic sea case study area

DATASET	SPATIAL DOMAIN AND RESOLUTION	UPDATE DATA	SOURCE
PHYSICAL AND ENVIRONMENTAL DATA			
Adriatic basin boundary	Adriatic sea, 1:50000	2013	http://atlas.shape-ipaproject.eu/
Marine administrative zones	Adriatic sea, 1:50000	2013	http://atlas.shape-ipaproject.eu/
Marine Protected areas (MPAs)	Global ocean 1: 1.000.000	2014	www.protectedplanet.net
	Adriatic sea, 1:50000	2013	http://atlas.shape-ipaproject.eu/
Sites of Community Importance (SCI), Zone of Special Protection (ZSP)	Adriatic sea, 1:50000	2013	http://atlas.shape-ipaproject.eu/
Nationally designated areas	Adriatic sea, 1:25000	2013	http://atlas.shape-ipaproject.eu/
Biologic protection zones (BPZ)	Adriatic sea, 1:10000	2013	http://atlas.shape-ipaproject.eu/
Fishing regulated areas	Adriatic sea, 1:1000000	2013	http://atlas.shape-ipaproject.eu/
EUSeaMap -seabed habitat map-	Adriatic sea, 1: 1.000.000	2014	http://www.emodnet.eu/seabed-habitats
Biodiversity Shannon's Index	Global scale, hex grid	2014	http://www.iobis.org/mapper/
Seagrass species richness	Global ocean 1: 1.000.000	2003	http://data.unep-wcmc.org/
ENDOGENIC AND EXOGENIC DRIVERS			
Ports and harbors	Adriatic sea, 1:50000	2014	http://atlas.shape-ipaproject.eu/
Platform and wells for hydrocarbon extraction	Adriatic sea, 1:50000	2014	http://atlas.shape-ipaproject.eu/
	European seas, 1:100000		http://www.emodnet.eu/human-activities
Regasification terminals	Adriatic sea, 1:500000	2014	http://atlas.shape-ipaproject.eu/
Underwater pipelines and cables	Adriatic sea, 1:50000	2014	http://atlas.shape-ipaproject.eu/
Foul areas	Adriatic sea, 1:50000	2014	http://atlas.shape-ipaproject.eu/
Wrecks	Adriatic sea, 1:50000	2014	http://atlas.shape-ipaproject.eu/
Dumping disposal sites	Adriatic sea, 1:100000	2014	http://atlas.shape-ipaproject.eu/
Dumped munitions sites	European seas, 1:100000	2014	http://www.emodnet.eu/human-activities
Dredge spoil dumping	European seas, 1:100000	2015	http://www.emodnet.eu/human-activities
Offshore dredged areas	Adriatic sea, 1:100000	2014	http://atlas.shape-ipaproject.eu/
Offshore sand deposits	Adriatic sea, 1:100000	2015	http://adriplan.eu/
Map of spatio-temporal distribution of trawling fishing pressure based on Vessel Monitoring System data (2007-2010)	Adriatic sea, 3x3Km grid	2010	http://adriplan.eu/
Mineral titles	Adriatic sea, 1:50000	2015	http://adriplan.eu/
Shipping traffic	Global ocean 1:1.000.000	2008	https://www.nceas.ucsb.edu/globalmarine
Ship accidents points - oil spills (1977-2014).	Mediterranean sea, 1:100000	2014	http://accidents.rempec.org/
Coastal artificial protection	Adriatic sea, 1:25000	2014	http://atlas.shape-ipaproject.eu/
Military practice areas	Adriatic sea, 1:50000	2014	http://atlas.shape-ipaproject.eu/
Sea surface temperature (SST)	Mediterranean sea, 1/7 degree	2015	http://www.perseus-net.eu
Chlorophyll 'a'	Mediterranean sea, 1/7 degree	2015	http://www.perseus-net.eu

As far as climate-driven pressures are concerned, sea temperature data in the Adriatic sea were provided by the Foundation Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC Foundation, www.cmcc.it) (Lovato et al., 2013; Oddo et al., 2014), whereas those on the chlorophyll 'a' variation (used for mapping nutrients input in the marine region) by the National Institute of Oceanography and Experimental Geophysics (OGS, http://www.ogs.trieste.it) (Lazzari et al., 2016 and 2014; Canu et al. 2015) within the climate simulation developed in the frame of the PERSEUS project '*Policy-oriented marine Environmental Research in the Southern EUropean Seas*' (http://www.perseus-net.eu). More specifically, since the assessment of potential impacts induced by temperature and nutrients input variation was focused on selected receptors such as shallow benthic habitats (e.g. seagrasses meadows and coral beds), sea surface data were used to represent water variations at the top layer of the Adriatic sea (Okey et al., 2015).

Both dataset were provided for the baseline and future climate change scenarios (i.e. 2000-2015 and 2035-2050) in order to evaluate the temporal evolution of key marine indicators for monitoring the progress towards the achievement of the Good Environmental Status (EC, 2008; EC, 2010). Climate projections used in the assessment were produced under the RCP 8.5 (Representative Concentration Pathways) emission scenario, representing rising radiative forcing pathway leading to 8.5 W/m2, due to an envisioned 2100 scenario including the absence of climate change policies and the increasing energy demand and GHG concentration. As a consequence, the sea surface temperature and chlorophyll 'a' projections represent the worst scenario in terms of radiative forcing (cumulative measure of human emissions of GHGs from all sources), (Riahi et al., 2011), thus applying in the assessment an highly precautionary perspective to these variables.

In some cases, the retrieved data were directly used to represent the intensity of pressures (e.g. intensity of shipping traffic already calculated by Halpern et al, 2008) or their mere presence/absence in the case study area (e.g. artificial benthic infrastructures leading to smothering and sealing of seabed). In other cases, when data on pressures' intensity and propagation were not available, different spatial modelling methodologies were used as proxies to derive pressures' spatial distribution and intensity (e.g. trawling fishing areas as a proxy for the seabed abrasion). In a nutshell, since there are no direct measurement for some of the considered pressures, they were estimated on the basis of the causative human activities, thus providing spatial modelling of their distribution on the marine area of concern (Andersen et al., 2013).

Finally, also the environmental dataset, supporting the identification of sensitive marine targets and the characterization of their vulnerability to the considered pressures, were mainly acquired by the web data portal of the SHAPE project (e.g. fishing regulated areas, marine protected areas, biological protection zones) with the exception of the seabed habitat map retrieved from the web-

GIS of the European Marine Observation and Data Network (http://www.emodnet.eu). Moreover, by means of the Ocean Biogeographic Information System (http://www.iobis.org/), a comprehensive open-access database of marine species datasets from all of the world's oceans, map representing the Shannon Diversity Index for the Adriatic sea, was retrieved with a hexagonal grid resolution (UNESCO, 2015).

All collected data were pre-processed in order to homogenize data format and their geographical reference system, as well as clip all layers on the Adriatic sea administrative boundaries for removing data outside the investigated area. As already mentioned, the process of data selection was focused on the availability of updated, homogenous and detailed (i.e. with high spatial resolution) data for the whole case study, in order to feature, as much as possible, marine targets and their vulnerability to the considered pressures in the area of concern. As a consequence, the accessible supporting dataset has played an important role in the definition of the multi-hazard methodology, leading to focus the analysis on environmental features and pressures that could be modelled with the available data.

4. Risk-based methodology for cumulative impact assessment in marine areas

The risk assessment methodology proposed in this thesis aims at evaluating cumulative impacts posed by multiple natural and anthropogenic pressures acting in concert on marine areas. More specifically, it supports the identification and relative ranking of multiple sources of hazard, habitats and targets at risk, and finally the integrated evaluation of cumulative environmental impacts in marine regions (Hayes & Landis, 2004).

The following Paragraphs describe the developed conceptual framework (Paragraph 4.1) and the step-by-step risk assessment procedure (Paragraphs 4.2-4.7), highlighting the input parameters and the mathematical equations applied in the Adriatic sea case study for the spatial modelling and aggregation of data in the final cumulative risk index (Paragraphs 4.3- 4.7).

4.1. Conceptual framework

The first step of an assessment process requires simple visualizing and summarizing linkages between all components and processes within complex environments, such as marine ecosystem. Accordingly, the development of a conceptual framework of relevant environmental and socio-economic impacts for the marine environment, including the qualitative evaluation of cause-effect processes is required. The Driver-Pressure-State change-Impact-Response (DPSIR) conceptual framework, developed by the European Environmental Agency (EEA, 1999), provides a widely recognized structure allowing to describe the relationships between the origins and consequences of environmental issues (Patrício et al., 2016; Gregory et al., 2013; Atkins et al., 2011; Borja et al., 2010). It is often used as the underlying concept for Risk Assessment and Risk Management (Borja et al. 2016; Cormier et al., 2010) since it helps to formalize the problem, showing in a systematic way the links between the source of risk, the pathways by which exposure might occur and the receptors. More specifically, the DPSIR framework defines a chain of causal links starting with the identification of the '*driving forces*' (D) representing natural and anthropogenic stressors which can lead to variations in the state of the environment and/or human systems. Driving forces, in turn, may exert intentionally or unintentionally exogenic (i.e. environmental pressures operating outside the control of management measures employed in a regional sea and where the management measures can only address the consequences rather than the cause) or endogenic (i.e. site-specific human activities carried out within an area) '*pressures*' on the environment. Pressures can change among geographic regions, spatial and temporal scales, leading to variation in the 's*tates*' of exposed systems. Finally, changes in the state of the system can cause multiple types of '*impacts*' (I) (e.g. biological, chemical physical) on the environment, human health and socio-economic activities, eventually leading to '*responses*' (R) (Kristensen, 2004).

Within this thesis it was adapted to identify main climate and land/sea-based drivers, as well as to highlight pathways of interaction between natural and anthropogenic pressures occurring in the case study area and potentially affecting sensitive receptors with high environmental and socio-economic value located in both seabed and water column (e.g. seagrasses, marine protected areas, aquacultures) (Figure 4.1). Moreover, in order to simplify framework's understanding, impacts (and related pressures) were distinguished according to their biological, chemical, climatic and physical nature.

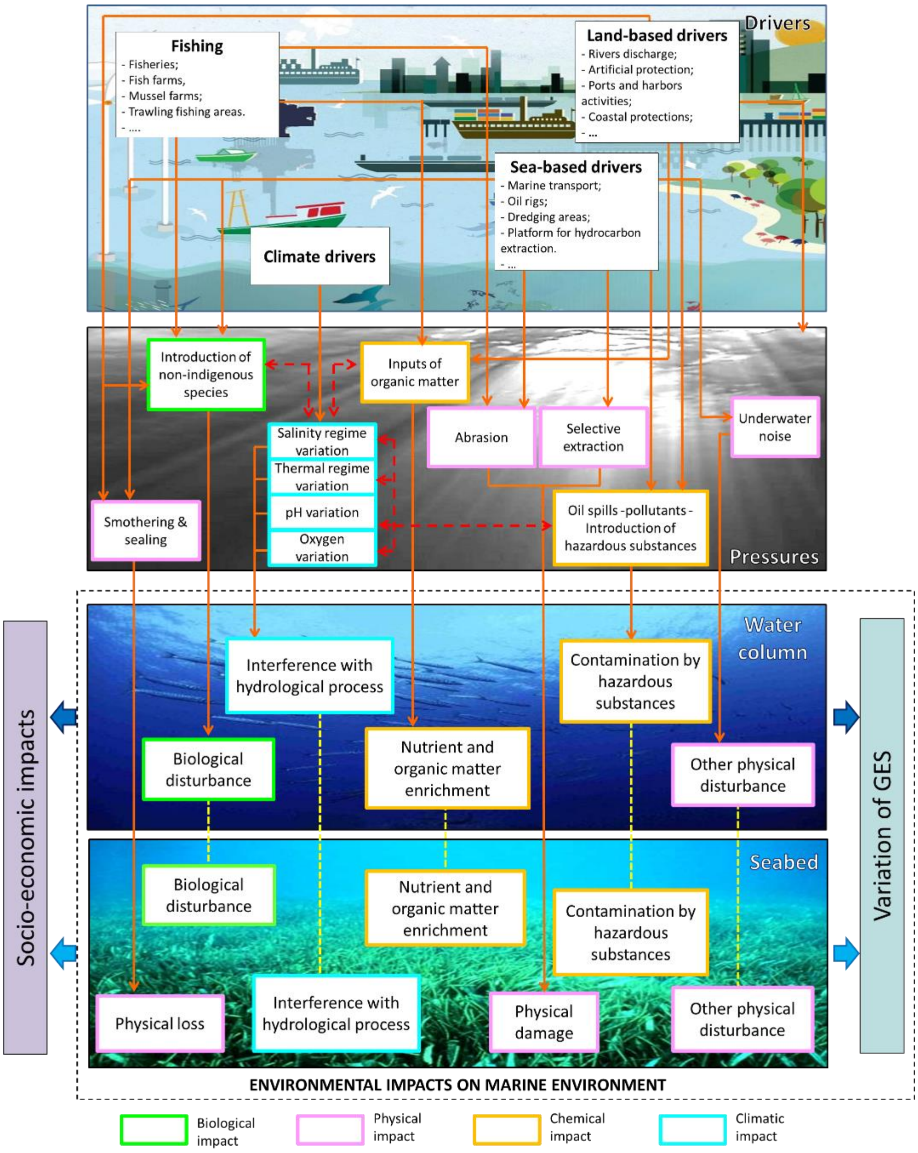


Figure 4.1 DPSIR-based conceptual framework highlighting pathways of interaction between selected drivers, pressures and impacts in the Adriatic sea case study

This framework was designed starting from the 8 impacts' categories (e.g. biological disturbance, physical damage, interference with hydrological processes) and related pressures listed in Annex 3, Table 2 of the Marine Strategy Framework Directive (MSFD, EC, 2008). Moreover, associated drivers to each pressures were identified based on the Italian Initial Assessment Reports of the marine environmental state, pointing out, for almost all pressures included in the MSFD, their drivers and suitable indicators and metrics for their evaluation in the different Italian marine assessment areas (ISPRA 2012a, b, c).

4.2. Multi-risk methodology

In line with the recent definitions of the IPCC (2014) and UNISDR (UN, 2009) the proposed multi-risk methodology is based upon the three main pillars of risk: hazard, exposure, and vulnerability considering risk as the potential adverse consequences for natural and human systems resulting from the interactions of hazards with vulnerabilities of the exposed systems (i.e. elements at risk).

Particularly, the proposed approach is composed of five consecutive steps: multi-hazard, exposure, vulnerability, risk and cumulative impacts assessment (Figure 4.2). Compared to traditional regional risk assessment (Torresan et al., 2016; Ronco et al. 2015; Sperotto et al., 2016), the first phase consists in the multi-hazard assessment which aggregates metrics and scenarios of climate, ocean, bio-geochemical and anthropogenic pressures (e.g. temperature variation, bottom stress by abrasion and sealing, oil-spill) in order to shape interactive behaviors between pressures leading to more severe hazards (e.g. biological hazard related to sea surface temperature variation, shipping traffic, ports activities, aquaculture), naturally occurring in complex and dynamic systems such as marine areas (Crain et al., 2008; Brown et al., 2014). The exposure assessment identifies and localizes key receptors that could be subject to potential losses in marine areas (e.g. seagrasses and coral and maërl beds). Subsequently, the vulnerability assessment, is aimed at evaluating the degree to which receptors could be adversely affected by the multiple types of hazards, based on their specific physical and environmental features (e.g. habitat extent and typology, biodiversity indexes). The following relative risk assessment phase combines all the information about the considered multi-hazards, exposure and vulnerabilities, thus supporting a quick screening of areas at greatest risk from the considered stressors, where the achievement of GES, as required by the MSFD (EC, 2008), could be compromised for specific environmental descriptors (e.g. sea-floor integrity, eutrophication, non-indigenous species). Finally, the conclusive cumulative impact assessment phase, supports the integration of all the analyzed risks in order to develop a synthetic index providing an overall picture of the areas mostly affected by cumulative impacts, where focused management actions and adaptation strategies would be best targeted.

A detailed explanation of the main terms applied within the developed multi risk methodology is included in the Annex B, supporting a better understanding of the differences that exist between concepts and terminologies used across risk assessment.

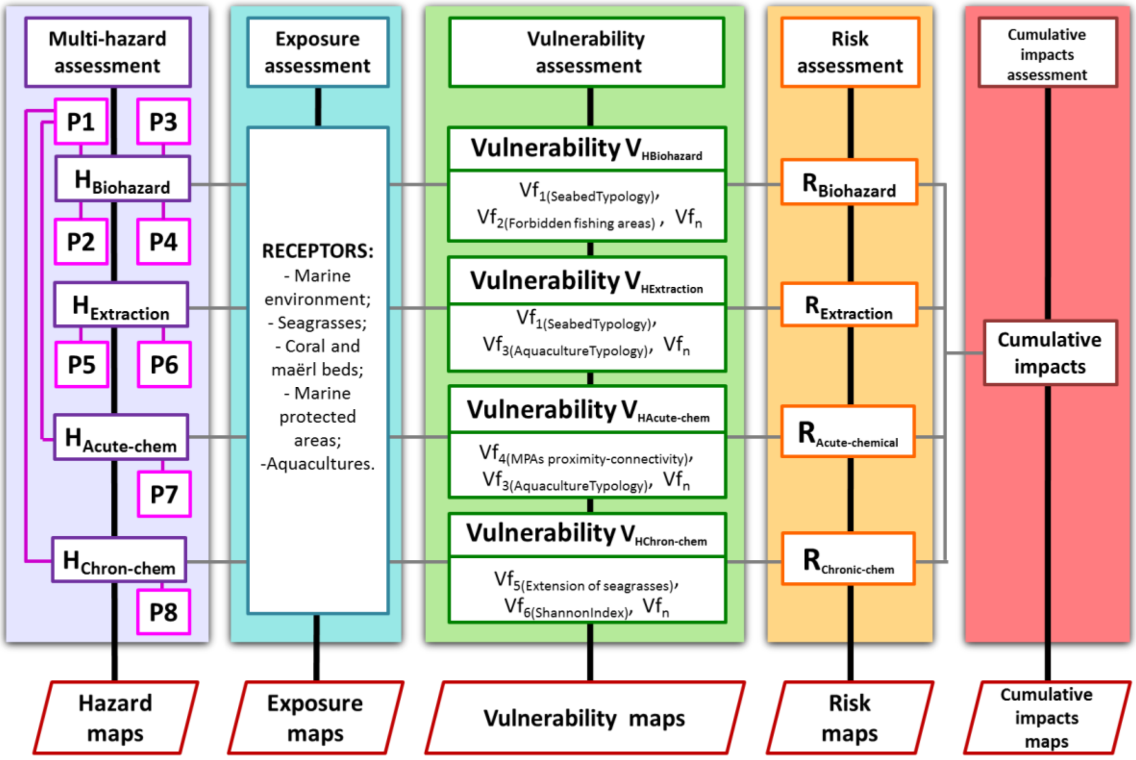


Figure 4.2 Risk-based conceptual framework for the evaluation of cumulative environmental impacts in marine areas

The application of each step of the methodology, described in the following paragraphs, requires the management and pre-processing of a huge amount of heterogeneous input data that are normalized and aggregated through Multi-Criteria Decision Analysis (MCDA), in order to provide spatial information useful to planners and decision makers involved in the management and setting of marine areas.

4.3. Multi-hazard assessment

The first step of the proposed methodology is the multi-hazard assessment which allows to aggregate information about multiple and overlapping hazards determined by natural and human pressures affecting the marine environment. The assessment can be performed for a baseline (reference) scenario representing the actual situation (e.g. 2000-2015) and for a future scenario (e.g. mid or long term timeframe) considering the potential effects of climate change and/or marine use changes.

To this aim it is firstly required to associate to each hazard all pressures concurring to its estimate (e.g. pressure of introduction of non-indigenous species related to the anthropogenic biohazard) and then identify their related main driving forces (e.g. maritime traffic, ports and harbors activities, aquacultures, temperature regime variation) which can often interact with each other. Based on the Italian Initial Assessment Reports (ISPRA 2012a, b, c) different metrics can be used to represent the intensity and spatial distribution of pressures based on their drivers (e.g. intensity of shipping traffic, variation in Chlorophyll 'a' concentration). Once modelled pressures, then it is necessary to evaluate how each pressure can interact with the others, determining triggering or synergic/antagonistic effects and thus a more complex hazard. Indeed, each hazard can be induced by single or multiple pressures, that acting in concert can assume additive (i.e. localization of benthic infrastructures leading to smothering and sealing of the seabed and, in turn to the anthropogenic introduced technological hazard) or interactive behaviors (e.g. nutrients input and temperature regime variation contributing to inputs of organic matter and, in turn the anthropogenic chronic chemical hazard).

Accordingly, the multi-hazard assessment phase is performed through the following operative steps:

1. Selection of the hazards of relevance for the case study and identification of their main pressures, drivers and related metrics.
2. Spatial representation of pressures into GIS-based data layers.
3. Integration and normalization of pressures through specific MCDA functions, in order to simulate interactive behaviours between pressures in the marine environment.

In the following Ppragraphs the multi-hazard assessment methodology, specifically developed for the Adriatic sea case study (Paragraph 3), is described, ad related resulting output, including GIS-based maps and statistics are showed in the Chapter 6.

4.3.1. Hazards selection and identification of main drivers, pressures and related metrics

For the application of the multi-hazard assessment phase in the Adriatic sea case study a set of 6 hazards representing human-derived stressors causing either temporary or permanent physical disturbance, loss or damage to one or several components of an ecosystems, were selected. As already anticipated (Paragraphs 4.1 and 4.3), they were chosen according to the Annex 3, Table 2 of the MSFD (e.g. smothering and sealing of seabed, abrasion and extraction of seabed, underwater noise, biological disturbance by the introduction of non-indigenous species; EC, 2008), whereas their driving-forces were identified according to the Italian Initial Assessment Reports of the marine environmental state (ISPRA 2012a; c; d). Moreover, the selection of hazards, and their related pressures at case study level, was influenced by the availability of homogeneous and high resolution data (Paragraph 3.2) covering the whole Adratic sea. As a consequence, not all pressures listed in the MSFD (Annex 3, Table 2) (EC, 2008) were included in this study (e.g. marine litter). The selected hazard, mentioned based on the definition provided by Patrício et al. (2014), are reported in Table 4.1 also including main pressures, drivers and the related metrics.

Table 4.1 Main pressures, drivers and metrics representing the selected hazards

Hazards	Pressures	Drivers	Metrics
Anthropogenic introduced technological hazard	Smothering and sealing of the seabed	Benthic infrastructures such as: platforms and wells for hydrocarbons' extraction, regasification terminals, coastal artificial protections, ports and harbors infrastructures, cables and pipelines, areas for unexploded ordinances' sinking, area of military practice, wrecks	Presence/absence of benthic anthropogenic infrastructures located on the seabed
Anthropogenic extractive technological hazard	Abrasion and extraction of seabed	Trawling fishing activities	Trawling fishing efforts expressed in hours of fishing activities
		Dredging and resources' extraction activities	Intensity of dredging activities, expressed in m3 of dredged material
Anthropogenic physical hazard by underwater noise	Underwater noise	Maritime traffic	Intensity of shipping traffic
		Platforms and wells	Activity of hydrocarbons' extraction
Anthropogenic biohazard	Introduction of non-indigenous species	Maritime traffic	Intensity of shipping traffic
		Ports and harbors activities	Intensity of ports activity based on the transport of goods, expressed in thousand tons per year
		Aquacultures	Presence/absence of aquacultures including fish and mussel farms
		Temperature regime variation	Number of unusually sea surface warm events
Anthropogenic chronic chemical hazard	Inputs of organic matter	Nutrient input by rivers discharge and urban waste water	Variation in sea surface Chlorophyll 'a' concentration (Chl 'a')
		Temperature regime variation	Number of unusually sea surface warm events
Anthropogenic acute chemical hazard	Introduction of hazardous substances by oil-spills	Maritime accidents leading to oil-spills	Occurrence of ship accidents resulting in oil spills
		Temperature regime variation	Number of unusually sea surface warm events

🟩 Biological impacts

🟥 Physical impacts

🟨 Chemical impacts

Based on the classification applied in the conceptual framework (Paragraph 4.1), hazards included in the pink cells concerns the physical impacts (i.e. physical damages and losses by abrasion and sealing of the seabed), the green one the biological impact (i.e. biological disturbance by the introduction of non-indigenous species) and, finally, hazards highlighted with the orange cells the

chemical impacts (i.e. chemical acute and chronic sea pollution by oil-spill and nutrients input).
Even though the MSFD doesn't explicitly account for climate change, despite it was given greater prominence in the proposed Directive (EC, 2005), the analysis was expanded by including exogenic pressures such as the variation in the sea surface temperature (SST) related to climate change. The main aim was to analyze how these pressures can interact with endogenic ones, thus leading to more severe hazards able to influence or inhibit the MSFD implementation and the achievement of GES (EC, 2008). Indeed, it is widely recognized how climate change is already affecting and will continue threatening the structure, function and processes of ecosystems (IPCC, 2014a) and, as such, will result in 'shifting baselines' which need to be accommodated in monitoring, and 'unbounded boundaries' (i.e. climate change-induced migrations and dispersal of highly-mobile, nekton and plankton specie) compromising the use of static reference conditions or targets in the evaluation of GES (Elliott et al., 2015; Patrício et al., 2014).

4.3.2. Spatial modelling of pressures' distribution in marine areas

Based on an in-depth literature review of already applied methodologies for cumulative impact assessment in marine areas (Paragraph 2) (Andersen et al., 2013; Micheli et al., 2013; Kappel et al., 2012; Korpinen et al., 2012; Ban et al., 2010; Halpern et al., 2008) the spatial modelling of pressures has followed specific procedures, aimed at developing credible scenarios representing potential circumstances where accidental emissions and pressures to the environment are thought to be most likely occurring based on the supporting dataset, and at locations where the most potential damage might occur in both the considered timeframes scenarios (i.e. 2000-2015 and 2035-2050). Moreover, some of the applied methodologies were fine-tuned according to the metrics and thresholds pointed out for the Adriatic sea in the Italian Initial Assessment Reports related to the MSFD (e.g. evaluation of nutrients input by assessing values of Chlorophyll 'a' exceeding the defined threshold of 0.2 µg/L) (ISPRA, 2012a). In order to maintain the highest spatial resolution and fit to the requirements of the Italian Initial Assessment Reports (ISPRA 2012b; c), the spatial modelling was based on a spatial unit (i.e. grid cell) of 100m. For each previously identified metrics (Table 4.1) (e.g. intensity of shipping traffic, number of unusually sea surface warm events, presence/absence of aquacultures) the following table (Table 4.2) summarizes the methodologies applied to spatially model pressures contributing to each hazard, also reporting the related equations (i.e. Equations 1-10).

Table 4.2 Metrics, methodologies and related equations applied to spatially model pressures contributing to each hazard selected for the Adriatic sea case study

Metrics	Spatial modelling	Equations
Presence/absence of benthic anthropogenic infrastructures	Human-made infrastructures built in the sea lead to smothering and sealing of seabed thus leaving a strong footprint of destroyed habitat where they are located. Based on the Italian initial assessment report on 'physical loss' (ISPRA, 2012) for spatially modelling this pressure data on benthic infrastructures (e.g. pipelines, platforms and wells for hydrocarbons' extraction, regasification terminals, coastal artificial protections) were collected and then merged in a unique raster map. Each cell of this map was then reclassified assigning a maximum intensity equal to 1 when benthic infrastructures are present and minimum intensity equal to 0 when they are not, thus representing a proxy of distribution and intensity of smothering and sealing of the seabed.	**Equation 1:** $I_{smoth-seal} = \begin{cases} 0 & \text{if no benthic infrastructures are present in the investigated cell} \\ 1 & \text{else} \end{cases}$ Where: $I_{smoth-seal}$= intensity of smothering and sealing of the seabed.
Trawling fishing efforts expressed in hours of fishing activities	According to the method pointed out in the Italian initial assessment report on 'physical damage'(ISPRA, 2012b), to model spatial distribution of trawling fishing, data representing the effort of trawling for demersal species was used, in which the pressure's intensity was featured based on the hours of activity per cell. Supporting dataset were estimated in the 2013 using the Vessel Monitoring System (VMS) (Russo et al., 2011).	**Equation 2:** $I_{traw} = \frac{\text{Tothtraw}_i}{\text{maxTothtraw}}$ Where: I_{traw}= intensity of trawling fishing effort; Tothtraw_i= total number of hours of trawling activities in the cell *i* evaluated for the 2013, by means of Vessel Monitoring System-VMS. maxTothtraw = maximum number of hours of trawling activities in the case study area for the 2013.
Intensity of dredging activities expressed in m3 of dredged material	In order to model spatial distribution of sands' dredging and extraction activities the location of exploited dredging areas was used, in which the pressure's intensity was featured based on the amount of dredged sands (cubic meters).	**Equation 3:** $I_{dredg} = \frac{\text{Totdredm}_i}{\text{maxTotdredm}}$ Where: I_{dredg}= intensity of sands' dredging and extraction on the seabed; Totdredm_i= total cubic meters of dredged sands in the cell *i* calculated in the 2013 for the extraction sites. maxTotdredm = maximum cubic meters of sands dredged in the extraction sites located in the case study area, calculated in the 2013.
Intensity of shipping traffic	For modelling spatial distribution of the maritime traffic map developed by Halpern et al. (2008) at the global scale was used. Data included in the Adriatic Sea case study were normalized in a 0-1 range based on the maximum intensity detected in the area of concern.	**Equation 4:** $I_{ship} = \frac{\text{ShipAdriatic}_i}{\text{maxShipAdriatic}}$ Where: I_{ship}= intensity of shipping traffic normalized for the Adriatic sea case study; ShipAdriatic_i= intensity of shipping traffic in the cell *i* within the Adriatic sea case study, as calculated by Halpern et al. (2008). maxShipAdriatic = maximum intensity of shipping traffic, calculated in the Adriatic sea by Halpern et al. (2008).

Metrics	Spatial modelling	Equations
Activity of hydrocarbons' extraction	To spatially model noise produced by the activity of hydrocarbons' extraction, starting from the localization of the extraction platforms and wells, a simplified spatial model was applied in order to represent the underwater noise propagation with a maximum limit of propagation set to 1 Km (i.e. local model, Andersen et al. 2013). More specifically in the applied model, the noise intensity linearly decrease from the maximum score equal to 1 (corresponding to the point where the extraction platform is located) to 0, for those pixels located to a greater distance than 1 Km, simulating, in this way, a 'proxy propagation' of sound waves in the sea (Andersen et al., 2013).	**Equation 5:** $I_{hyd} = \sum_{p \in P} \max\left(0, 1 - \frac{d(p)}{k}\right)$ Where: P= total amount of platforms and wells for hydrocarbon extraction located in the case study area. k= constant threshold for underwater noise propagation (i.e. 1km for the case study area) as defined by Andersen et al. (2013). $d(p)$ = distance function which returns the point's distance p from the pixel of concern.
Intensity of ports' activities	To model spatial distribution of ports' activities, the location of ports and harbors in the Adriatic sea was used, in which the pressure's intensity was shaped based on the mean value of tons of goods transported in the 2000-2012 time window (Eurostat data, http://maratlas.discomap.eea.europa.eu).	**Equation 3:** $I_{ports} = \frac{\text{MeanTons}_i}{\text{maxMeanTons}}$ Where: I_{ports}= intensity of ports' activities; MeanTons $_i$= mean value of tons of goods transported in the cell *i* in the 2000-2012 time window, within the Adriatic sea. maxMeanTons = maximum average value of tons of goods transported in the ports of the Adriatic sea, in the 2000-2012 timeframe.
Presence/absence of aquacultures including fish and mussel farms	In order to model spatial distribution of aquaculture activities data on fish and mussel farms were collected and then merged in a unique raster map. Each cell of this map was then reclassified assigning a maximum intensity equal to 1 when benthic aquacultures are present in the case study and minimum intensity equal to 0 when they are not, thus representing a proxy of distribution and intensity of aquaculture activities.	**Equation 7:** $I_{aqua} = \begin{cases} 0 & \text{if no aquaculture are present in the investigated cell} \\ 1 & \text{else} \end{cases}$ Where: I_{aqua}= intensity of aquaculture activities in the Adriatic sea case study.
Number of unusually sea surface warm events	According to (Halpern et al., 2008), intensity of sea surface temperature (SST) variation was modelled by calculating the total number of positive anomalies of SST for each cell of the case study area, representative of unusually warm in the baseline 2000-2015 and future scenario 2035-2050. More specifically, the procedure consists of the following steps: 1. Evaluation of the weekly temperature means for the considered timeframe scenario (2000-2015 and 2035-2050, climatology) (e.g. mean value of SST of the first week of January for all the years of the analyzed scenarios). 2. Based on the evaluated mean, calculation of the standard deviation; 3. Sum of the mean and the standard deviation in order to define the reference threshold for the identification of unusually warm temperatures in both scenarios; 4. Evaluation of the positive anomalies between the defined threshold and the daily SST value (i.e. number of events exceeding the defined threshold for each week and year of the considered timeframes). 5. Estimate of the total number of positive anomalies for each cell of the case study area and considered timeframes. Resulting values were normalized in a 0-1 range for both the considered timeframe scenarios (baseline 2000-2015 and future 2035-2050 scenarios), based on the maximum number of sea surface temperature positive anomalies calculated in the case study area	**Equation 8:** $I_{SST} = \frac{\text{TotSSTanom}_i}{\text{maxSSTanom}}$ Where: I_{SST}= intensity of the sea surface temperature regime variation; TotSSTanom$_c$ = total number of sea surface temperature positive anomalies (unusually warm events) calculated in the cell *i* for the case study area and considered timeframe scenarios 2000-2015 and 2035-2050; maxSSTanom = maximum number of sea surface temperature positive anomalies (unusually warm events) calculated in the case study area and considered timeframe scenario scenarios 2000-2015 and 2035-2050.

Metrics	Spatial modelling	Equations
	within both scenarios.	
Variation in Chlorophyll concentration (Chl ‘a’)	Based on the Italian initial assessment report on ‘enrichment of nutrients and organic matter’ (ISPRA, 2012a) to each cell (pixel) of the developed raster map, an intensity values of chlorophyll ‘a’ variation was assigned in relation to areas where values of chlorophyll 'a' were greater than 0.2 µg/L. This value corresponds to the threshold pointed out by ISPRA as the limit below which the impact can be considered negligible when assessing GES for the MSFD descriptor 5 ‘Eutrophication’ (ISPRA, 2012a; EC, 2008). Resulting values were normalized in a 0-1 range for both the considered timeframe scenarios (baseline 2000-2015 and future 2035-2050 scenarios), based on the maximum sea surface chlorophyll ‘a’ concentration calculated in the case study area within both scenarios.	**Equation 9:** $I_{Chl'a'var} = \frac{[Chl\ 'a']_i}{\max[Chl\ 'a']}$ Where: $I_{Chl'a'var}$= intensity values of chlorophyll ‘a’ variation in the Adriatic sea case study; $[Chl\ 'a']_i$ = sea surface chlorophyll ‘a’ concentration in the cell i for the baseline scenario 2000-2015 and future scenario 2035-2050; $\max[Chl\ 'a']$ = maximum sea surface chlorophyll ‘a’ concentration calculated in the case study area within the future scenario 2035-2050.
Occurrence of ship accidents resulting in oil spills	According to Micheli et al. (2013) intensity of oil-spill was spatially modelled by assigning an intensity value ranging from 0 to 1 depending on the presence and frequency of shipping accidents resulting in oils-spill in the Adriatic sea between 1977-2014. A simplified spatial model was applied (Andersen et al., 2013) shaping hydrocarbons’ propagation in the case study with a maximum limit of propagation set to 25 Km (Micheli et al., 2013). The intensity value of oil-spill was evaluated, for each cell of the case study, as the distance-weighted number of detected shipping accidents resulting in oils-spill within a 25 km radius. These values linearly decrease from the maximum intensity value equal to 1 (corresponding to the location where, according to the collected data, a shipping accident is occurred) to 0 for all cells located at a greater distance of 25 Km.	**Equation 10:** $I_{oilspill} = \frac{\sum_{p \in P} \max\left(0,1-\frac{d(p)}{k}\right)}{\text{maxOilSpill}}$ Where: $I_{oilspill}$= intensity of oil-spill due to shipping accidents in the Adriatic sea; P = total amount of shipping accidents resulting in oils-spill in the case study area; k = constant thresold for the hydrocarbons’ propagation (i.e. 25km for the case study area); $d(p)$ = distance function which returns the point's distance p from the pixel of concern.

4.3.3. Integration and normalization of pressures to shape the multi-hazard

Once developed all the raster maps, representing the spatial distribution and intensity of pressures contributing to the selected hazards (e.g. anthropogenic extractive technological hazard, anthropogenic biohazard), specific MCDA aggregation functions were applied in order to shape the final hazard scenarios for the case study. MCDA includes a large class of methods for the evaluation and ranking of different alternatives, that considers all the aspects of a decision problem involving many actors (Malczewski, 1999; Giove et al., 2009).

As far as physical hazards are concerned (i.e. anthropogenic extractive technological hazard, anthropogenic physical hazard by underwater noise) a simplified additive MCDA model was applied, in order to integrate all pressures contributing to the final hazard scenarios. More specifically, to evaluate the hazard scenario related to the **anthropogenic extractive technological hazard** raster maps with spatial distribution and intensity of the considered pressures (i.e. abrasion and extraction of seabed due to trawling fishing and dredging and resources' extraction activities) were added up and then the resulting values normalized (in a 0-1 range) for the maximum value obtained in the case study area.

The hazard score for the anthropogenic extractive technological hazard was, therefore, evaluated as follows:

$$Hs_{extr} = \frac{(I_{traw}+I_{dredg})_i}{\mathrm{maxItot}} \qquad \text{Equation 11}$$

Where:

Hs_{extr}= hazard score related to the anthropogenic extractive technological hazard, due to the abrasion and extraction of the seabed;

$(I_{traw} + I_{dredg})_i$ = sum of the 'intensities' evaluated for the sands' dredging and extraction and trawling fishing for the cell *i*.

$\mathrm{maxItot}$ = maximum intensity of sand dredging and trawling fishing activities, calculated in the Adriatic sea case study.

Regarding the **anthropogenic physical hazard induced by underwater noise**, once computed the raster maps of the two considered activities (i.e. maritime traffic and of hydrocarbons' extraction), the obtained values were summed up and then normalized (in a 0-1 range) for the maximum value gets in the case study area. The hazard score for the anthropogenic physical hazard by underwater noise was, therefore, calculated as follows:

$$Hs_{noise} = \frac{(I_{ship} + I_{hyd})_i}{\text{maxItot}} \qquad \text{Equation 12}$$

Where:
Hs_{noise}= hazard score related to the anthropogenic physical hazard induced by underwater noise;
$(I_{ship} + I_{hyd})_i$ = sum of the intensities linked with the maritime traffic and the activities for the hydrocarbons' extraction for the cell i.
maxItot = maximum intensity linked with the maritime traffic and the activities for the hydrocarbon extraction in the case study area.

For what concern the **anthropogenic biohazard and the chronic and acute chemical hazards**, a different approach was applied, by considering interactive behaviors between pressures contributing to the same hazard scenarios (e.g. interactive pressures of shipping traffic, ports and aquacultures activities and SST variation contributing to the biological hazard).

In this case, the MCDA aggregation function selected for shaping the hazard scenarios was the Choquet integral which allows, by the use of a mapping between criteria values and scores established by environmental experts, to mimic non-linear behaviour and supply a complete ordered ranking of the considered alternatives (Choquet, 1954; Murofushi and Sugeno, 1989). It is a discrete fuzzy integral introduced by Choquet (1954), which has found increasing application in the context of environmental assessment and management (Delavar et al., 2015; Zabeo et al. 2010, 2011; Pizzol et al. 2011; Paoli et al., 2007). It generalizes additive operators, such as the ordered weighted average (OWA) or the weighted mean, and perfectly fits in situations where antagonistic and synergic effects are present between the criteria to be aggregated (e.g. interacting pressures in the marine environment).

The advantage of the proposed methodology consists in the possibility to evaluate also conflicting or synergic effects among all the considered pressures thus shaping natural interaction occurring in dynamic ecosystems such as marine areas. As a drawback, it requires many more parameters than other MCDA methods but it can be used to approach many cumbersome problems (Zabeo et al., 2011). Indeed, the application of the Choquet integral requires to assign specific weights (i.e. interaction weights) to each combinations that can occur between the interactive pressures considered for each hazard, where the number of coalitions to be evaluated depends on the number of the considered parameters (in this case the selected pressures for each hazard). As a consequence, the resulting hazard scenario is not represented by a linear function, and experts' knowledge about synergic interactions between pressures is embedded in the MCDA integration model.

In order to set these interaction weights, for all the pressures' combination, a questionnaire was developed and provided to selected experts across Europe in the field of environmental/marine sciences and chemistry, risk assessment, ecological and physical modelling and maritime spatial planning and management. This questionnaire, after a short description of the issue of concern and the case study area, provides one table to be filled in for each analysed hazard (i.e. anthropogenic biohazard and chronic and acute chemical hazards), representing all the potential coalitions between pressures (Annex C). Table 4.3 shows an example of the tables included in the questionnaire, providing all the coalition scenarios within the biological hazard. In every table, experts are called to assign an interaction weight in the [0,100] closed set to a certain scenario, identified by combinations of interactive pressures for the related hazard to be investigated (i.e. rows of the questionnaire's tables). Each pressure is classified in the 0-1 range (after applying the normalization functions for spatial modelling pressures, Paragraph 4.3.2) where 1 stands for the presence of the pressures in its maximum value within its ranging classes (i.e. maximum influence in the hazard estimation) and 0 stands instead for its presence at the minimum value (i.e. minimum influence in the hazard estimation). The assigned interaction weight, for each pressures' combination, represents the hazard level of the analyzed scenario, where 0 should be interpreted as the hazard null and 100 to the maximum.

Table 4.3 Table included in the questionnaire provided to selected experts in the field of marine science to elicit the interaction weights between pressures considered for the biological hazard

Anthropogenic biohazard				
SST variation	Shipping traffic	Port activity	Aquaculture	**Interaction weight**
0	0	0	0	
1	0	0	0	
0	1	0	0	
0	0	1	0	
0	0	0	1	
1	1	0	0	
1	0	1	0	
1	0	0	1	
0	1	1	0	
0	1	0	1	
0	0	1	1	
1	1	1	0	
1	1	0	1	
1	0	1	1	
0	1	1	1	
1	1	1	1	

In order to better fill in the questionnaire, the three following axioms were provided to the experts, explaining the basics concepts of the Choquet integral:

- 0: an empty set has no importance (0).
- 1: the maximum set has a maximal importance (100).

- A new added criterion cannot make the importance of a coalition (a set of p) decrease. For instance, if the expert assigns a score equal to 20 to the coalition 1-0-0, then the combination 1-1-0 can assume only values higher than 20.

The first and the second conditions are intuitive border conditions, while the second one is a monotonicity constraint that intuitively states that when more criteria are satisfied (concurring pressures), the global satisfaction cannot decrease (Choquet, 1954).

The resulting output from the collected questionnaire are shown in the three tables included in Table 4.4, summarizing the interaction weights provided by the involved experts for all the coalition scenarios between pressures, against the three hazards of concern (i.e. anthropogenic biohazard, anthropogenic chronic and acute chemical hazard). Weights defined by experts were aggregated by calculating the average values between responses provided for all the combinations, in order to get a final measure (i.e. interaction weight) to be integrated in the developed MCDA model.

Table 4.4 Tables representing the interaction weights assigned by involved experts to all the coalition scenarios within the anthropogenic biohazard (A), anthropogenic chronic (B) and acute chemical hazard (C)

Anthropogenic biohazard				
SST variation	Shipping traffic	Port activity	Aquaculture	**Interaction weight**
0	0	0	0	0
1	0	0	0	42
0	1	0	0	17
0	0	1	0	19
0	0	0	1	8
1	1	0	0	58
1	0	1	0	61
1	0	0	1	48
0	1	1	0	36
0	1	0	1	25
0	0	1	1	28
1	1	1	0	82
1	1	0	1	72
1	0	1	1	69
0	1	1	1	43
1	1	1	1	100

Anthropogenic acute chemical hazard		
SST variation	Oil-spill	**Interaction weight**
0	0	0
1	0	8
0	1	85
1	1	100

Anthropogenic chronic chemical hazard		
SST variation	Nutrient input	**Interaction weight**
0	0	0
1	0	26
0	1	70
1	1	100

Once measures to be used for shaping the final hazard scenarios are defined (i.e. normalized intensity of interactive pressures and interaction weights for each pressures' coalitions), the Choquet integral, parameterized on these measures, can be applied.

The Choquet integral is defined as follows (Choquet, 1954):

Let $\boldsymbol{\mu}$ (i.e. interaction weights) be a measure on $\boldsymbol{X}$ (i.e. considered interactive pressures for each hazard), whose elements are denoted $\boldsymbol{x_1}, \dots, \boldsymbol{x_2}$ here (i.e. intensity of interactive pressures).
The discrete Choquet integral of a function $\boldsymbol{f}: \boldsymbol{X} \rightarrow \mathbb{R}^+$ with respect to $\boldsymbol{\mu}$ is defined by:

$$\boldsymbol{H_\mu}(\boldsymbol{f}) \coloneqq \sum_{\boldsymbol{i=1}}^{\boldsymbol{n}} \left(\boldsymbol{f}\left(\boldsymbol{x}_{(\boldsymbol{i})}\right) - \boldsymbol{f}\left(\boldsymbol{x}_{(\boldsymbol{i-1})}\right)\right) \boldsymbol{\mu}(\boldsymbol{A}_{(\boldsymbol{i})}) \qquad \text{Equation 13}$$

Where:

$\cdot_{(\boldsymbol{i})}$ = indicates that the indices have been permuted so that $\boldsymbol{0} \leq \boldsymbol{f}(\boldsymbol{x}_{(\boldsymbol{1})}) \leq \cdots \leq \boldsymbol{f}(\boldsymbol{x}_{(\boldsymbol{n})})$, $\boldsymbol{A}_{(\boldsymbol{i})} \coloneqq \{\boldsymbol{x}_{(\boldsymbol{i})}, \dots, \boldsymbol{x}_{(\boldsymbol{n})}\}$, and $\boldsymbol{f}\left(\boldsymbol{x}_{(\boldsymbol{0})}\right) = \boldsymbol{0}$.

In the proposed case the $\boldsymbol{f}$ function is set to be the identity function such that $\boldsymbol{f}(\boldsymbol{x}) = \boldsymbol{x}$, therefore the results of the application of the Choquet integral are directly related only to the measure $\boldsymbol{\mu}$ (interaction weights) and the values in $\boldsymbol{X}$ (intensities of the interactive pressures).
The assigned scores to each combinations of interactive pressures (for the related hazard) were mathematically integrated and processed through specific developed GIS-tools (Zabeo et al., 2011), leading to produce the final hazard scenarios, representing the integration of every kind of combination among pressures, as the ones that can naturally occur on the case study area. The resulting hazard score ranges from 0 to 1, in which 0 represent cells with hazard null (i.e. there is no interactive pressures) whereas 1 the higher hazard in the investigated area.

4.4. Expoure assessment

The exposure assessment phase aims to identify, select and localize key receptors (i.e. elements potentially at risk) and hot-spot areas characterized by high environmental and socio-economic value that could potentially be in contact with the considered hazard and, therefore, exposed to losses in affected marine areas. More specifically, this step allows the identification of all the receptors (i.e. r1, r2, r3,…, rn) to be considered in the geographic marine sub-region and for the selected timeframe; they can be chosen according to the objectives of the study, the spatial scale of the analysis and the available dataset. In this study, receptors were selected according to the availability of homogeneous dataset for the area of concern as well as to the requirements of the MSFD thus focusing on relevant targets for the evaluation of the marine environmental state (i.e. environmental state's indicators) (EC, 2008; EC, 2010). As a consequence the assessment was focused on valuable habitats such as seagrasses meadows and coral and maërl beds, both playing an important role as nursery areas for several species as well as for carbon regulation and fisheries

(Salomidi et al., 2012; Savini et al., 2012). Moreover, according to their relevance in maintaining biodiversity in marine regions, as also underlined by the MSFD (EC, 2008), protected areas located in the case study area, including marine protected areas (MPAs), Site of Community Importance (CEC, 1992), zone of biological protection and nursery habitat, were included in the analysis. Finally, even though they represent a driver of pressure in marine areas, we also considered as target of the analysis the aquacultures (i.e. including mussel and fish farms), due to their high economic relevance in the Adriatic sea as a significant sources of income (Allison et al., 2009). However other relevant receptors could be considered in the assessment process (e.g. marine relevant mammals and fish species), but homogenous dataset were not available for the case study. Table 4.5 summarizes receptors considered in the analysis, also providing a brief description of their main environmental features and value in the area of concern.

Table 4.5 Marine receptors selected for the case study area according to the requirements of the MSFD

RECEPTOR	DESCRIPTION
Seagrasses meadows	Seagrasses are submerged flowering plants, located in shallow marine waters such as bays and lagoons. Due to their slow growth rates, strict ecological requirements and overall sensitivity, seagrasses are generally considered as indicators of environmental quality (Montefalcone, 2009; EC, 2008). They perform a wide range of functions within ecosystems assuming both economic and ecological value.
Coral and maërl beds	Coralligenous outcrops and maërl beds are typical Mediterranean underwater seascapes, comprising coralline algal frameworks that grow in dim light conditions. They have a complex three-dimensional structure that act as a refuge for prey as well as a spawning and nursery area for many species including some of economic interest (Tursi et al., 2004). Due to their extent, biodiversity and production, they rank among the most important ecosystems in the Mediterranean Sea, and they are considered of great significance both for fisheries and carbon regulation (Savini et al., 2012).
Marine protected areas	Marine protected areas represent regions designated for protecting marine ecosystems, habitats and species in which human activity is limited under legal restrictions, in order to protect the natural environment, its surrounding waters and the occupant ecosystems. This receptor includes marine protected area as well as Sites of Community Importance (CEC, 1992) located in the case study area.
Aquacultures (fish and mussel farms)	Aquaculture is the production of aquatic organisms, mainly fish and shellfish, confined and controlled by man in specific marine areas. Seafood products represent an important source of protein globally, with coastal and oceanic fish and mussels providing essential fatty acids, vitamins, and minerals. The aquaculture support economies and important social structures in many nations (Allison et al., 2009) and represent a valuable solution to the increasing market demand for fish and shellfish.

In order to keep the highest feasible detail, according to the available dataset (Paragraph 5.2), the exposure assessment was based on a spatial unit (i.e. grid cells) of 100m as applied in the multi-hazard assessment phase (Paragraph 3.2). An exposure score equal to 1 was assigned to cells where the receptor is located and equal to 0 in case of absence.

The exposure score is, therefore, evaluated as follows:

$$E = \begin{cases} 0 & \text{if no receptor is present in the investigated cell} \\ 1 & \text{else} \end{cases} \qquad \text{Equation 14}$$

Where:

$E =$ represents the exposure score related to the geographical area covered by the investigated marine receptors.

Equation14 returns a value of 0 in the cell where no receptors are located whereas 1 where there is the presence of one or more overlapping receptors. The main output of this step is the exposure map showing the localization and geographic extent of all the investigated elements potentially at risk from multiple endogenic and exogenic pressures in the case study.

4.5. Vulnerability assessment

The third phase of the developed methodology is the vulnerability assessment aimed at evaluating the degree to which receptors could be adversely affected by the considered hazard, based on site-specific physical and environmental indicators (e.g. seabed typology, species diversity index, habitat extension, protection level, habitat connectivity). The choice of relevant vulnerability factors was performed according to the environmental state indicators pointed out by the MSFD (EC, 2008; EC, 2010) as well as the available dataset for the Adriatic sea case study (Paragraph 3.2). For each considered hazard a set of vulnerability factors was selected in order to characterize environmental vulnerability of the area of concern to the analyzed pressures (Table 4.6). For instance, for what concern the physical hazards (i.e. anthropogenic introduced and extractive technological hazards), vulnerability factors more related to the seabed features (where these kind of hazards mainly threaten) were selected (e.g. seabed typology extension of coral and maërl beds, extension of seagrasses). On the other side, vulnerability factors such as the ‘forbidding fishing areas’ were associated to the physical hazards induced by underwater noise and extractive activities (including trawling fishing), since the presence or absence of specific regulations, can limit or not the shipping traffic (one of the main source of noise in marine areas) and extraction of resources on a marine area.

Table 4.6 Vulnerability factors VS hazards matrix

	VULNERABILITY FACTORS							
HAZARDS	Seabed typology	MPAs proximity-connectivity	Extension of coral and maërl beds	Extension of seagrasses	Seagrasses species richness	Shannon index	Aquaculture typology	Forbidden fishing areas
Anthropogenic introduced technological hazard		▨	▨	▨				
Anthropogenic extractive technological hazard	▨	▨	▨	▨	▨			▨
Anthropogenic physical hazard by underwater noise		▨				▨		▨
Anthropogenic chronic chemical hazard	▨	▨	▨	▨	▨	▨		
Anthropogenic acute chemical hazard	▨	▨	▨	▨	▨	▨	▨	
Anthropogenic biohazard	▨	▨	▨	▨	▨	▨	▨	

Once vulnerability factors were selected for each hazard, they were then classified and scored, in a 0 to 1 range, following the qualitative linguistic evaluations reported in Table 4.7. Scores were assigned according to expert judgement and literature review (Halpern et al., 2008; Micheli et al., 2013; Salomidi et al., 2012; Astles et al., 2009), in order to allow the process of integration of vulnerability scores, by the application of MCDA functions, in the relative risk estimate and provide a ranking of more vulnerable areas.

Table 4.7 Linguistic evaluation supporting expert/decision makers in the assignation of relative scores, ranging from 0 to 1, to the defined vulnerability classes

Linguistic Evaluation	Scores ($s_{i,n}$)
Most important class	1
Weakly less important class	0.8
Rather less important class	0.6
Strongly less important class	0.4
Less important class	0.2
No vulnerability/hazard	0

The results of this process are summarized in Table 4.8 reporting, for each selected factors, classes and scores considered during the application of the methodology in the Adriatic sea.

Table 4.8 Classes and scores associated to the all vulnerability factors identified for the considered hazards in the Adriatic sea case study

VULNERABILITY FACTORS	CLASS	SCORE
MPAs proximity-connectivity (km)	0 - 25.63	0,2
	25.64 - 48.33	0,4
	48.34 - 70.58	0,6
	70.59 - 95.54	0,8
	95.55 - 137.55	1
Extension of seagrasses (Km^{2})	0.02 - 6.01	1
	6.02 - 27.37	0,6
	27.38 - 103.75	0,2
Shannon Index	1.39 - 2.62	1
	2.63 - 3.65	0,8
	3.66 - 4.34	0,6
	4.35 - 4.80	0,4
	4.81 - 5.55	0,2
Extension of coral and maërl beds habitats (Km^{2})	0.07 - 17.79	1
	17.80 - 53.45	0,6
	53.46 - 2014.49	0,2
Aquaculture typology	Fish farms	0,6
	Mussel farms	1
Forbidden fishing areas	Forbidden areas	0,2
	Not forbidden areas	0,5
Seagrasses Species Richness	Very low richness (n° 1 of species)	1
	Low richness (n° 2 of species)	0,8
	Medium richness (n° 3 of species)	0,6
	High richness (n° 4 of species)	0,4
	Very high richness (n° 5 of species)	0,2

Almost all the selected vulnerability factors were considered as hazard-independent (e.g. extension of seagrasses, Shannon Index) and, as a consequence, score associates to each class doesn't change depending on the considered hazard. Differently, the factor related to the 'seabed typology' a specific vulnerability score was assigned to each typology according to the different hazards (Table 4.9) (Halpern et al., 2008; Micheli et al., 2013).

More specifically, for what concern the anthropogenic introduced technological hazard, we considered all the seabed types as equally vulnerable, since this hazard includes the complete smothering and sealing of the seabed due to the placement of benthic infrastructures (e.g. cables and pipelines, platform for hydrocarbon extraction). To the anthropogenic extractive technological hazard, different vulnerability scores were associated to the identified seabed typologies since, for instance, coral and maërl have an high recovery time (decades/centuries) and a very slow growth rate compared to the seagrasses meadows (Astles et al., 2009).

As far as the anthropogenic biohazard is concerned according to Salomidi et al. (2012) the most affected areas to the introduction of non-indigenous species are the seagrasses and the coral and maërl beds, although for the latter there are still few studies to support the phenomena. Lower vulnerability scores were instead assigned to the deeper seabed layers (i.e. bathyal abyssal sediment) assuming a reduced biogenic level. Finally, considering the two selected chemical hazards (i.e. anthropogenic chronic and acute chemical hazard) based on Waycott et al. (2011) higher vulnerability scores were assigned to biogenic layers and then, decreasing values according to the probability of re-suspension of contaminants deposited on different layers, considering that finer layers (muddy and sandy seabed) can be more subjected to re-suspension than the coarser layers. The lower scores were assigned to the deeper layers where local currents are less intense and therefore there is less re-suspension and more probability that contaminants are less bioavailable (immobilized).

Table 4.9 Classes and scores associated to the vulnerability factor ‘seabed typology’ for each considered hazard

		HAZARD			
VULNERABILITY FACTOR	**CLASS**	**Anthropogenic extractive technological hazard**	**Anthropogenic biohazard**	**Anthropogenic chronic chemical hazard**	**Anthropogenic acute chemical hazard**
Seabed typology	Mediterranean coralligenous communities	1	1	1	1
	Shallow sublittoral rock and biogenic reef	1	1	1	1
	Shallow sublittoral coarse sediment	0,2	0,5	0,5	0,5
	Shallow sublittoral sand	0,2	0,5	0,7	0,7
	Shallow sublittoral mud	0,2	0,5	0,8	0,8
	Shallow sublittoral mixed sediment	0,2	0,5	0,7	0,7
	Maerl beds	1	1	1	1
	Sublittoral seagrass beds including Cymodocea and Posidonia beds	0,6	1	1	1
	Bathyal sediment	0,4	0,2	0,2	0,2
	Abyssal sediment	0,4	0,2	0,2	0,2

After the normalization, vulnerability factors were then aggregated by applying the “probabilistic or” function (Kalbfleisch J. G, 1985), aimed at providing a single normalized score of physical and environmental vulnerability for each cell (i.e. pixel of raster map) and considered hazard of the area of concern, following the Equation 15:

$$V_h = \otimes_i^n [vf_i] \qquad \text{Equation 15}$$

Where:

V_h= physical and environmental vulnerability score, representing the predisposition of the territory to be affected by the considered hazard h;

$\otimes$= "probabilistic or" function (see Table 4.10);

vf_i = i^{th} physical and environmental vulnerability factor.

Table 4.10 "Probabilistic or" function applied within the vulnerability assessment

"Probabilistic or" function (Kalbfeisch J.G., 1985)	The process can be repeated until evaluating all operands. If just a factor (*f*) assumes the maximum value (i.e. 1) then the result of the "probabilistic or" will be 1. On the other side, *f* with low scores contributes in increasing the final "probabilistic or" score: the more is the number of low factor scores, the greater is the final score.
$\otimes_{i=1}^{4}[f_i] = f_1 \otimes f_2 \otimes f_3 \otimes f_4$ $f_1 \otimes f_2 = f_1 + f_2 - f_1\ f_2 = F_1$ $F_1 \otimes f_3 = F_1 + f_3 - F_1\ f_3 = F_2$ $F_2 \otimes f_4 = F_2 + f_4 - F_2\ f_4 = \otimes_{i=1}^{4}[f_i]$ Where $f_1 = i -$ th generic factor f	

Applying the "probabilistic or" function (Equation 15), if just a vulnerability factor (*vf*) assumes the maximum value (i.e. 1) then the final vulnerability score will be equal to 1. On the other side, many *vf* with low scores contribute in increasing the final vulnerability score: the more is the number of low vulnerability factor scores, the greater is the final vulnerability. Resulting score ranges from 0 (i.e. no vulnerability) to 1 (i.e. higher vulnerability in the case study area) and is calculated cell by cell aggregating information from overlaid vulnerability factors for each considered hazard.

4.6. Risk assessment

The risk assessment phase allows to integrate information about all the considered hazard with the receptors' exposure and related vulnerability, in order to identify and prioritize areas ad targets (i.e. key marine targets and hotspots) at higher risk in the investigated area and timeframe (EC, 2008).

According to the IPCC (2014), the aggregation of hazard, exposure and vulnerability scores support the assessment of risk in the case study, by applying the general function as follow:

$$R_h = f(H, E_j, V_h) \qquad \text{Equation 16}$$

Where:

R_h = risk score related to the hazard of concern h;

H = hazard score depending on Equations 11-13 (Paragraph 4.3);

E_j = exposure score according to the presence/absence of the receptor j, according to Equation 14 (Paragraph 4.4);

V_h = physical and environmental vulnerability score of the investigated cell and related to the hazard of concern h, according to Equation 15 (Paragraph 4.5).

The result of this step is a set of risk maps one for each selected hazard (Table 4.1), highlighting areas and targets more affected by multiple endogenic and exogenic risks, considering different hazards stressing the marine region of concern and related vulnerabilities. As for the other assessment phases, resulting risk score ranges from 0 to 1, in which 0 represent cells with risk null (i.e. there is no hazard or no physical and environmental vulnerability) whereas 1 the higher risk in the investigated area.

4.7. Cumulative impact assessment

Once calculated all risks related to the selected hazards and for both the considered timeframe scenarios (i.e. 2000-2015, 2035-2050), the final step of the developed methodological approach is the cumulative impact assessment allowing to integrate all the information calculated so far for the whole case study in a synthetic indicator.

Based on the approach developed by Halpern et al. (2008) for the evaluation of cumulative impacts at the global scale (Paragraph 2.1), the integration of all the calculated risks in the case study area is based on the following function:

$$\mathrm{CI}_c = \sum_{i=1}^{m} R_{i,c} \qquad \text{Equation 17}$$

Where:

CI $_c$ = cumulative impact calculated in the cell c for the case study area and considered timeframe scenarios (2000-2015 and 2035-2050);

c = the cell of concern;

m = 6 anthropogenic and natural risks;

$R_{i,c}$= is the normalized value (scaled between 0 and 1) of anthropogenic and natural risk i in the cell c (Paragraph 4.6).

The result of this conclusive phase is represented by a single cumulative impact showing areas and targets potentially affected by cumulative impacts in both the considered timeframe scenarios (i.e. baseline 2000-2015 and future 2035-2050 scenarios). In this case, based on the normalized values assumed by the risk maps (i.e. from 0 to 1) and the applied aggregation function, the resulting cumulative impact score can ranges from 0 to 6, in which 0 represent cells where the cumulative impact is null (i.e. there is no any kind of risks overlaid in the area and target of concern) whereas 6 the higher cumulative impact.

5. Multi-scenarios' analysis by means of GIS-based Bayesian Belief Networks

Marine managers and policy makers are increasingly calling for new approaches and tools able to account for changing conditions over time due to natural processes, as well as different management options for the marine environment. Improving our capacity to model and evaluate the combined effects of multiple stressors (e.g. temperature variation, shipping traffic, aquaculture, ports' activities, nutrients input), in decisional contexts where data are limited and uncertainty is high, is therefore essential to address the future planning and management of our seas.

In this setting, Bayesian Belief Networks (BBNs) are finding increasing application in the context of impacts assessment and marine management (Uusitalo et al. 2015; Ban et al., 2014; Stelzenmüller et al. 2014). BBNs are probabilistic graphical models which represent the system's components (variables) and their relationships by combining principles of Graph theory and Probability theory (Pearl, 2011). They represent a flexible modelling tool, as they can be adapted in order to suit the context in which they are applied, as well as updated as new knowledge is available (Pollino et al., 2010). Being graphically-based they facilitate the rapid conceptualization of the system to be managed (e.g. marine region) and the evaluation of the dependence/independence between data and their inherent uncertainty as belief probabilities. Indeed, they allow to consider multiple stressors and endpoints in the same framework, thus consenting to be effectively applied to model and analyze complex marine environments.

Their combination with GIS represents a real opportunity to address marine spatial planning (MSP, EC, 2014) (Paragraph 1.2.2) and related decision making processes since, together, they allow to spatially represent and evaluate environmental risks under multiple model-based climate scenarios and management measures (Stelzenmüller et al. 2014 and 2010; Johnson et al., 2012). Despite, the use of BNs in a geospatial context results particularly attractive for environmental risk assessment, it has been performed only in a limited extent, since it poses both methodological and software challenges (e.g. limited systems coupling BBNs with geospatial software) (Jolma et al., 2011).

Within this thesis, as final ring of the designed multi-risk approach, the probability (and related uncertainty) of cumulative impacts (already calculated in the Adriatic sea, Paragraph 6), under different climate and management scenarios, was analyzed by designing and training a BBN based on the developed multi-hazard, vulnerability, risk and cumulative impacts GIS maps. The main aim was to test the potential of an integrated BBN–GIS framework to support adaptive marine management, by simulating and evaluating multiple 'what/if' scenarios envisioned for the Adriatic sea case study. The developed BBN aspires to be an operational tool to support marine planners and decision makers developing and implementing robust and adaptive measures able to deal with risks and uncertainties arising from incomplete knowledge about the ecosystem and the future natural and human-made pressures.

The following paragraphs describe the BBN development for the Adriatic sea case study, starting from the design of the conceptual model of the system (Paragraph 5.1) to the implementation of the operative steps for model parametrization and evaluation (Paragraphs 5.2.1 and 5.2.2) and the scenarios analysis (Paragraph 5.2.3).

5.1 Bayesian Belief Network development: the conceptual model of the system

Once model's objectives are defined, the development of a BBN requires the definition of the main structure of the network and its representation using a conceptual or influence 'box and arrow' diagram. The network conceptualization includes the identification of the main system variables (i.e. nodes) as well as the establishment of the links between them (i.e. directed arcs) (Kragt, 2009). The structure of a BBN is defined graphically, where nodes are connected by unidirectional arrows in a graphical structure and parameters represent the conditional probability distributions of the observed variables (i.e. nodes).

Within this thesis the open-source software R (https://www.r-project.org), with its specific libraries devoted to BBNs, was used to develop and train the network for the specific geographical context of the Adriatic sea case study. More specifically, based on the developed multi-risk framework (Paragraph 4.2), the conceptual model of the BBN, including the identification of the main nodes of the system and relationships between them (i.e. pressures, hazard, vulnerability factors, vulnerability, risks and cumulative impact), was defined. As a consequence, in the resulting network all nodes converge to the final step (and related values) of the assessment process, the cumulative impact, representing thus the final objective or endpoint of the BBN. As shown in figure 5.1, the BBNs is composed of six main modules as follows:

- Module pressures (nodes represented in light blue).
- Module hazards (nodes represented in violet).
- Module vulnerability factors (nodes represented in light green).
- Module vulnerability (nodes represented in green).
- Module risk (nodes represented in orange).
- Module cumulative impact (nodes represented in red).

In the developed BNN model (Figure 5.1) the overall cumulative impacts within the Adriatic sea case study is represented as a function of the main risks threating the marine environment, which in turn derive from the intensity of ten interactive natural and anthropogenic pressures leading to six different hazards, and the vulnerability of the marine environment to these hazards. In a nutshell, endogenic and exogenic pressures as well as vulnerability factors are parent nodes in the defined model and, in turn, hazards and vulnerability are the related child nodes.

Finally, nodes representing risks are child nodes of the hazards and vulnerabilities and, the cumulative impact node is the child node of the risk nodes. As a consequence, the likelihoods of states of the cumulative impacts are predicted as a function of the likelihood of pressures, hazards, vulnerability and risks within the analyzed area. The model nodes and associated data are described in more detail in Annex D, within the model parametrization (Paragraph 5.2).

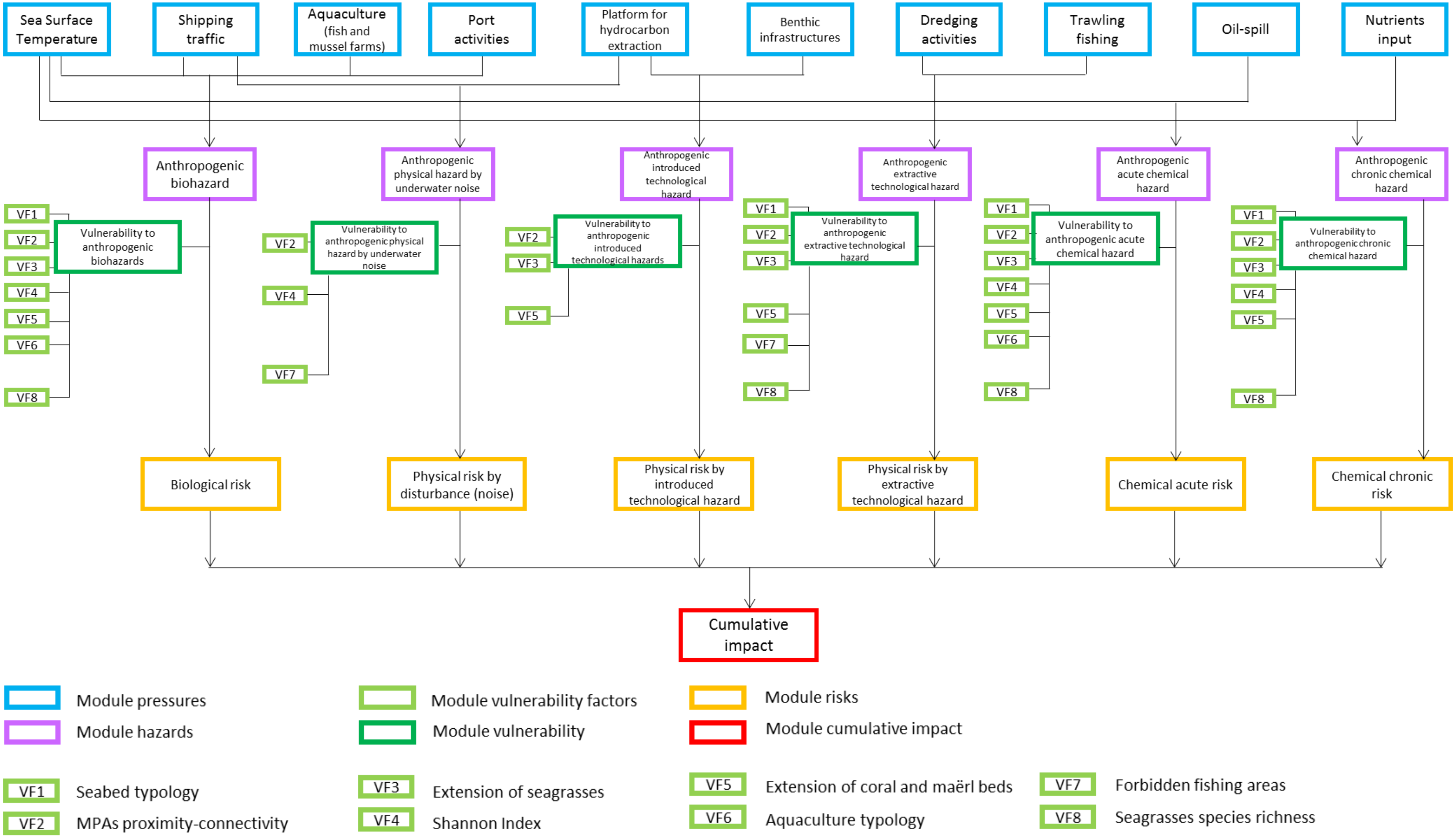


Figure 5.1 Conceptual model of the system showing the key variables used to predict the probability of cumulative impacts in the Adriatic sea as a function of hazard, vulnerability and risk

5.2 Model parametrization

Following the development of the conceptual model of the BBN, the second step involves assigning states and probabilities to all the considered variables. The states for each node represent the potential values or conditions that the node can assume in the analyzed system (Kragt, 2009).

States can be featured in different way, representing numerical values, intervals, probability distributions or categorical definitions (de Santa Olalla et al., 2005). Within this thesis, resulting pressure, hazard, vulnerability (with also all the associated vulnerability factors, Paragraph 4.4), risks and cumulative impacts raster maps (already normalized in a 0-1 range based on equations 1-17, Chapter 4), served as input data for the parametrization of the BBN model. More specifically, the centroid of each pixels of the developed raster maps was calculated by applying specific GIS tool within the ArcGis software. To each of these points, spatially located in the case study area (i.e. longitude and latitude for each point), all the 66 calculated variables (i.e. all pressures, hazards, vulnerability factors, vulnerabilities, risks and cumulative impact) with their related values, were associated through a dedicated spatial join. It has to be underlined that input data used in this process, concern the baseline scenario 2000-2015, with the overall extent of the Adriatic sea case study. As a consequence of the high size of these data, in order to allow and speed up the computational process within ArcGis and R, raster maps were previously resampled with a spatial grid resolution of 1km. The resulting table from this process (including all the 66 estimated variables), was used as input for learning the parameters of the BBN for the Adriatic sea case study. Variables concerning hazards, vulnerability and risks in continuous ranges, were handled in R by dividing their range from 0 to 1 (as already normalized through GIS) into 5 equal sized classes (i.e. states on the BBN), based on the equal interval classification (Zald et al, 2006), as already applied within the cumulative impact assessment process (Chapter 4). For some other variables (i.e. pressure related to aquaculture activities, vulnerability factor concerning the extension of seagrasses, cumulative impacts), other classification methods were applied according to the specific values assumed by each variable in the case study and the related probability distributions. Table included in Annex D presents an overview of the model nodes and states applied within the learned BBN, also providing a short description of the corresponding categories.

The probability of each node was then estimated based on the observed frequencies of each corresponding variable (Nyberg et al., 2006). For this study, probabilities of nodes were defined based on GIS data and not on expert opinion, thus the model reflects the current level of ‘evidence’ for relationships calculated through the application of the risk-based methodology in the Adriatic sea (Stelzenmüller et al., 2010).

Finally, the Conditional Probabilities (CP), representing the strength of relationships between the systems' variables, were specified for all combinations of states of their parent nodes. Specifically, CP represented in the Conditional Probability Table (CPT) describe the probability of node of being within a state, given the combination of values of parent states. As a consequence, the dimension of this table, for each considered variable, is represented by the product of the numbers of states of the child node and of all its parent nodes. If a node has no parents (i.e. it is a root node), it can be described probabilistically by a marginal probability distribution. Within this application, the developed BNN, and related conditional probability tables for all model nodes, were populated from the attribute tables of the vector grid generated through GIS (i.e. centroid of the developed raster maps), for all the considered variables (e.g. pressures, vulnerabilities, risks). Once the probability distributions of each node have been defined, the network can be solved thorough specific algorithms which allow an efficient probability propagation and updating of parameters.

5.3 BBN sensitivity and testing

After the model has been defined and estimated it requires to be evaluated and tested. In this setting Parameter Sensitivity Analysis was performed in order to analyze how sensitive are model outcomes to variations of the value of a parameter of the model. More specifically, sensitivity analysis within the application of BBN can measure the sensitivity of outcome probabilities to changes in input nodes or other model parameters, such as changes in node's type of states (Kragt, 2009).

Based on the empirical approach proposed by Pollino et al. (2007) the sensitivity of the 'cumulative impact' node to the influence of its parent nodes (i.e. risks, vulnerabilities, hazards and pressures) was evaluated by modifying one by one the input parameter, and then observing changes in the cumulative impact node in terms of posterior probabilities. This methodology allows identifying the most influential set of variables, those have the greatest influence on the model endpoints, as well as to rank the relevance and strength of the BBN inputs in determining the variation of the observed model output (i.e. changes in the cumulative impact node).

5.4 Scenario analysis

Once the BBN parameters have been estimated using the collected data (i.e. valued linked to the centroid of the GIS-based developed raster maps), they can be used for scenarios analysis.

The main aim of this study was to simulate future climate and planning scenarios, and the related achievement of predefined objectives and targets (e.g. reduce the overall cumulative impacts), in the Adriatic sea case study. As a consequence, the developed BBN was used to infer the behavior and responses of the variables at stake against different what/if scenarios, predicting both the consequences of the envisioned management measures or conditions required to achieve specific management and environmental targets. In this context BBNs represent a useful decision support tool, allowing potential end- users to test multiple scenarios by defining different probability distribution in selected nodes as well as to analyze the associated outcome probabilities. Indeed, by specifying the state for one or more input nodes (i.e. setting an evidence), the impacts on other nodes are propagated and thus easily predicted (Kragt, 2009). Downward propagation of evidence through the BNN is based on the law of total probability, through a form of the joint probability calculation (Ames et al., 2005). BNN can be also used for diagnostic analyses, by defining precise targets or threshold to be achieved in selected nodes. To this aim, a specific state of an output node has to be set, and then the probability that the input nodes need to be in a particular state can be observed. In this case upward propagation of evidence is applied based on the Bayes' Rule (Pollino et al., 2010).

For the Adriatic sea there are currently no specific planning objectives, however, some recommendations for its planning and management can be gathered from the EU Strategy for the Adriatic and Ionian Region (i.e. EUSAIR) (EC, 2014), jointly developed by the Commission, together with the Adriatic-Ionian Region countries (i.e. four EU Member States -Croatia, Greece, Italy, Slovenia- and four non-EU countries -Albania, Bosnia and Herzegovina, Montenegro, Serbia) and stakeholders, in order to address together common challenges and planning objectives. The strategy promotes economic and social prosperity and growth in the region by improving its attractiveness, competitiveness and connectivity, focusing efforts in the macro-regional approach and the integration of no EU countries. Based on its four pillars (i.e. i) blue growth; ii) connecting the region; iii) environmental quality; iv) sustainable tourism) (http://www.adriatic-ionian.eu/about/pillars), related specific environmental objectives (e.g. Pillar 3 - To ensure a good environmental and ecological status of the marine and coastal environment by 2020) and indicative actions to achieve them (e.g. Enhancing the network of Marine Protected Areas, drafting and implementation of a joint contingency plan or oil spills and other large-scale pollution events), different management options for the case study were envisioned, as follow:

Scenario 1:

How does environmental vulnerability and cumulative impacts change due to the establishment of new Marine Protected Areas –MPAs-, leading to reinforce ecological connectivity in the Adriatic sea?

For shaping this scenario, within the developed BBN the probability of the first state of the vulnerability factor related to the ‘MPAs proximity-connectivity’ (Paragraph 4.5) (i.e. 0-0.2, corresponding to the minimum distance between MPAs in the range of 0-25.63km) (Annex D) was set equal to 100%. Information between nodes were then propagated, in order to estimate probabilities of the other variables under the defined evidence condition.

Scenario 2:

What is the influence of rising sea temperature on the anthropogenic chronic and acute chemical hazard, the biological hazard and the resulting cumulative impacts, under the effect of future climate changing conditions?

This scenario tested the BBN to evaluate the potential effects of climate change on marine environments, setting the evidence of the higher state of pressure related to the sea surface temperature variation (i.e. state with score ranging from 0.8- 1, corresponding to a rising number of unusually sea surface warm events in the range of 1467-1577, envisioned in a future timeframe) (Annex D) equal to 100%. Accordingly, the defined evidence was propagated to the parent node concerning the pressure of concern to its child nodes, focusing analysis on the linked hazards and, finally, to the resulting cumulative impacts for the overall Adriatic sea case study.

Scenario 3:

Increasing nutrient input in the Adriatic sea, as a consequence of a unmanaged territorial planning (e.g. no wastewater treatment plants), can highly influence cumulative impacts in the basin?

In order to frame this scenario, the evidence for the upper state of the parent node related to the nutrient input (i.e. 0.8-1 corresponding to a Chl 'a' concentration in the range of 1.15 - 1.44 µg/L) (Annex D), was set equal to 100%. Information between all nodes, linked with this pressure, were then propagated (i.e. anthropogenic chronic chemical hazard and related risk) in order to evaluate the probability of cumulative impacts against the defined condition.

Scenario 4:

What are the required management measures and adaptation strategies to reduce the overall cumulative impacts in the Adriatic sea?

This scenario aims to simulate the management objective to keep the cumulative impact in the Adriatic sea within its first state (i.e. in the range 0-0.2) (Annex D), using BNN for diagnostic analysis (Paragraph 5.4). Accordingly, the likelihood of the cumulative impacts in the state 0–0.2 was set to 100%, and then propagating information between nodes, the probabilities for all the other variables were inferred. As a consequence, through this scenario, changes in the intensities of natural and anthropogenic pressures, as well as vulnerabilities and related vulnerability factors were estimated, which in turn reflect different management options that would be required to achieve the predefined planning objective.

SECTION C: APPLICATION TO THE CASE STUDY AREA

6. Application of the cumulative risk assessment methodology in the Adriatic sea

The application of the operative steps presented in the paragraphs 4.3-4.7 allowed to produce a wide array of GIS-based multi-hazard, exposure, vulnerability, risk and cumulative impacts maps for both the baseline scenario 2000-2015 and the future one 2035-2050. Moreover, specific statistics were calculated for the whole case study and selected marine targets (e.g. alterations of physical and chemical parameters due to chronic and acute chemical hazards, extent of relevant habitat potentially affected by cumulative impacts) in order to summarize the results of the assessment and simplify comparison among resulting maps and scenarios.

The following paragraphs describe, for each step of the proposed procedure, the output obtained for the Adriatic sea case study (Paragraphs 6.1-6.6), underlining their utility in a planning and management perspective of marine areas, as well as for the implementation of the Marine Strategy Framework Directive -MSFD- (EC, 2008).

6.1. Multi-hazard maps

The implementation of the hazard assessment phase in the Adriatic sea case study (Paragraph 4.3) has led to the development of a set of GIS-based hazard maps (Annex E), representing potentially significant hazard scenarios, against which the marine environments and habitats need to adapt in order to maintain their ecological functions. Multi-hazard maps ranging in a continuous scale from 0 to 1, were classified by applying the Equal Interval classification method, allowing the division of scores into 5 equal sized classes (i.e. very low, low, medium, high and very high) (Zald et al, 2006), thus simplifying maps understanding and ensure comparability among resulting maps.

More specifically, for what concern the biological and chemical hazards (acute and chronic) a specific map for each considered timeframe scenario (i.e. baseline 2000-2015 and future 2035-2050) was developed in order to evaluate both the progress toward the achievement of the Good Environmental Status -GES- (EC, 2008), and the potential effects of long-term climate changes in the Adriatic sea. Instead, a far as the physical hazards are concerned (i.e. anthropogenic introduced and extractive technological hazard, anthropogenic physical hazard by underwater noise) a single map related to the baseline scenario 2000-2015 was created, since no information about the future planning of human uses of the sea (e.g. shipping traffic, ports and harbors activities, trawling fishing) were available for the case study.

Figure 6.1 provides two examples of the developed maps, focusing on the physical hazards. More specifically, analyzing Figure 6.1A concerning the **anthropogenic extractive technological hazard**, moderate hazard scores, mainly ranging from 0.2 to 0.6, can be observed in the western part of the Adriatic Sea, caused by the high exploitation of the area for trawling fishing, unlike the North Adriatic sea where severe restrictions limit this activity in the area. Moreover, observing the other hazard map in Figure 6.1B, regarding the **anthropogenic physical hazard by underwater noise**, higher hazard scores (i.e. ranging from 0.4 to 1) can be detected in the central part of the case study, mainly due the massive maritime traffic in this area where most of the shipping routes intersect, recognized as one of the main forcing of this hazard (ISPRA, 2012).

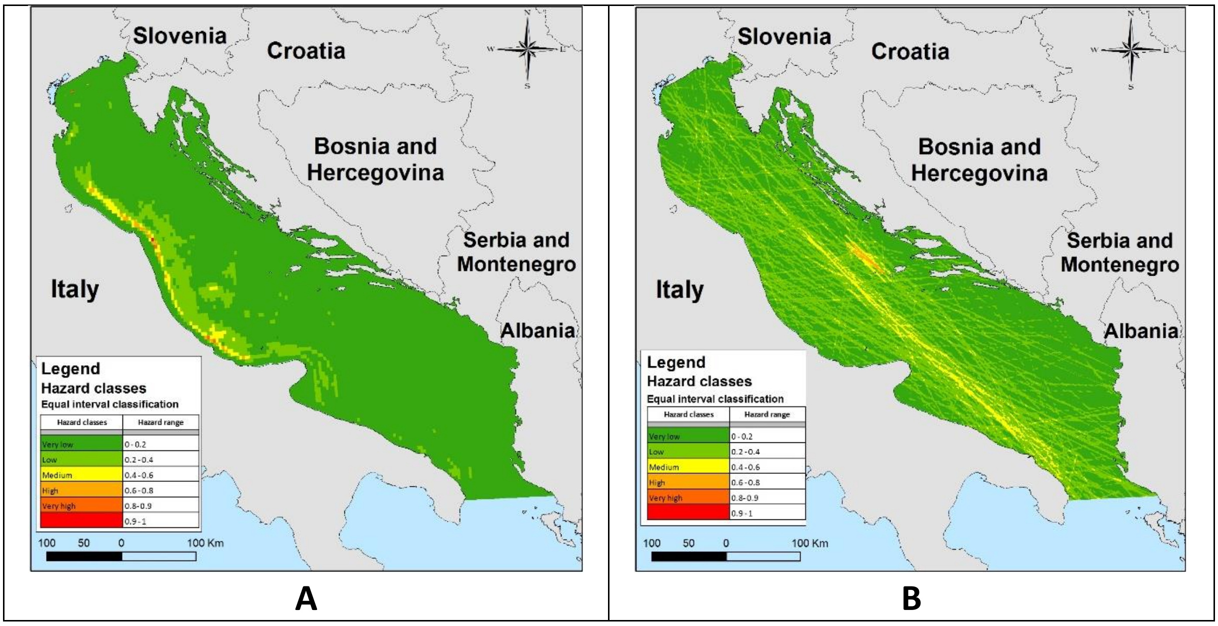


Figure 6.1 Example of hazard maps developed for the Adriatic sea case study, representing the anthropogenic extractive technological hazard (A) and the anthropogenic physical hazard by underwater noise (B)

Focusing on the resulting hazard maps for the biological and chemical hazards (acute and chronic), as already mentioned, two different maps were developed and analyzed against the considered timeframe scenarios (i.e. baseline 2000-2015 and future 2035-2050). Figure 6.2 shows the resulting maps for the **acute chemical hazard** comparing both temporal scenarios.

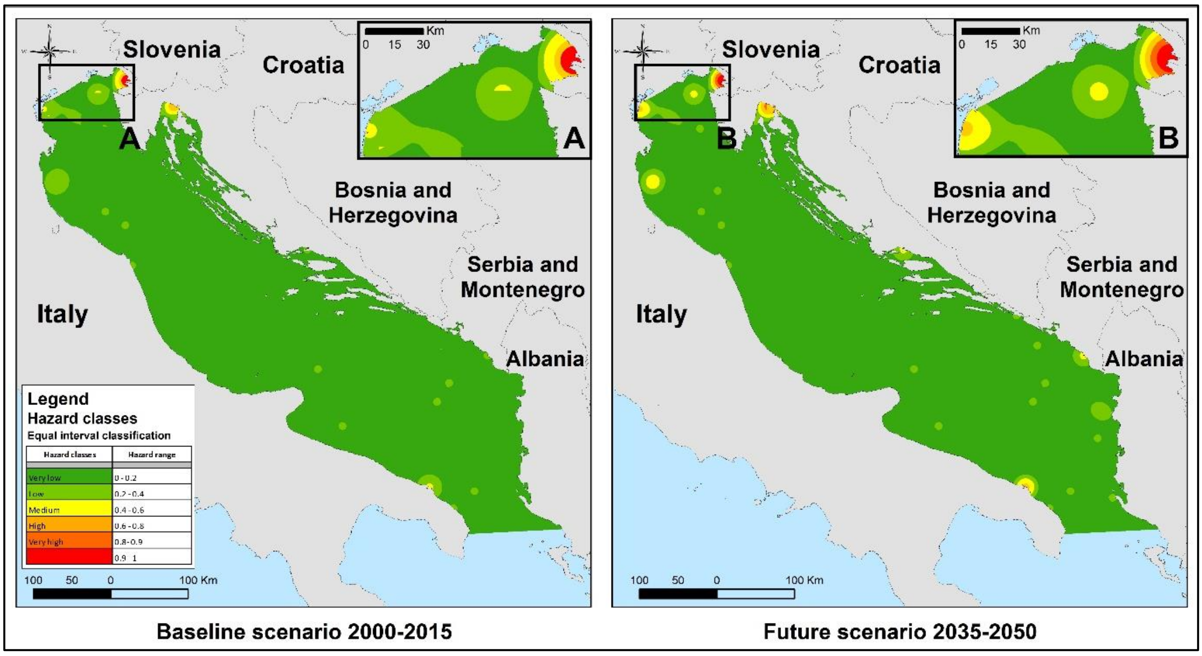


Figure 6.2 Hazard maps produced for the Adriatic sea case study, representing the acute chemical hazard for the baseline 2000-2015 and future 2035-2050 timeframe scenarios

Higher hazard scores (i.e. ranging from 0.4 to 1) are located in the North Adriatic sea, close to the port of Trieste, where several shipping accidents have been occurred in the 1977-2014 timeframe (IMO/UNEP, 2011; http://accidents.rempec.org/). Moreover, by comparing the two zooms A and B, can be observed that the final hazard score slightly increases in the future scenario 2035-2050 due to the rising number of unusually warm events calculated in this time window (Paragraph 4.3.2). However, this increase is minimal since experts have assigned a lower interaction weight to the sea surface temperature (SST) respect to pressure related to the oil-spill, recognized by experts as the main driver of the acute chemical hazard in the Adriatic sea (Paragraph 4.3.3). Has to be underlined that changes for this hazard, in the future scenario 2035-2050, are determined by the influence of the SST for which future projections were available through climate modelling.

As far as the **chronic chemical hazard** is concerned, Figure 6.3 shows the resulting hazard maps where higher score can be detected in both scenarios in the areas located around the Po delta river, highly affecting with its nutrient loads trophic levels of the Adriatic sea (ISPRA, 2012a). Comparing the two timeframe scenarios, it is evident how the hazard score increases as result of the rising SST, but, above all in this case, due to the higher concentration of chlorophyll ‘a’, projected for the future scenario 2035-2050. Indeed, for this hazard future projections of both the considered pressures were available.

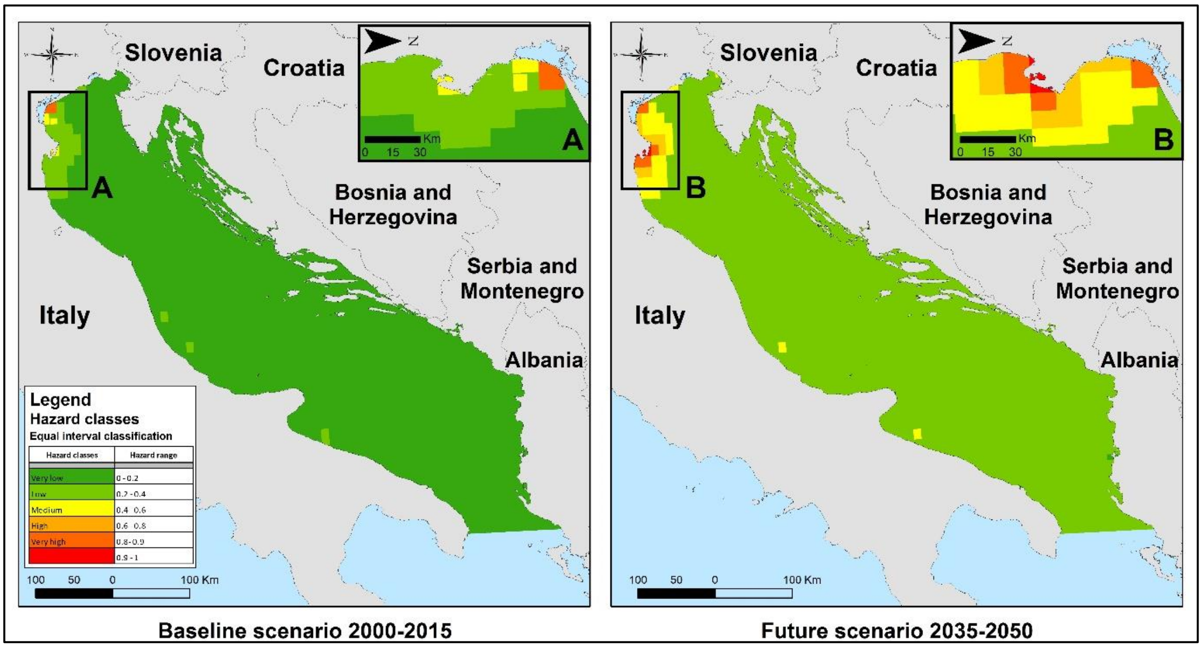
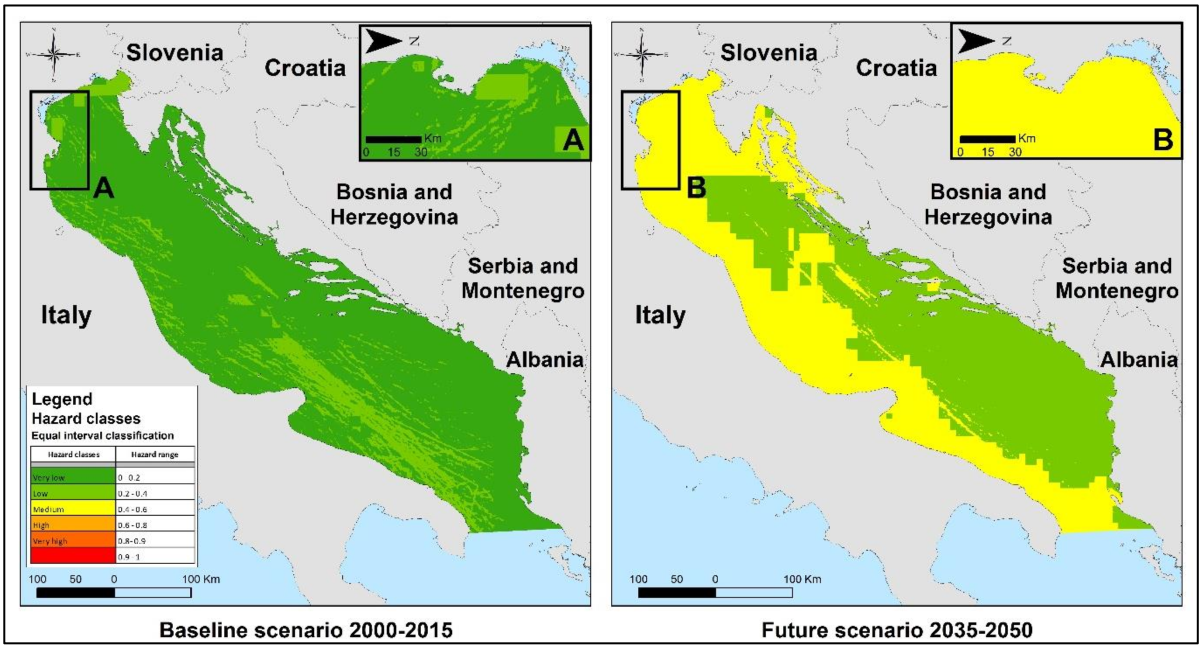


Figure 6.3 Hazard maps produced for the Adriatic sea case study representing the chronic chemical hazard for the baseline 2000-2015 and future 2035-2050 timeframe scenarios

Finally, by analyzing the resulting maps for the **biological hazard** (Figure 6.4), higher hazard scores (ranging from 0-0.4) can be observed, in the baseline scenario, corresponding to the most congested shipping routes in the central and southern part of the basin (where shipping traffic is more intense), and the location of the main commercial and touristic ports (i.e. Venice and Trieste in the north Adriatic sea and Bari and Brindisi in the south). The final hazard scores increase in the future scenario 2035-2050 especially in the Nord Adriatic sea and along the Italian Exclusive Economic Zone (EEZ), as result of the rising number of unusually warm events calculated in the future scenario, identified by experts as the major driver of this hazard (Paragraph 4.3.3). However, the final scores assume relative low and moderate values (ranging from 0-0.6) in both scenarios, never reaching the maximum hazard score equal to 1. This is due to the combination between the four pressures concurring to the overall biohazard (i.e. SST variation, shipping traffic, port and aquaculture activities), since the coalition in their maximum intensity never occurs in the case study in both timeframes. As for the acute chemical hazard changes in this hazard, within the future time window (i.e. 2035-2050), are only induced by the influence of the SST for which future projections were available.



Baseline scenario 2000-2015

Future scenario 2035-2050

Figure 6.4 Hazard maps produced for the Adriatic sea case study, representing the biological hazard for the baseline 2000-2015 and future 2035-2050 timeframe scenarios

In order to support the cross comparison of results of this phase, for both the analyzed timeframe scenarios (i.e. baseline 2000-2015 and future 2035-2050), based on the developed hazard maps bar charts comparing the percentage of surface of the case study included in each hazard class (Figure 6.5) were developed.

Both the bar charts show quite low and moderate scores for all the considered hazards, with almost all the surface of the case study included in the very low to medium hazard classes (ranging from 0.2 to 0.6). Higher hazard score can be observed for the anthropogenic introduced technological hazard, with about the 5% of the Adriatic sea included in the very high hazard class (score ranging from 0.8 to 1), since pressures related to this hazard (i.e. smothering and sealing of seabed) create a severe physical loss of the seabed but in limited areas of the overall case study. Finally, as already showed in the resulting GIS-based maps, rising hazard scores can be noticed comparing baseline (Figure 6.5A) and future (Figure 6.5B) scenarios, especially for what concern the anthropogenic biohazard, with a shift of the hazard values from the lower classes (score ranging from 0 to 0.4) to the medium one (from 0.4 to 0.6). The same behavior can be detected for the anthropogenic chronic chemical hazard where hazard values, mainly included in the lower classes within the baseline scenario (score ranging from 0 to 0.4), completely move to the upper classes with moderate hazard scores (from 0.2 to 0.6) in the future one.

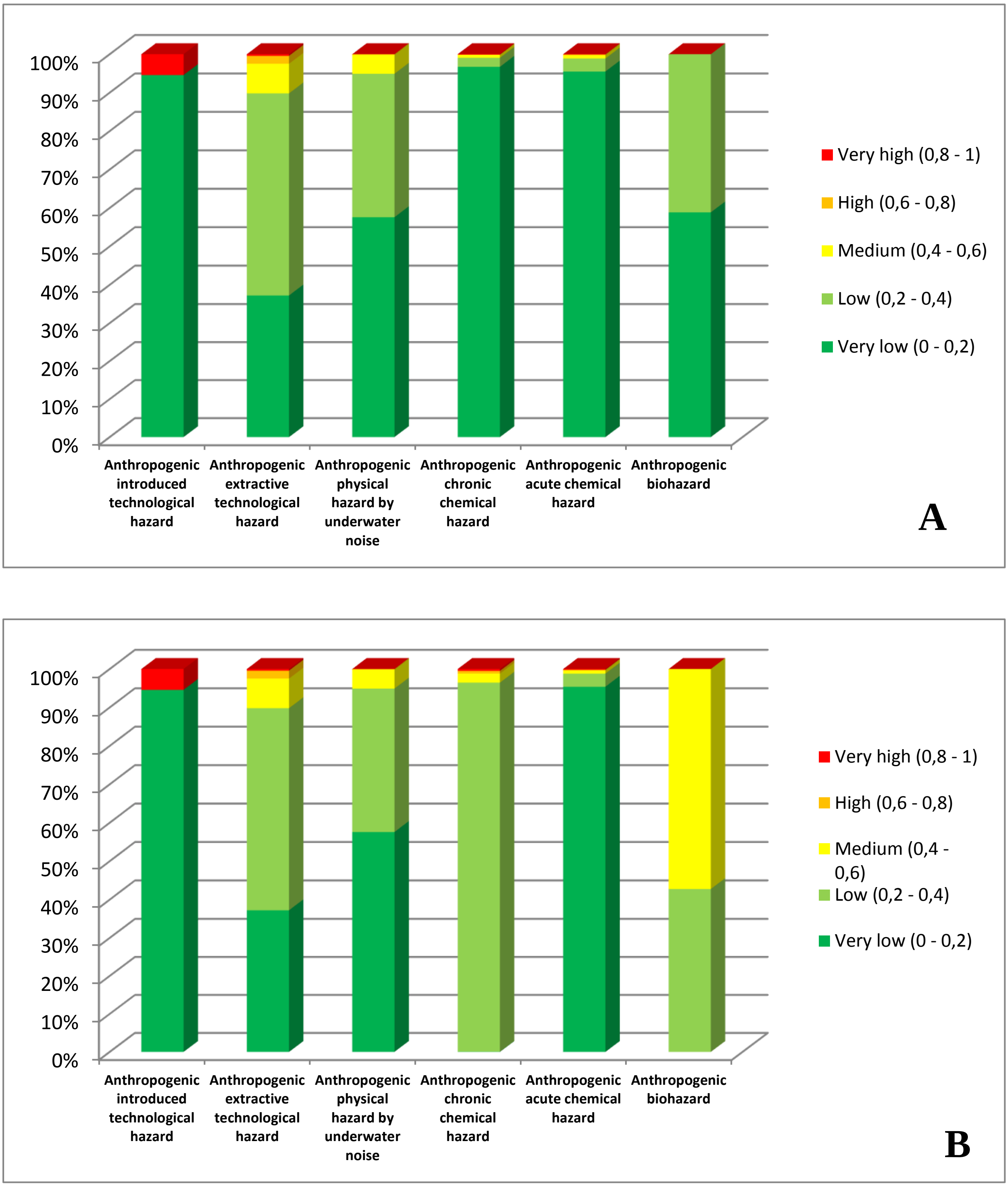


Figure 6.5 Bar charts representing the percentage of surface of the Adriatic sea case study included in each hazard class for all the considered pressures in the baseline scenario 2000-2015 (A) and future scenario 2035-2050 (B)

Hazard maps, and related statistics, may facilitate the communication to potential end-users (e.g. policy makers, planners) about the most significant sources of hazard in the region and their spatial pattern, thus increasing knowledge and awareness on main environmental issues which need to be faced in the area of concern. Moreover, since most of them were developed starting from methods pointed out in the Italian Initial Assessment Reports related to the MSFD implementation, hazard maps can be used by public authorities implementing the directive requirements (EC, 2008). More specifically, they can support the assessment of different pressures' indicators for selected environmental descriptors (e.g. D2- Non- indigenous species, D5– Eutrophication, D6- Sea-floor integrity) (EC, 2010) thus evaluating progress toward achieving GES in the Adriatic sea.

6.2. Exposure map

The exposure map produced by implementing procedure presented in paragraph 4.4 allowed the identification and spatial localization of key marine receptors featured by high environmental and socio-economic values (i.e. elements at risk), that can be subject to potential losses and damages due to the considered hazards. Figure 6.6 shows the exposure map for the Adriatic sea case study considering as main elements at risk the marine environment of the Adriatic sea as a whole (blue boundary) and as hotspots targets: the seagrasses meadows (filled green pattern), coral and maërl beds (filled red pattern), the protected areas (filled pattern with oblique pink lines) and the aquacultures (filled yellow pattern).

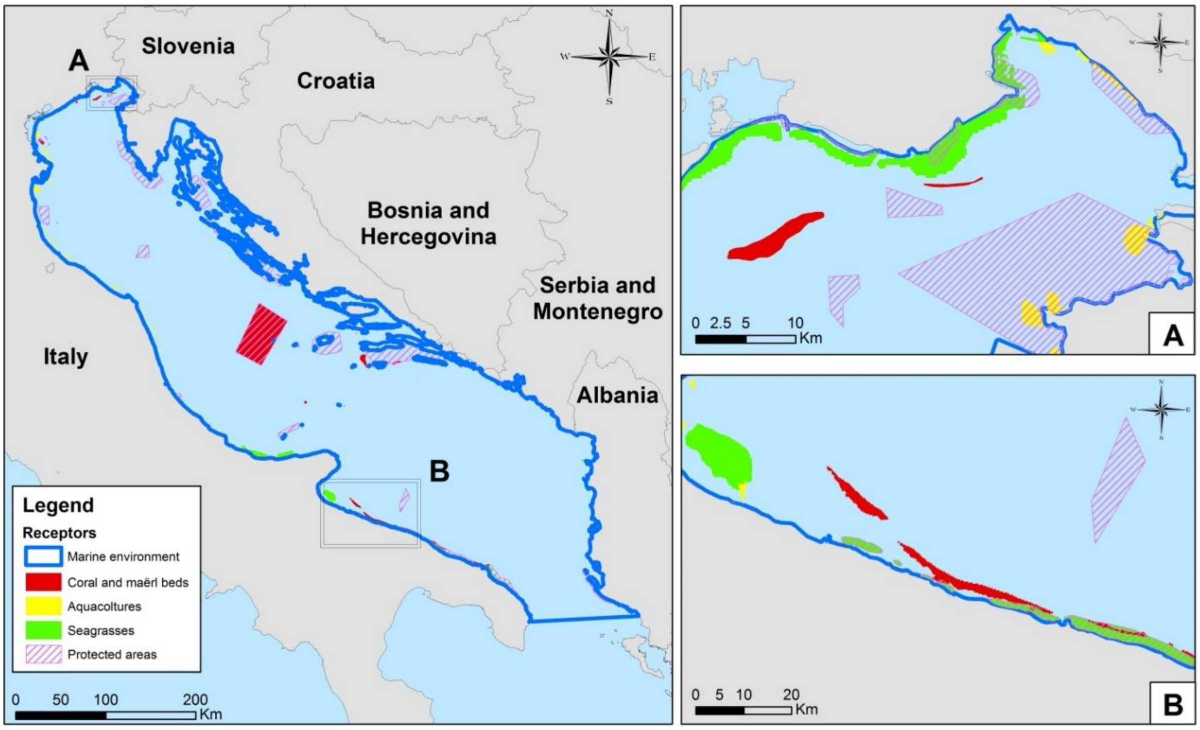
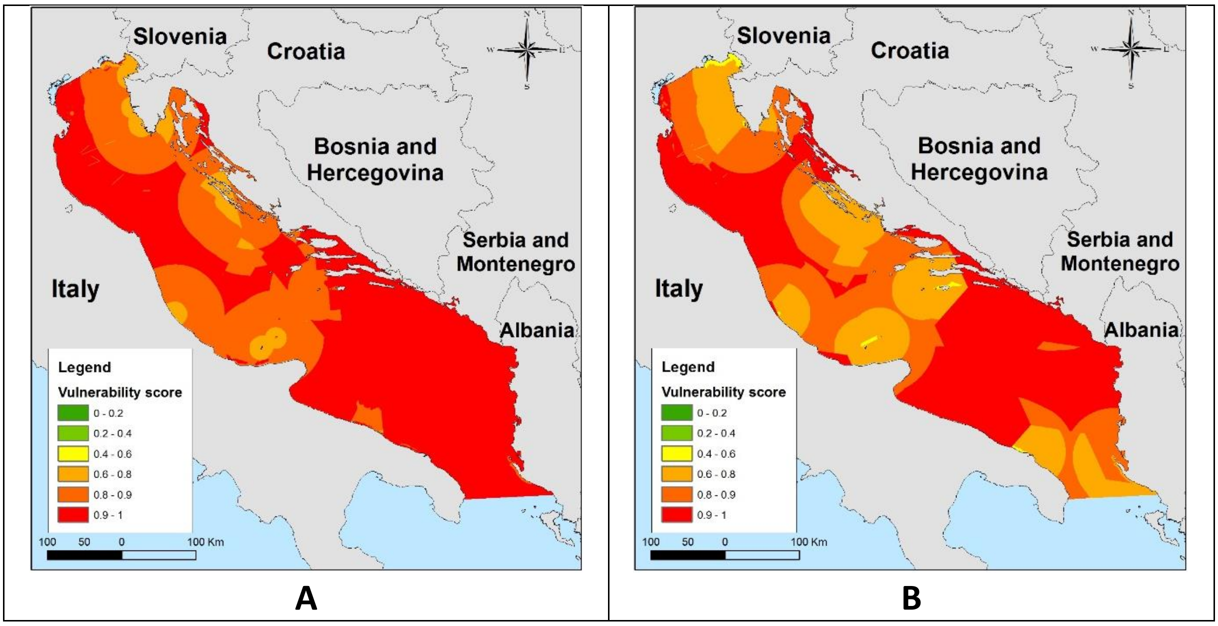


Figure 6.6 Exposure map identifying key receptors located in the Adriatic sea case study area, with a specific focus for the North Adriatic sea (A) and the marine area close to the Apulia region (B)

Seagrasses ad coral and maërl beds are mainly located close to the Italian coast (i.e. Veneto and Friuli Venezia region in the northern part and the Apulia region and the southern one) and represent about the 2% of the case study, whereas aquacultures are mostly focused in the Northern Adriatic sea (i.e. Italy, Slovenia and Croatia). As showed in zoom in Figure 6.6A and 6.6B most of the seagrasses and coral and maërl beds overlap with the marine protected areas established in the Adriatic sea, respectively the 30% and 99% of the related surface, underling complex and fragile ecosystems requiring specific protection status for their conservation.

6.3. Vulnerability maps

The final output of the vulnerability assessment is represented by the vulnerability maps (Annex F), evaluating the degree to which receptors could be adversely affected by the investigated hazards based on site-specific bio-physical and environmental features. As for the hazard maps, vulnerability maps were classified using the Equal Interval classification method setting the entire vulnerability values' range (i.e. from 0 to 1) in five categories equal in size (Zald et al., 2006). As can be observed in Figure 6.7, representing the vulnerability to the anthropogenic extractive technological hazard (Figure 6.7A), the anthropogenic physical hazard by underwater noise (Figure 6.7B), the anthropogenic biohazard (Figure 6.7C) and to the anthropogenic acute chemical hazard (Figure 6.7C), vulnerability scores assume homogenous relatively very high values in the whole case study (i.e. score ranging from 0.6-1), depending on the considered vulnerability factors and scores assigned to related classes.



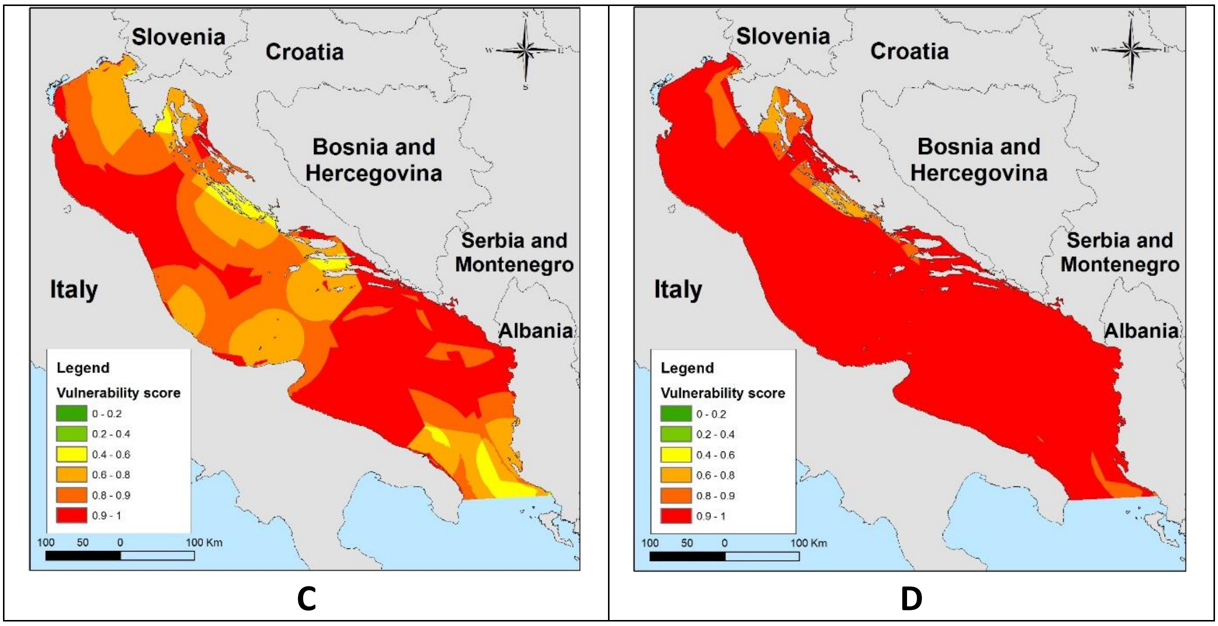


Figure 6.7 Example of vulnerability maps produced for the Adriatic sea case study representing: vulnerability to the anthropogenic extractive technological hazard (A), anthropogenic physical hazard by underwater noise (B), anthropogenic biohazard (C) and anthropogenic acute chemical hazard (D)

Results of the vulnerability assessment are summarized by the bar chart in Figure 6.8 representing the percentage of surface of the case study included in each vulnerability classes for the eight selected hazards.

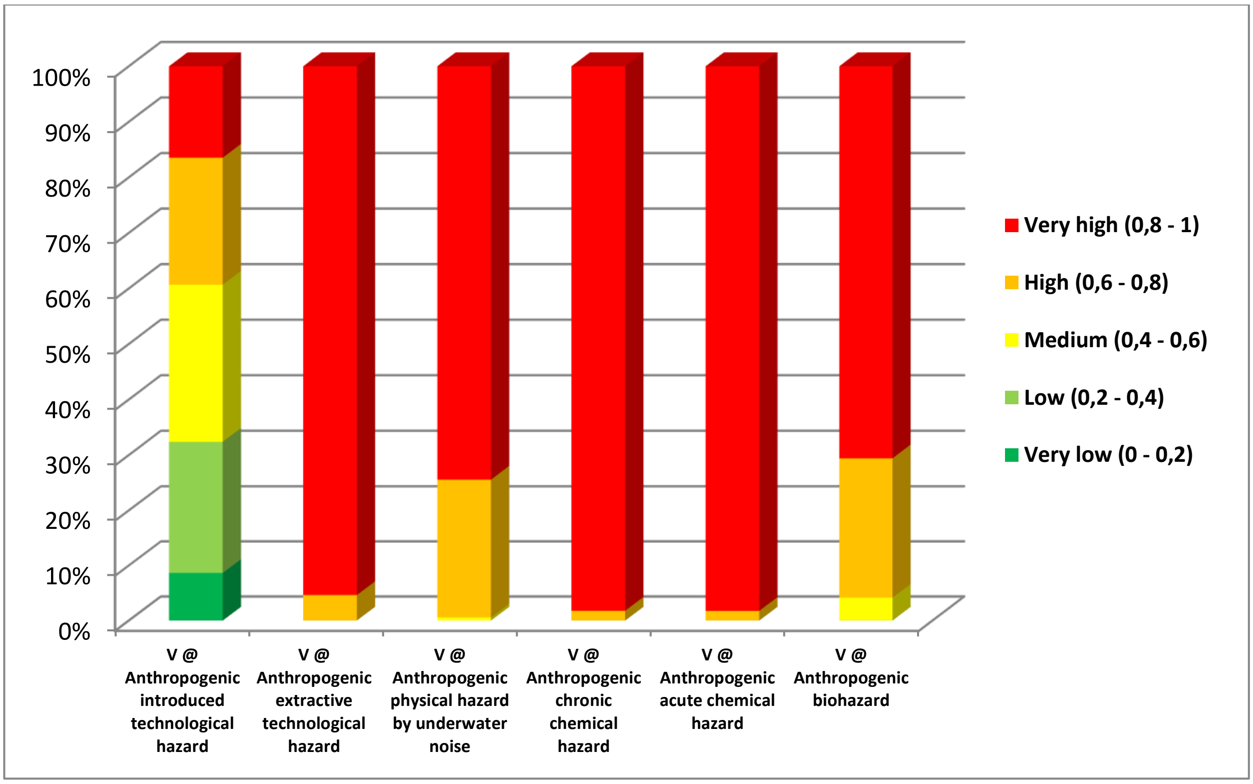


Figure 6.8 Bar chart representing the percentage of surface of the Adriatic sea case study included in each vulnerability classes for all the considered hazards

Vulnerability maps and related statistics provide an overall picture of the vulnerability of the analyzed marine ecosystem, and related receptors, to the multiple considered hazards. Being GIS-based, they can be used for identifying which factors have the most influence to increase the vulnerability of an area, thus providing valuable information for a more robust science-based decision making. More specifically, these kind of maps can support marine planner and managers designing and implementing management tools and nature-based solutions aimed at increasing the resilience of vulnerable targets to the considered impacts. These actions can include, for instance, the establishment of new MPAs providing a focal area for protecting relevant ecosystems such as salt marshes and seagrass beds, as well as for monitoring environmental conditions and trends, acting in this was as 'sentinel sites' of changes. More specifically, when appropriately placed and managed, MPAs can contribute on conserving biological diversity, restoring fish populations and protecting relevant spawning areas and nursery habitats (Halpern, 2010; Selig & Bruno, 2010). A well-planned and functionally connected MPAs network can provide benefits that go beyond those of a single area, acting as a corridor for shifting species and habitats, thus maximizing ecological connectivity between single MPAs and serving to increase protection for marine resources (NOAA, 2013; IUCN-WCPA, 2008). Other solutions for increasing resilience of marine habitat can also include the widespread transplantations of submerged seagrasses representing an important carbon sink, helping to mitigate climate change impacts. Seagrasses meadows contribute to improve water transparency and quality through trapping and storing solids particles and dissolved nutrients (Short aet al., 2007) and they can attenuate physical impacts influencing the hydrodynamic environment through reducing current velocity, dissipating wave energy and stabilizing the sediment (Ondiviela et al., 2014).

6.4. Risk maps

The implemented risk assessment phase has led to the development of a set of relative risk maps, one for each selected hazard (Paragraph 4.3.1) and considered timeframe scenarios (i.e. baseline 2000-2015 and future scenario 2035-2050). As already applied in the other assessment phases, they were classified by using the equal interval classification method (i.e. very low, low, medium, high, very high) (Zald et. al, 2006).

According to the Equation 16 (Paragraph 4.6) risk maps show significant spatial variations in the case study area, mainly due to the spatial localization and intensity of human activities in the Adriatic sea, since vulnerability assumes quite homogeneous maximum value equal to 1 for almost all the considered pressures. These results are further proved by the two bar charts in Figure 6.9

representing the percentage of surface of the Adriatic sea case study included in each risk class, for both the considered timeframe scenarios (i.e. 2000-2015 and 235-2050).

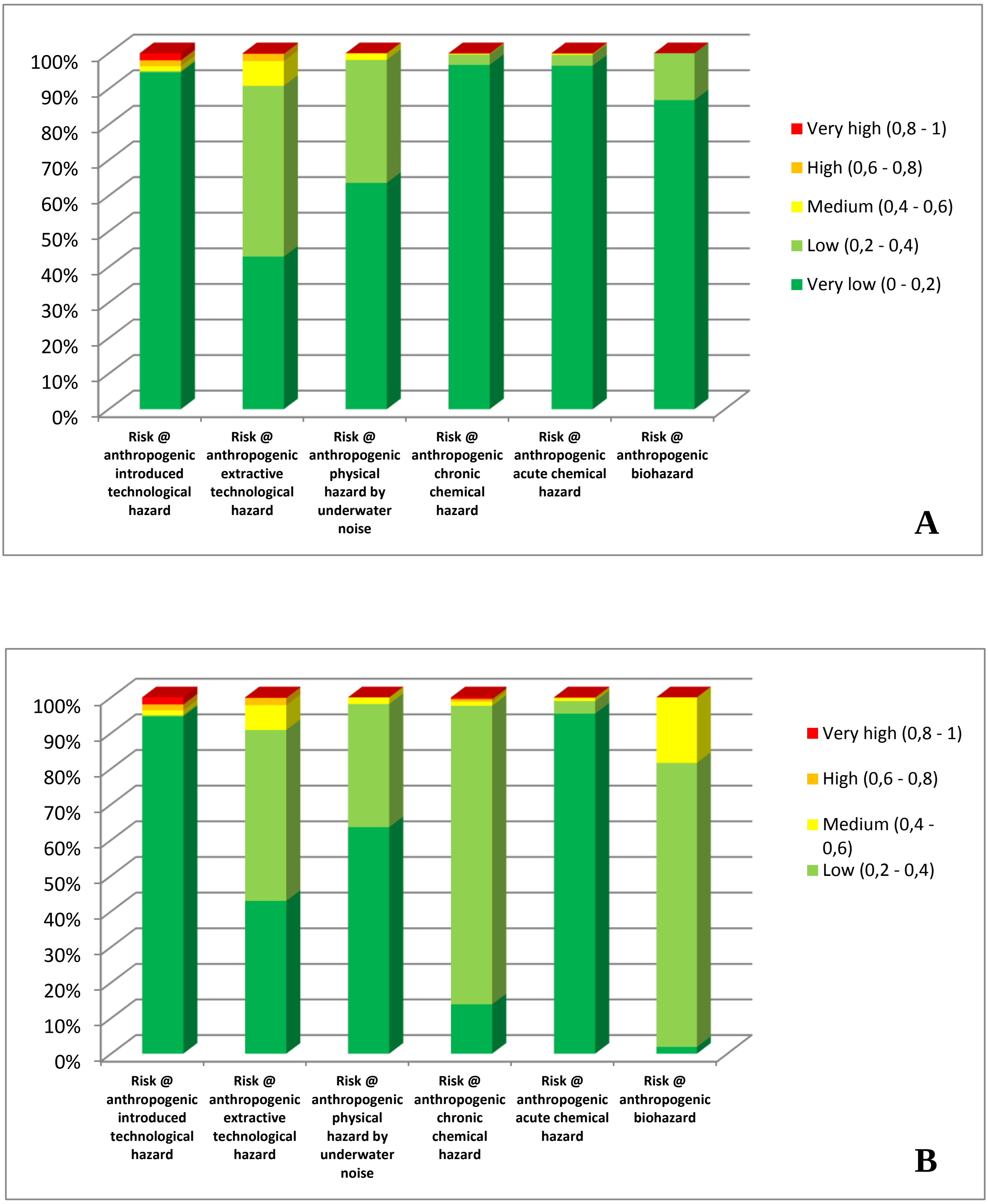


Figure 6.9 Bar charts representing the percentage of surface of the Adriatic sea case study included in each risk class for all the considered pressures in the baseline scenario 2000-2015 (A) and future scenario 2035-2050 (B)

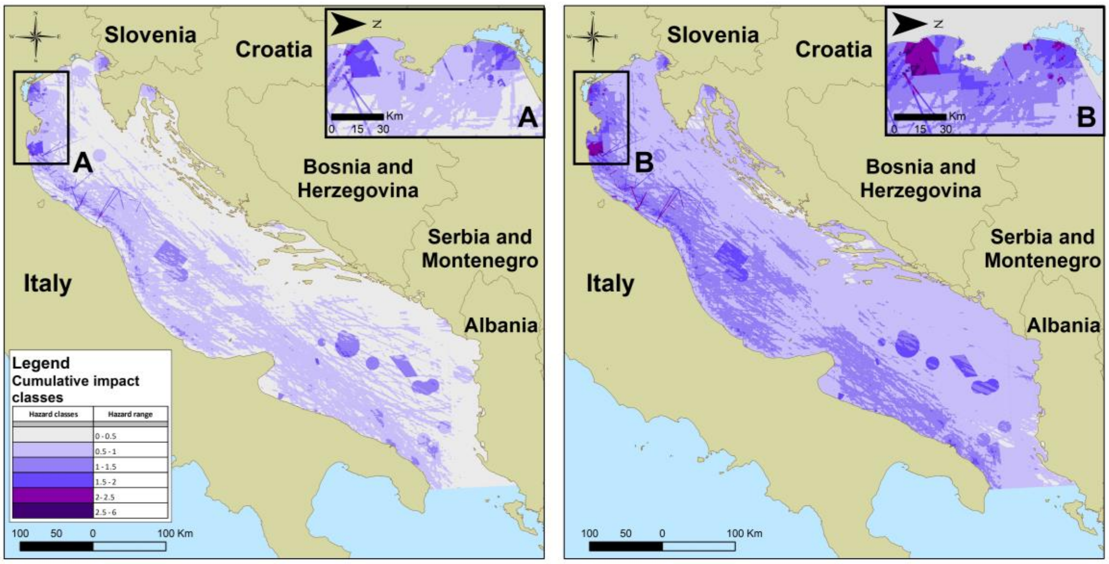
Can be observed that risk generally assumes lower values than the hazard ones represented in the bar charts Figure 6.5, as they are multiplied by vulnerability (i.e. scores ranging in 0-1), however the same trend of hazard is visible. Indeed, both the bar charts show low and moderate scores for all the considered risks, where higher score can be detected for risk related to the anthropogenic extractive technological hazard, with more than 50% of the Adriatic sea included in the low and moderate risk classes (i.e. score ranging from 0.2 to 0.6). The background changes a little bit in the future timeframe scenario (i.e. 2035-2050) where the major risk to marine environment is represented by the biological hazard with a shift of risk values from the lower classes (i.e. score ranging from 0 to 0.4 in the baseline scenario) to the upper ones with moderate risk scores (i.e. from 0.2 to 0.6). Similar changes can be noticed for the risk to the anthropogenic chronic chemical hazard, where risk scores, mostly included in the lower classes for the baseline scenario (i.e. score ranging from 0 to 0.4), completely move to the risk classes with scores ranging from 0.2 to 0.6.

By integrating hazard with exposure and susceptibility, risk maps allow a quick screening of areas and receptors at greatest risk from multiple stressors , where the achievement of GES, as required by the MSFD (EC, 2008), can be compromised. With this background, they can be effectively used by planners and policy makers for the design of science-based policies and management measures of marine areas that consider spatially relevant issues and are consistent with the objectives of MSFD (EC, 2008). Identifying the major risks contributing to the overall cumulative impacts and ranking more potentially affected targets, risk maps can support local public authorities to set priorities in maritime spatial planning and management (EC, 2014), focusing economic efforts on more urgent actions. Moreover, by also analyzing risks induced by land-based drivers, which inevitably affect the sea (i.e. rivers discharge of nutrients and eutrophication-inducing substances), risk maps can be also used for addressing territorial planning and the development of new infrastructures (e.g. build of wastewater treatment plants) in order to reduce pressures on the sea and improve a land-sea interface planning and management.

Finally, by taking into account future climate change scenarios for parameters related to the variation in sea surface temperature and Chlorophyll ‘a’ concentration, resulting risk maps can be used to aid decision-makers in the development of national and regional adaptation strategies, as well as cross sectorial risk management plans, aimed on one side to reduce exposure to climate related impacts, on the other side to increase resilience of marine ecosystems to rising threats.

6.5. Cumulative impact maps

Once implemented the risk assessment phase, resulting risk maps, for both the considered timeframe scenarios (i.e. 2000-2015, 2035-2050), were integrated based on the Equation 17 (Paragraph 4.7), leading to the development of two cumulative impact maps. The cumulative impact scores, ranging from 0 to 6, were classified by using manual intervals, in order to better visualize moderate values of cumulative impacts ranging from 0 to 2,5 (classified in 5 classes equal in size), and isolate the higher values (restricted in small areas of the case study) in a unique class ranging from 2,5 to the maximum score equal to 6. In this case, manual assignment of classes represents a useful technique for isolating and highlighting the higher cumulative impact scores in the case study that, however, assume the maximum value equal to 2.63 in the baseline scenario and 2.98 in the future one. Indeed, as showed in figure 6.10 the resulting cumulative impacts maps for the baseline and future scenarios, show basically low and moderate cumulative impact scores ranging from 0 to 2. They are mostly focused in the Italian Exclusive Economic Zones (EEZ), mainly due to the massive shipping traffic, the trawling fishing activities taking place seawards from the Italian coast, and the location of benthic infrastructures leading to severe physical impacts on the seabed. More specifically, higher cumulative impacts scores (always remaining in the moderate classes) can be detected in the Nord Adriatic sea in both the timeframe scenario. More specifically highly affected areas are located around the Po delta river and the ports of Trieste and Venice (Figure 6. 10A and B) due to the intense shipping traffic and ports activities as well as the high nutrient input in the area.

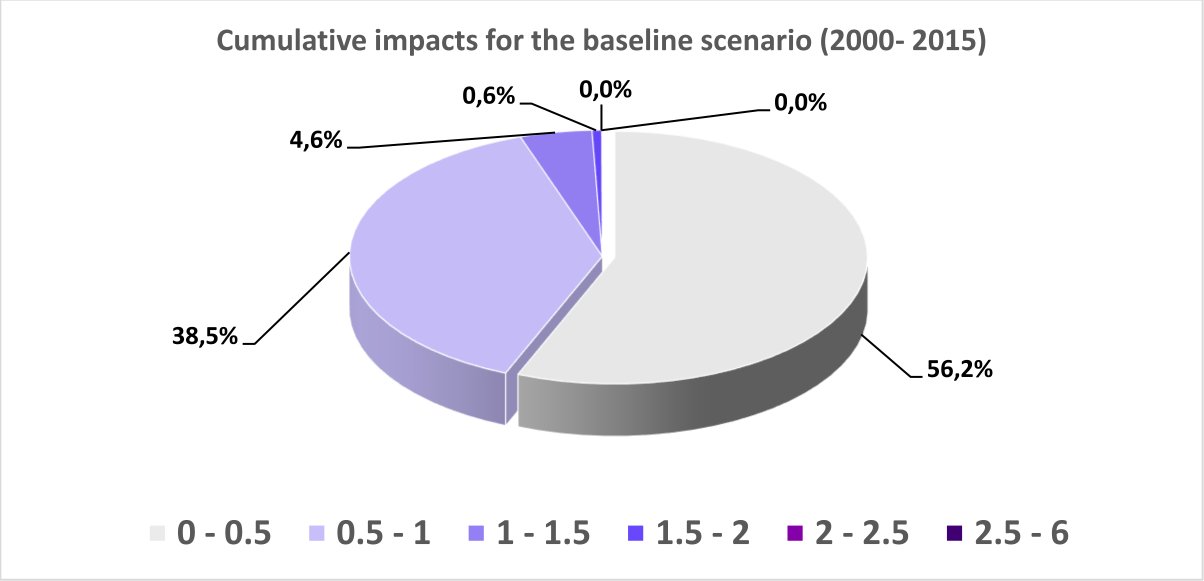


Baseline scenario 2000-2015

Future scenario 2035-2050

Figure 6.10 Cumulative impacts maps developed for the Adriatic sea case for the baseline (2000-2015) and future (2035-2050) scenarios

Moreover, by analyzing maps for the two different timeframe scenarios and the related summarizing statistics at the case study level (figure 6.11), a rising cumulative impact score can be observed. Indeed, comparing baseline with future scenario, it is evident how in the baseline scenario almost all the surface of the Adriatic sea case study is included in the lower classes with scores ranging from 0 to 1 (about 95%) whereas in the future ones in classes with values extending from 0.5 to 2 (about 99%). This output is strictly connected to the rising sea surface temperature (increased number of unusually warm events calculated in future scenario) that, interacting with the other endogenic pressures (e.g. shipping traffic, ports activities, nutrient input, oil-spill), highly contributes to the raised cumulative impacts in the case study.



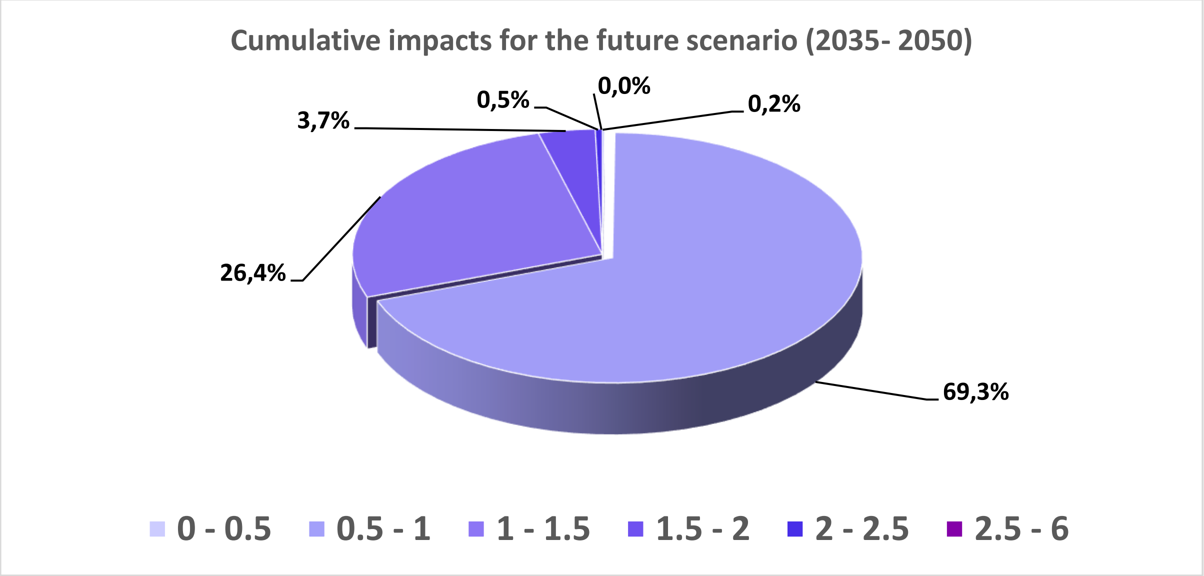
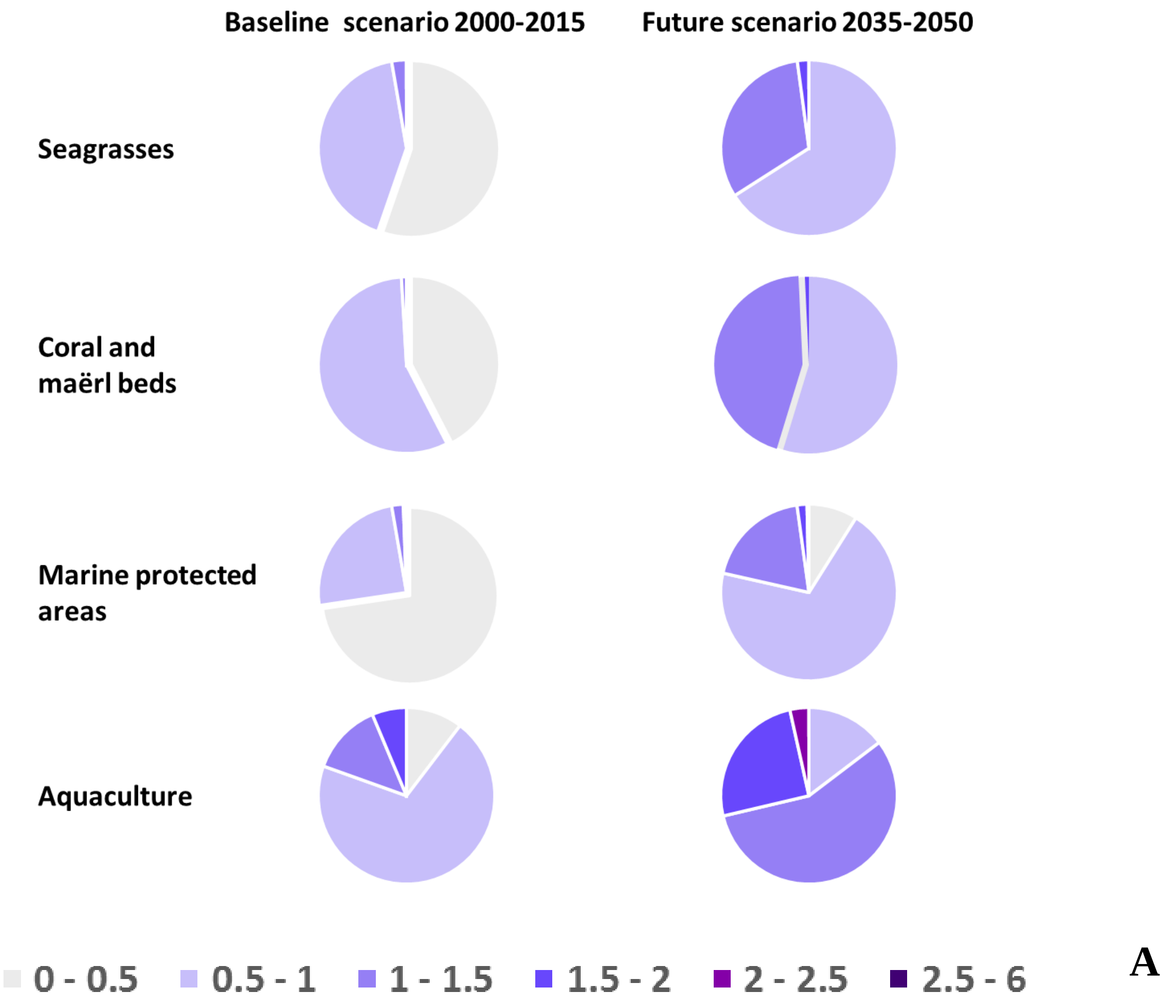


Figure 6.11 Pie charts representing the percentage of surface of the Adriatic sea case study area included in each cumulative impacts class for the baseline (2000-2015) and future (2035-2050) scenarios

By focusing the analysis on the exposed targets (i.e. seagrasses, coral and maërl beds, aquacultures and protected areas), Figure 6.12A shows that they could be all adversely affected by cumulative impacts, especially as baseline will move due to climate change leading to unusually warm condition (i.e. rising temperature). Indeed, as highlighted at the case study level (Figure 6.10 and 6.11), the same trend in the increasing of the cumulative impact scores from the baseline scenario to the future one can be noticed. More specifically, a general shift from the lower class with scores ranging from 0 to 0.5 to the upper ones from 0.5 to 1.5 can be observed in almost all the considered targets (i.e. seagrasses, coral and maërl beds and protected areas). The higher values of cumulative impact, always included in the lower and moderate classes, are assumed by the receptor 'aquacultures' where, in the future scenario 2035-2050, more than the 25% of the related surface is included in the class with scores ranging from 1.5 to 2 (Figure 6.12B). Considering the others receptors, the percentage of surface in the same class is always lower (around the 1-2%). Moreover, although in small extent (i.e. about the 0.03%), in the future scenario part of the surface of the receptor aquaculture is included in the higher cumulative impact class (i.e. scores ranging from 2.5 to 6), due to the localization of this target along the coast of the North Adriatic sea, especially around the Po delta river, where higher cumulative impacts scores were detected both in the baseline and future scenarios (Figure 6. 10A and B). Also the receptor MPAs in the future scenario shows a small percentage of its surface (i.e. about the 0.11%) included in the higher cumulative impact class, since a wide protected area (i.e. a biological protection zone established under the Italian Ministerial Decree 16/03/2004) is right located in the southern part of the Po delta river, where cumulative impacts values are higher (Figure 6.10B).



	Seagrasses		Coral and maërl beds		Aquaculture		Marine protected areas	
Classes Cumulative impact score	*CI baseline scenario (2000-2015)*	*CI future scenario (2035-2050)*	*CI baseline scenario (2000-2015)*	*CI future scenario (2035-2050)*	*CI baseline scenario (2000-2015)*	*CI future scenario (2035-2050)*	*CI baseline scenario (2000-2015)*	*CI future scenario (2035-2050)*
0 - 0.5	55.30%	0.00%	42.42%	0.00%	10.36%	0.00%	72.66%	8.94%
0.5 - 1	41.98%	65.97%	56.64%	54.73%	70.11%	14.66%	24.63%	69.59%
1 - 1.5	2.68%	31.90%	0.92%	44.53%	13.20%	56.67%	2.13%	19.28%
1.5 - 2	0.03%	2.10%	0.02%	0.74%	6.33%	25.18%	0.53%	1.83%
2 - 2.5	0.00%	0.03%	0.00%	0.01%	0.00%	3.46%	0.06%	0.25%
2.5 - 6	0.00%	0.00%	0.00%	0.00%	0.00%	0.03%	0.00%	0.11%

B

Figure 6.12 Pie charts (A) and related table (B), representing the percentage of surface of the selected receptors (i.e. seagrasses, coral and maërl beds, marine protected areas, aquacultures) included in each cumulative impacts class for the baseline (2000-2015) and future (2035-2050) scenarios

Cumulative impacts maps and related statistics provide and overall picture of areas mostly affected by cumulative impacts in the Adriatic sea case study, thus providing to marine planners and managers a valuable support for the development and implementation of cross-sectoral policies and plans. More specifically, they can back the development and implementation of integrated policies and plans aimed on one side at managing the conflicting uses of the sea thus reducing endogenic pressures (e.g. limit the shipping traffic on specific areas featured by vulnerable marine habitat), on the other side accommodating changes produced by exogenic unmanaged pressures (i.e. climate change) acting at the effective management scale on causes (need to be addressed locally) and consequences (require global action with mitigation strategies) (Patrício et al., 2014).

7. Implementation of the Bayesian Belief Network for multi-scenarios' analysis in the Adriatic sea

Based on methodology explained in Chapter 5, a GIS-based Bayesian Belied Network (BBN) was developed in order to analyze alternative credible scenarios envisioned for the Adriatic sea case study. The analysis led to the design of a set of scenarios analyzing the probability (and related uncertainty) of cumulative impacts under different climate and management options. Indeed, simulated scenarios allowed to integrate multiple management perspectives and objectives, in the form of increasing evidences specified in the BBN system for one or more input nodes and related states. Through downward (i.e. prediction) and upward propagations of evidences (i.e. diagnostic analysis) implications induced by all the defined potential scenarios were explored, thus supporting the identification of the most suitable integrated management schemes able to balance use/exploitation and conservation of the Adriatic sea.

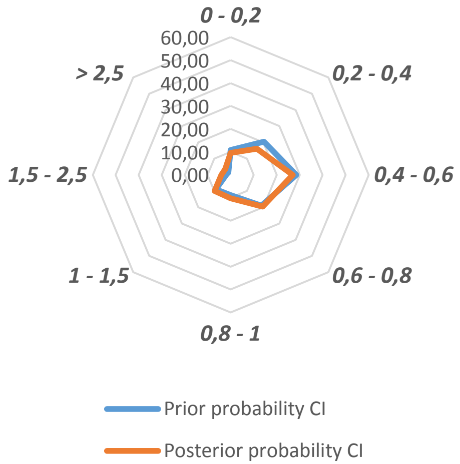
After a short description of the main findings from the Parameter and Evidence Sensitivity Analysis (Paragraph 7.1), the following paragraphs describe the results obtained from the application of the BBN for scenarios' analysis, providing the bar charts summarizing probabilities distributions for selected variables where changes in the simulated scenarios were more evident (Paragraph 7.2).

7.1. BNN sensitivity and testing

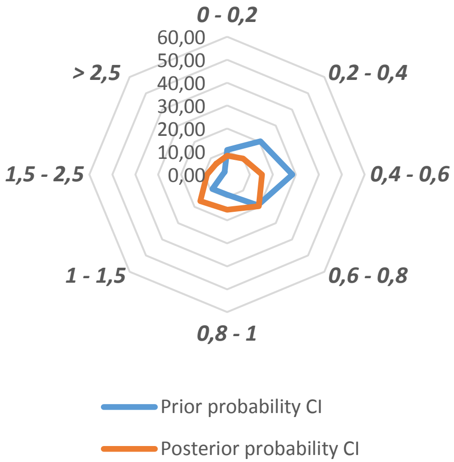
Sensitivity analysis is used to measure the sensitivity of variations in probabilities of query nodes when inputs parameters are changed. The query nodes in this study was the model endpoint related to cumulative impacts. As a consequence, the performed 'sensitivity to parameters' (Pollino et al., 2007) considers how the posterior probability of the cumulative impact node (CI) changes when input parameters are altered. More specifically, based on the empirical approach proposed by Pollino et al. (2007) (Paragraph 5.3), each parent nodes of the CI endpoint were changed by setting the higher state of each variable (i.e. state with score ranging from 0.8- 1) equal to 100%. Cross comparison between the simulated evidences were performed according to the main modules of the model (i.e. module pressures, hazards, vulnerability and risks) (Paragraph), contributing together to the overall estimate of the CI score at the case study level.

Results of the sensitivity analysis, based on changes in the parents nodes related to pressures, are shown in figure 7.1, including the radar charts comparing prior and posterior probability of the CI node under the simulated scenarios for all the model's pressures.

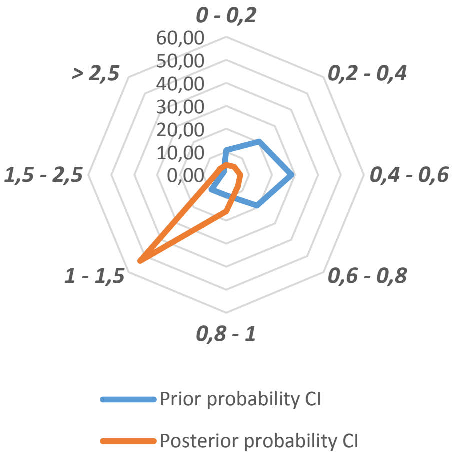
Aquaculture (fish and mussels farms)



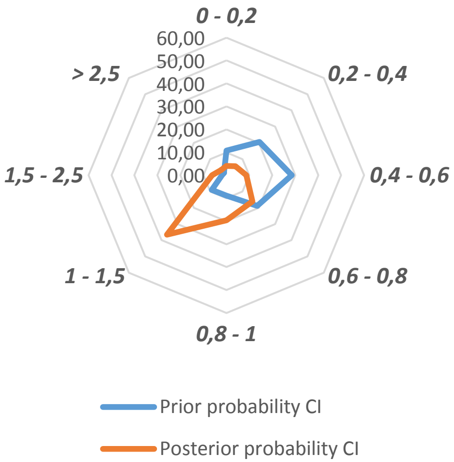
Nutrients input



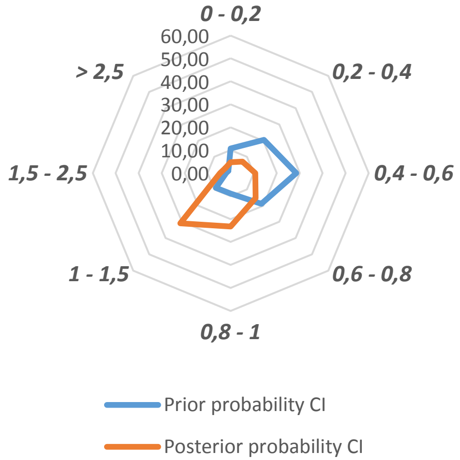
Dredging activities



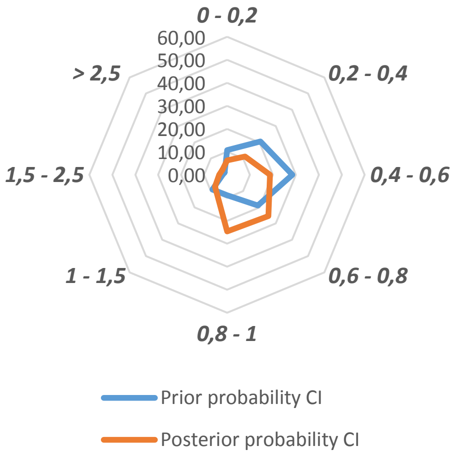
Benthic infrastructures



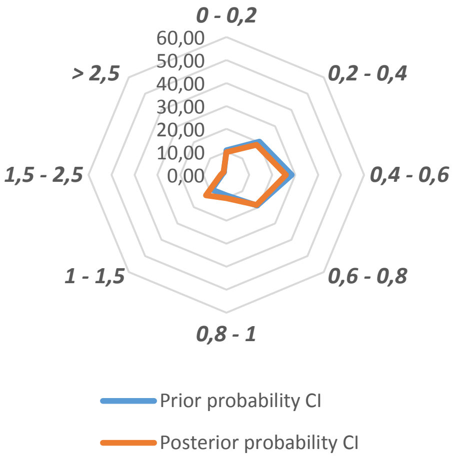
Oil-spill



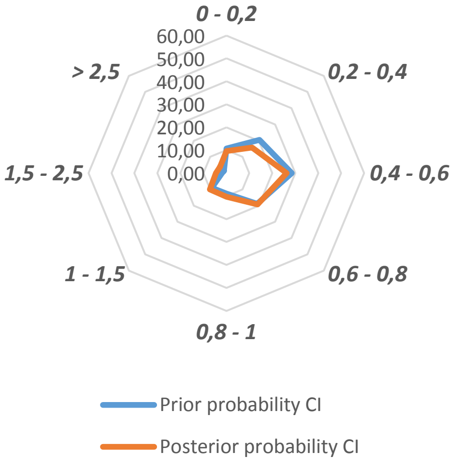
Platform for hydrocarbon extraction contributing to underwater noise



Platform for hydrocarbon extraction contributing to introduced technological hazard



Port activities



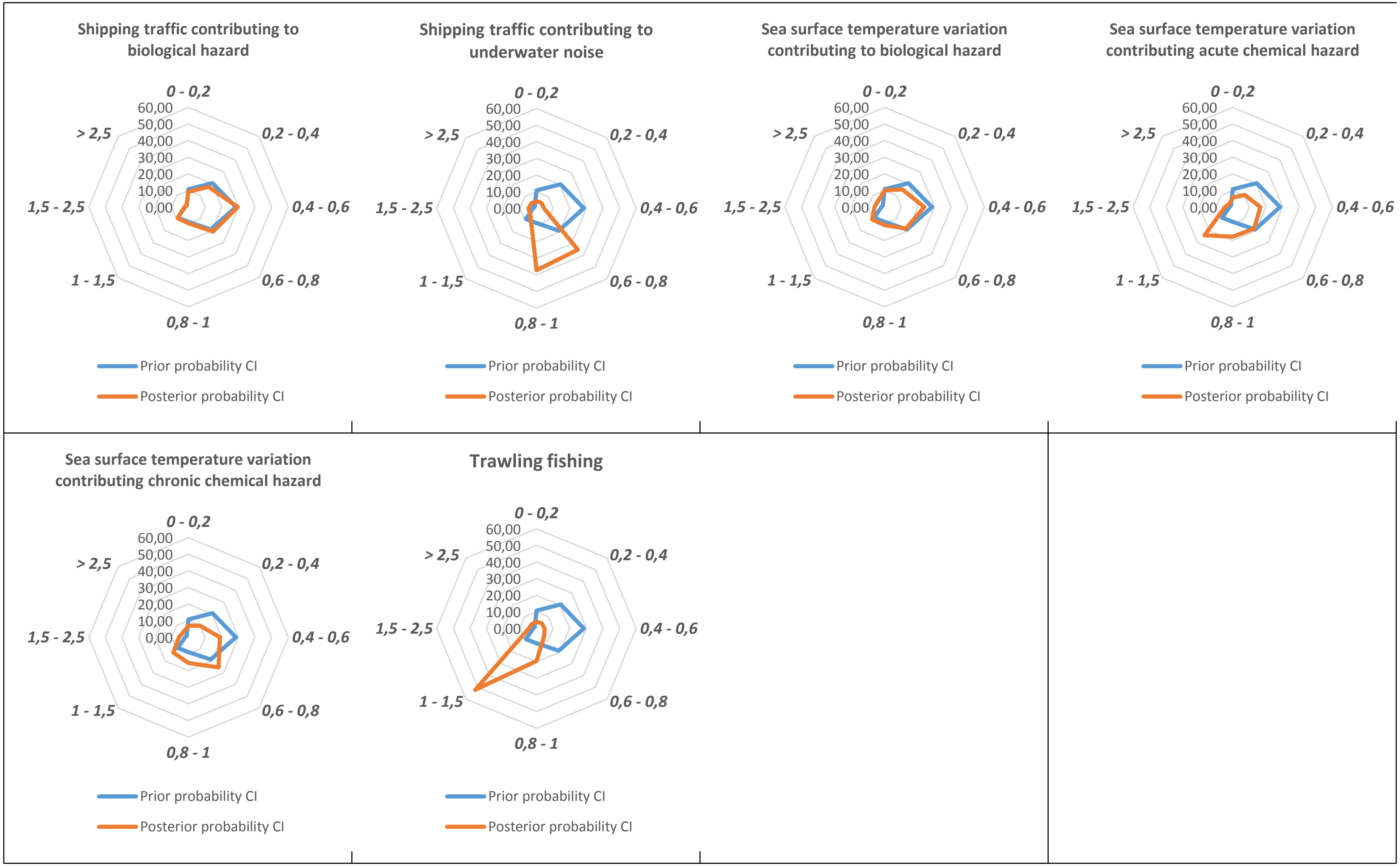


Figure 7.1 Radar charts comparing prior and posterior probability of the CI node under the simulated scenarios for all the model's pressures

Observing the bar charts in figure 7.1, higher variation in the posterior probabilities of the CI node can be noticed under changes (evidence set) in pressures related to the dredging activities and trawling fishing, with an important shift from the lower classes (i.e. score ranging from 0 to 0.8) to the moderate one with scores from 1 to 1.5. Alteration in the prior probabilities of the CI node, although in minor extent, can be detected also under the simulated scenarios for the benthic infrastructures, shipping traffic (contributing to the underwater noise) and oil spill. Changes due to the other simulated scenarios are less evident.

As far as the hazards' module is concerned, a similar pattern can be observed due to the direct relationship between pressures and hazards (i.e. interacting pressures contributing to the definition of the related hazards) (Paragraph 4.1). As a consequence, as shown in figure 7.2, higher changes in the posterior probabilities of the CI node can be noticed for the anthropogenic extractive technological hazard under the influence of dredging activities and trawling fishing leading together to seabed abrasion, as well as for the anthropogenic physical hazard by underwater noise due to shipping traffic. Relevant contribution to the variation of the CI posterior probability it is also induced by changes in the anthropogenic acute chemical hazard, where interacting pressures related to the sea surface temperature variation and oil-spill create a moderate shift from the lower classes (i.e. score ranging from 0 o 0.8) to the moderate one (i.e. score from 1 to 1.5).

By focusing on the vulnerabilities module, a different behavior in the variation among the prior and posterior probabilities (under the simulated scenarios) can be noticed (Figure 7.3), mainly due to the lower influence of the considered environmental vulnerabilities on the final estimate of the cumulative impact score.

Finally, for what concern the risks module, parameter sensitivity analysis was applied only to the physical risks induced by the introduced and extractive technological hazards and the acute and chronic chemical risks, since limited observations were available in the higher classes to simulate scenarios for the other considered risks (i.e. biological risk, physical risk by disturbance –noise-). This analysis proved again the higher sensitivity of the CI node to changes in the physical risk produced by the extractive technological hazard, strictly linked to dredging activities and trawling fishing. In line with this result, as already identified for the related hazards and pressures nodes (Figure 7.1 and 7.2), a moderate variation of the prior probabilities of the CI node can be noticed also due to the scenarios simulated for the physical risk by the introduced technological hazard and the acute chemical risk.

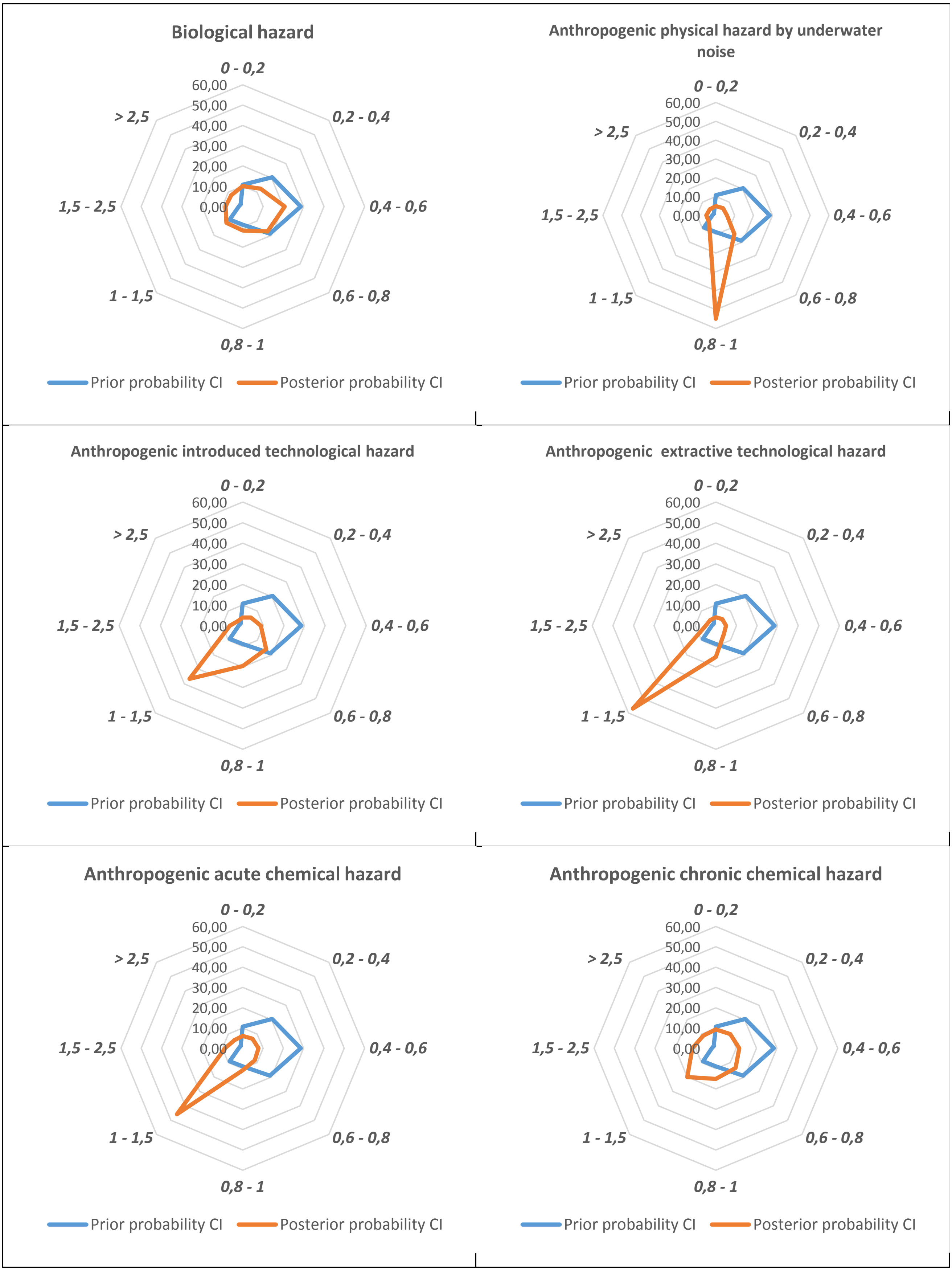


Figure 7.2 Radar charts comparing prior and posterior probability of the cumulative impacts node under the simulated scenarios for all the model's hazards

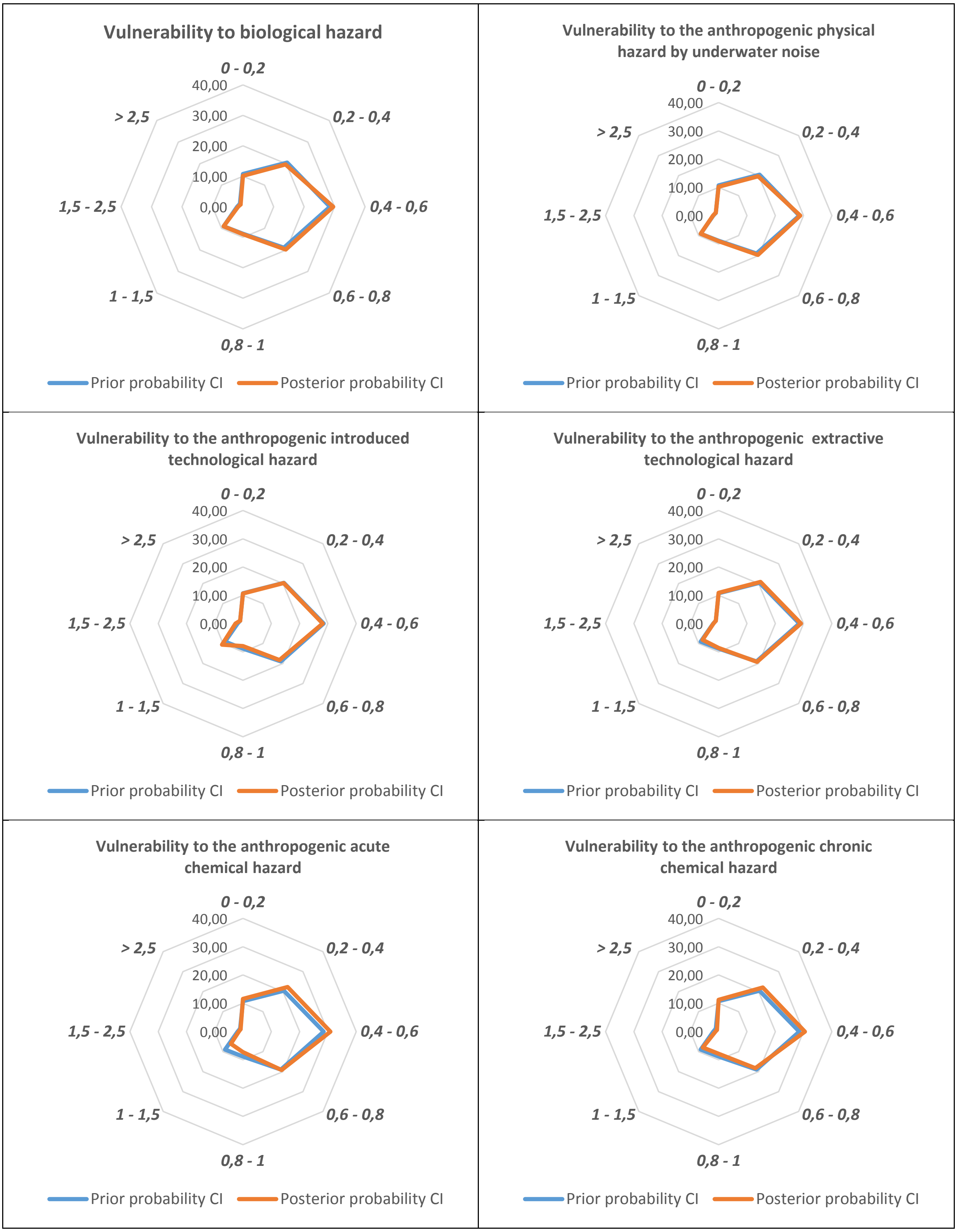


Figure 7.3 Radar charts comparing prior and posterior probability of the cumulative impacts node under the simulated scenarios for all the model's vulnerabilities

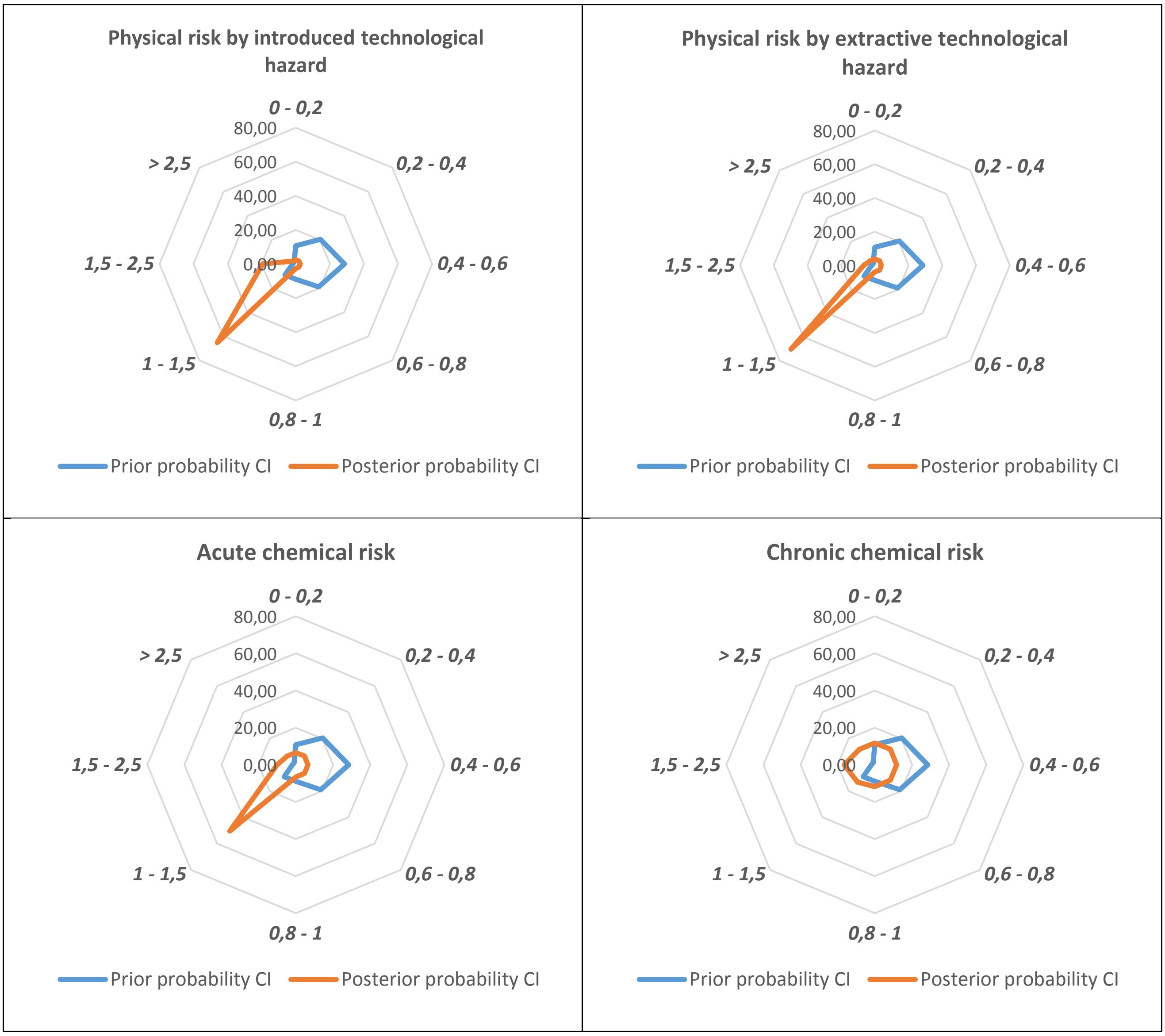


Figure 7.3 Radar charts comparing prior and posterior probability of the cumulative impacts node under the simulated scenarios for the model's risks

7.2. Marine planning and climate scenarios

Scenario 1:

The first scenario developed through the trained BBN, simulated the establishment of new Marine Protected Areas -MPAs- in the Adriatic sea, reinforcing ecological connectivity between marine habitat and, as a consequence, reducing the overall vulnerability of the marine environment to the hazards of concern (Paragraph 5.4). Comparison of the vulnerability states' probabilities, before and after the designation of conservation areas (i.e. MPAs) are presented in the bar charts included in figure 7.5. They were developed for selected variables of the BBN, where changes, under the defined evidence, were more evident. Moreover, in order to allow and speed-up computation within the software R, during the application process the name of the variables in the BBN was codified as follow (as reported in the bar charts):

- VH1: overall vulnerability of the Adriatic sea to the anthropogenic biological hazard (H1).
- VH2: overall vulnerability of the Adriatic sea to the anthropogenic physical hazard by underwater noise (H2).
- VH3: overall vulnerability of the Adriatic sea to the anthropogenic introduced technological hazard (H3).
- VH4: overall vulnerability of the Adriatic sea to the anthropogenic extractive technological hazard (H4).

Results of Scenario 1 showed an evident reduction of the overall vulnerability of the marine area of concern to the related hazards (Figure 7.5). More specifically, by analyzing the vulnerability to the anthropogenic introduced technological hazard (Figure 7.5C), the reference scenario revealed that there is about 0-70% chance that vulnerability stands in the higher and moderate states (i.e. vulnerability score ranging from 0.4-1). In contrast, as expected after the simulated establishment of new MPAs in the Adriatic sea, the BNN calculated a substantially change, with a 0–98% chance of being in the first state corresponding to the lower vulnerability (i.e. in the 0-0.2 range).

A similar pattern, though less pronounced, can be observed for the vulnerability to the anthropogenic biological hazard (Figure 7.5A), the anthropogenic physical hazard by underwater noise (Figure 7.5B) and the extractive technological hazard (Figure 7.5D), with a general shift of likelihood from the upper state with higher vulnerability (i.e. vulnerability score ranging from 0.8-1) to the immediately lower one (i.e. ranging from 0.6-0.8). Results obtained from Scenario 1 suggest that the establishment of new MPAs, with the associated reduction of the minimum distance between them, would lead to reduce the overall vulnerability within the area of concern, as the number of grid cells being in states with higher scores tend to decrease.

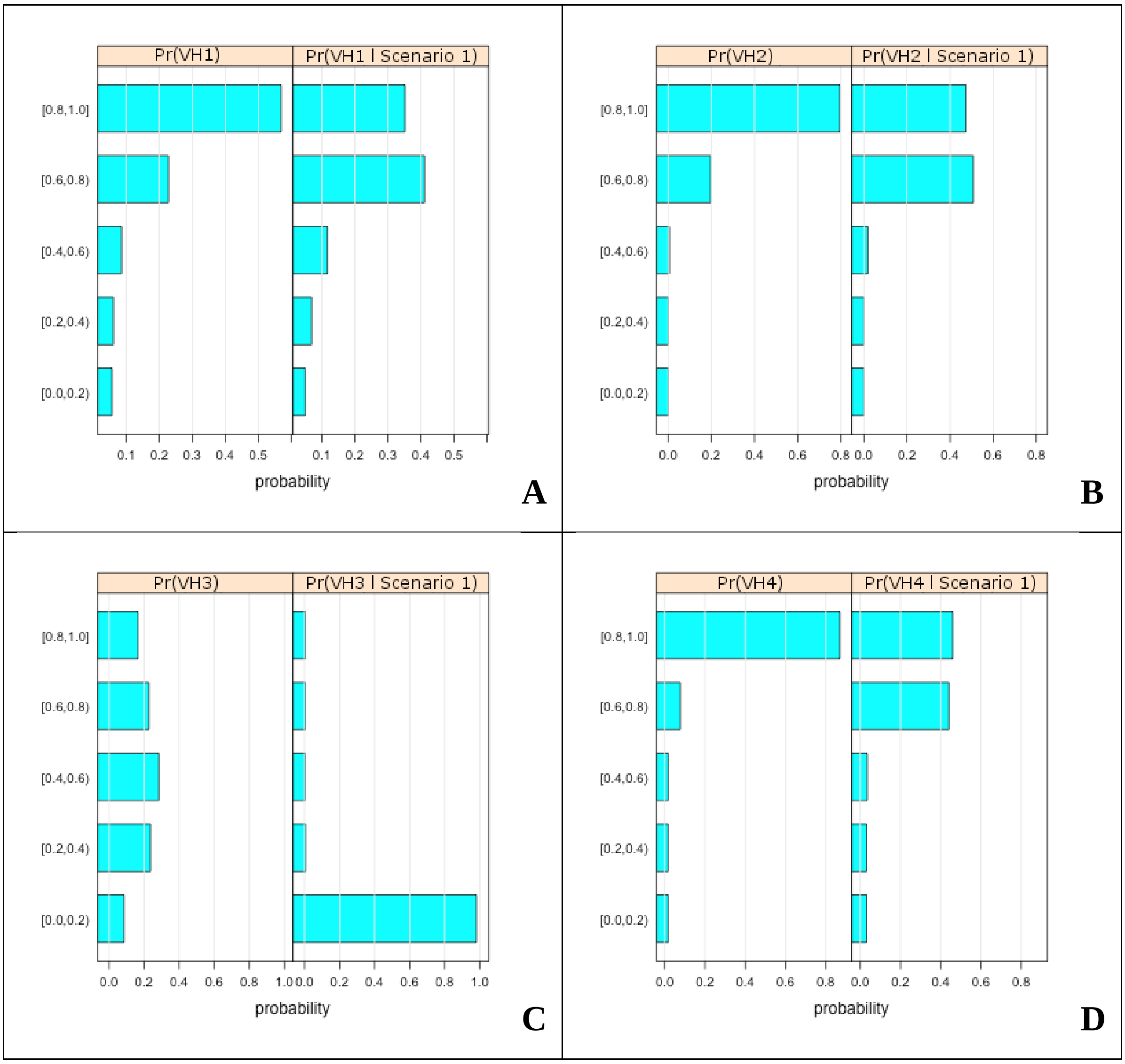


Figure 7.5 Bar charts representing the probability distributions of the vulnerability to the anthropogenic biohazard (A), anthropogenic physical hazard by underwater noise (B), anthropogenic introduced (C) and extractive (D) technological hazards, under the reference and simulated Scenario 1

However, by analyzing the bar charts representing the cumulative impact (CI) under the reference and simulated Scenario 1 (Figure 7.6), it is evident as the latter doesn’t decrease in a considerable way, as a consequence of the simulated conservation measure (i.e. evidence set in the BBN). Indeed, a minimum shift from states with moderate and higher CI (i.e. score ranging from >=2.5 to 1) to those with lower ones (i.e. from 0 to 1) can be observed. This result mainly relates to the influence of pressures (and related hazards) in the final estimate of the CI score, highly contributing to increase all the considered risks and, in turn, the overall CI for the case study.

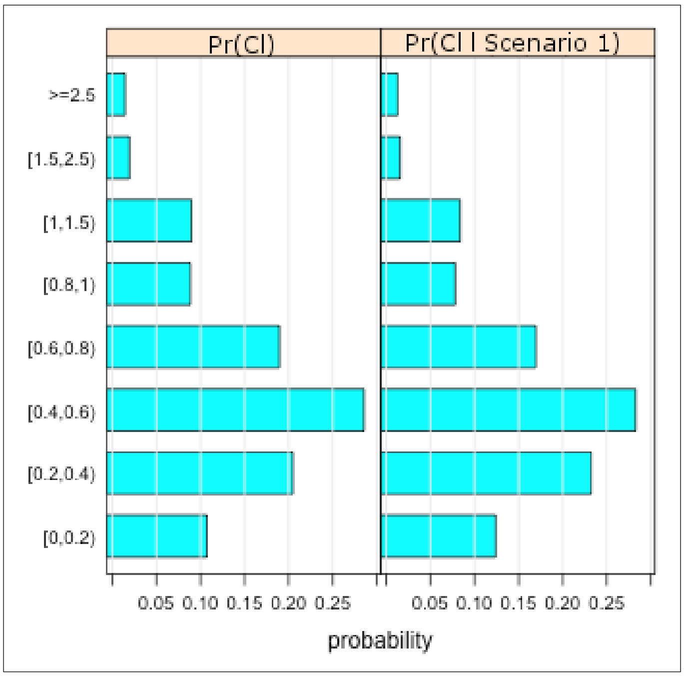


Figure 7.6 Bar charts representing the probability distributions of cumulative impacts under the reference (on the right) and simulated Scenario 1 (on the left)

This final result, compared with bar charts focusing on vulnerabilities (Figure 7.5), demonstrates that an integrated approach to marine management and planning is required, in order to better balance use and exploitation of marine space with its conservation and, where required, restoration of threatened habitat (EC, 2008; EC, 2014).

Scenario 2:

The second scenario simulated through the developed BBN, focused on the analysis of the potential effects induced by a rising sea surface temperature (SST), on all the hazards where this exogenic pressure interacts with endogenic ones (i.e. anthropogenic biological hazard, chronic and acute chemical hazards) (Paragraph 5.4). Comparison of changes in the states' probabilities of these hazards, for the reference and simulated Scenario 2, are shown in the bar charts included in figure 7.7. As already applied within the previous scenario, variables' name in the BBN was codified as follow (as reported in the bar charts):

- H1: anthropogenic biological hazard.
- H5: anthropogenic acute chemical hazard.
- H6: anthropogenic chronic chemical hazard.

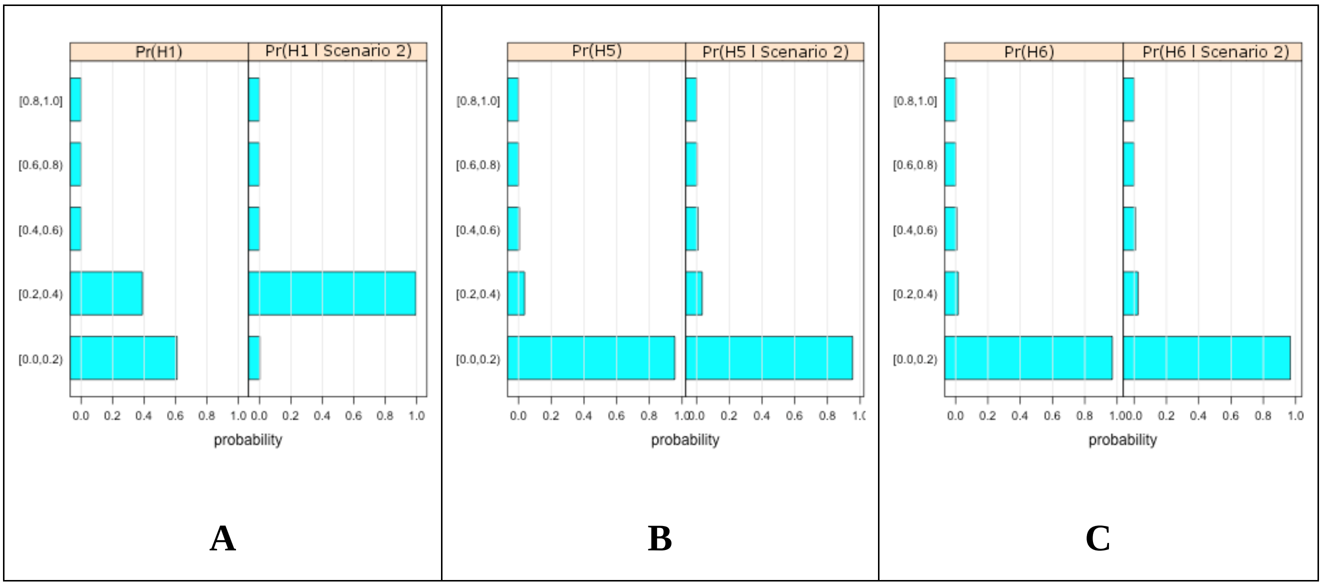


Figure 7.7 Bar charts representing the probability distributions of the anthropogenic biological hazard (A), anthropogenic acute (B) and chronic chemical hazards (C), under the reference and simulated Scenario 2

By focusing on the biological hazard (Figure 7.7A) where changes are more evident, the proportion of cells in the second state (i.e. in the range of 0.2-0.4), increased from the 40% in the reference scenario to about the 100% in the simulated one, with a complete shift of the lower state to the immediately upper one. However, the calculated variations for the other hazards are minor, since a lower interaction weight was assigned to pressure related to SST respect to those linked with the oil-spill (i.e. acute chemical hazard) and nutrient input (i.e. chronic chemical hazard) (Paragraph 4.3.3). Accordingly, as shown in Figure 7.8, an increase of the overall CI score can be detected, especially around the moderate CI states (i.e. 0.4-1.5).

Results obtained from this second scenario demonstrates that more severe potential cumulative impacts are expected in a future scenario, under the effects of changing climate conditions. As a consequence, appropriate adaptation strategies are required in order to increase resilience of marine habitat to rising threats due to ongoing and future climate changes.

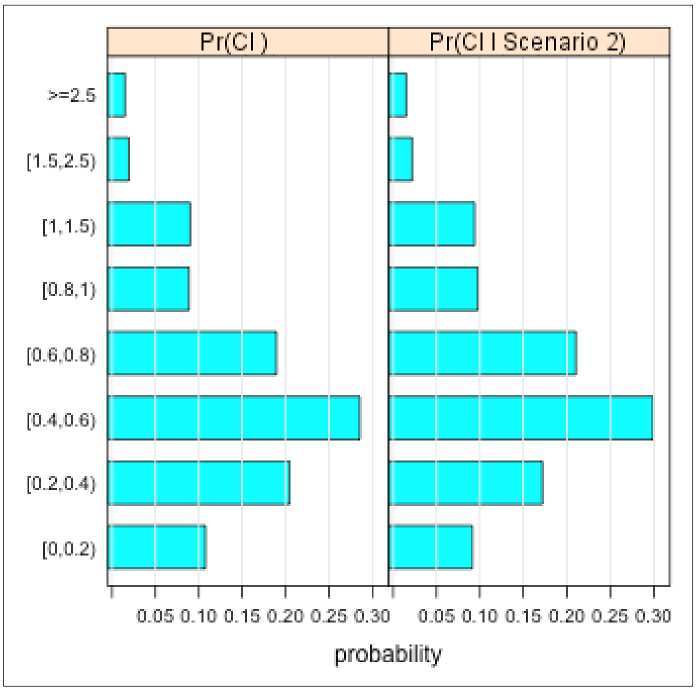


Figure 7.8 Bar charts representing the probability distributions of cumulative impacts under the reference (on the right) and simulated Scenario 2 (on the left)

Scenario 3:

This scenario was aimed at evaluating consequences (i.e. increasing of CI) induced by a higher nutrient input in the Adriatic se case study, simulating a rising Chl 'a' concentration in the range of 1.15 - 1.44 µg/L (Paragraph 5.4), by setting the evidence of the upper state of this variable equal to 100%. Drawing on the developed conceptual model of the system (Paragraph 5.1), comparison between reference and simulated Scenario 3 focused on changes in the states’ probabilities of the anthropogenic chronic chemical hazard and the related risk, as well as on the probability of CI against the defined evidence. The resulting output of this analysis are represented in the two bar charts included in figure 7.9 where variables’ name was codified as follow:

- H6: anthropogenic chronic chemical hazard.
- RH6: risk to the anthropogenic chronic chemical hazard.

Results of the assessment showed a significant change in amount of pixel included in the first state of the node related to the anthropogenic chronic chemical hazard (i.e. hazard score ranging from 0-0.2), with a general shift of the likelihood toward the higher states (i.e. in the range of 0.2-1). The variation are above all evident in the second state (i.e. in the range of 0.2-0.4) with an increase from about the 2% in the baseline scenario to 60% in the Scenario 4 (Figure 7.9A). The same behavior can be noticed for the related risk (i.e. risk to the anthropogenic chronic chemical hazard), since vulnerability to the hazard of concern assumes quite homogeneous scores equal to 1 in the whole case study (Paragraph 6.3) (Figure 7.9B).

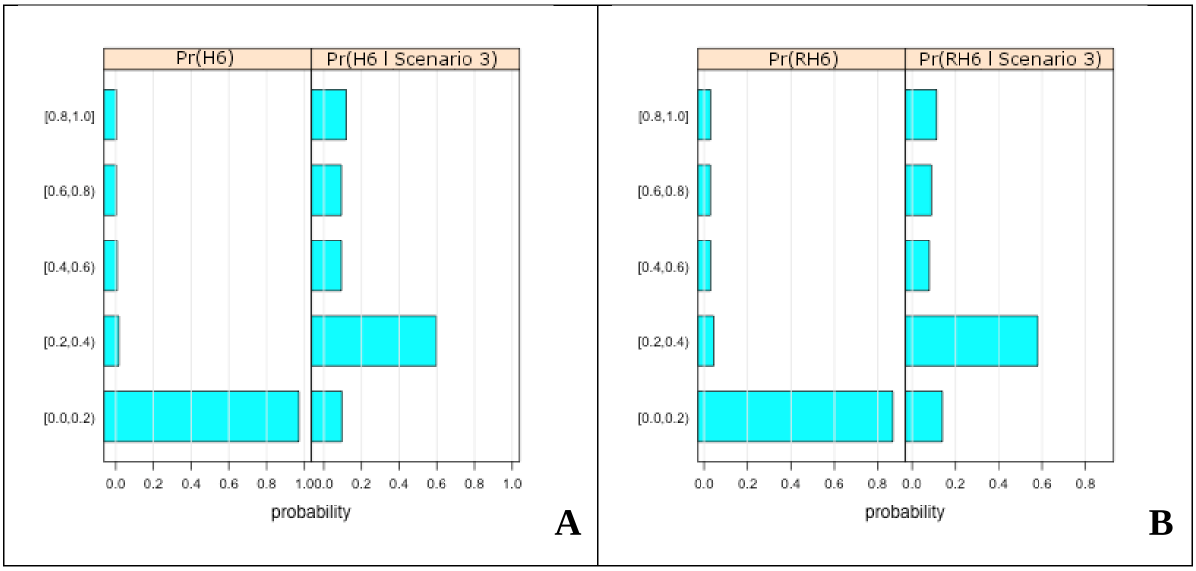


Figure 7.9 Bar charts representing the probability distributions of the anthropogenic chronic chemical hazard (A) and related risk (B) under the reference and simulated Scenario 3

Finally, as a consequence of changes within hazard and risk, as shown in figure 7.10, an increase of the probability of CI to be in the upper states (i.e. in the rage from 0.6- >=2.5) can be detected.

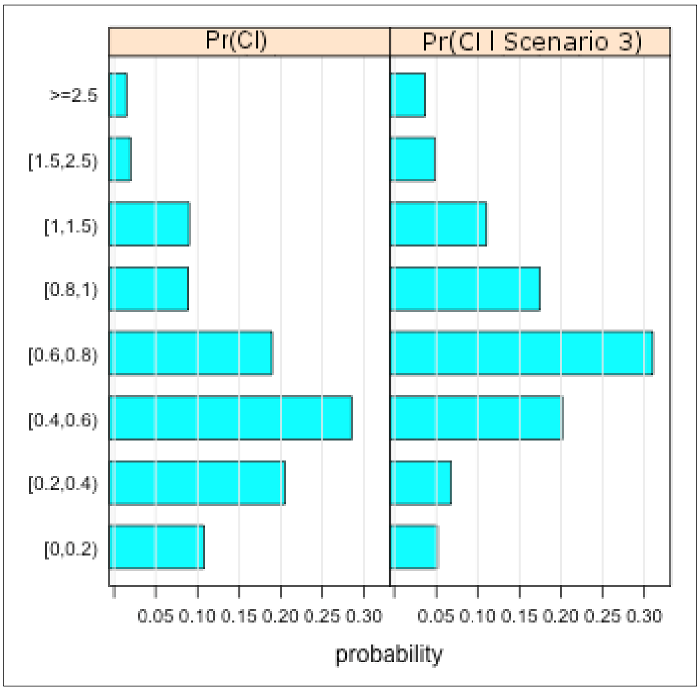


Figure 7.10 Bar charts representing the probability distributions of cumulative impacts under the reference (on the right) and simulated Scenario 3 (on the left)

More specifically, changes are mostly visible for the state with CI scores ranging from 0.6 to 0.8, where the reference scenario showed that there is a 0-19% of probability to stand in this state whereas in the simulated scenario the 0-32%.

These results demonstrates that the land-sea interface approach to management is required (EC, 2013) in order to address territorial planning and infrastructures' design (e.g. development of new infrastructures for wastewater treatment), in order to reduce hazards and associated risks induced by land-based drivers which unavoidably lead to chronic pollution of the closer sea.

Scenario 4:

The fourth scenario focused on the application of the BBN for diagnostic analysis, trying to estimate the required management measures and adaptation strategies to achieve an overall reduction of CI in the Adriatic sea case study (i.e. lower state of CI in the range of 0-0.2) (Paragraph 5.4). The results of this scenario are shown in figure 7.11, representing bar charts related to selected variables where changes, under the defined evidence, were more evident. Variables' name in the BBN was codified as follow:

- ShipH1: pressure related to shipping traffic contributing to the final anthropogenic biological hazard.
- ShipH2: pressure related to shipping traffic contributing to the final anthropogenic physical hazard by underwater noise.
- Trawl: pressure related to trawling fishing activities contributing to the final anthropogenic extractive technological hazard.
- H1: anthropogenic biological hazard.
- H2: anthropogenic physical hazard by underwater noise.
- H4: anthropogenic extractive technological hazard.

The bar charts showed that trawling fishing and shipping traffic i.e. (parents' nodes in the developed system) are the pressures mostly influencing the reduction of the final CI in the case study (Figure 7.11A, B, C). Indeed, the percentage of grid cells in the lower state (i.e. lower intensity of pressure in the range 0-0.2) for the shipping traffic contributing to the overall anthropogenic physical hazard by underwater noise (Figure 7.11B), increased from about the 58% in the reference scenario to 85% in the simulated one. Analogous shift of likelihood, though less pronounced, from the upper states with higher pressure intensity (i.e. score ranging from 0.2-1) to the lower one (i.e. ranging from 0-0.2) can be noticed also for the trawling fishing activity (Figure 7.11C). Finally, as cascading effect of changes in pressures, in the related hazards (Figure 7.11D, E,

F) a similar pattern, but less pronounced, can observed. The calculated changes for the other activities (and related hazards and risks on the marine environment) are minor.

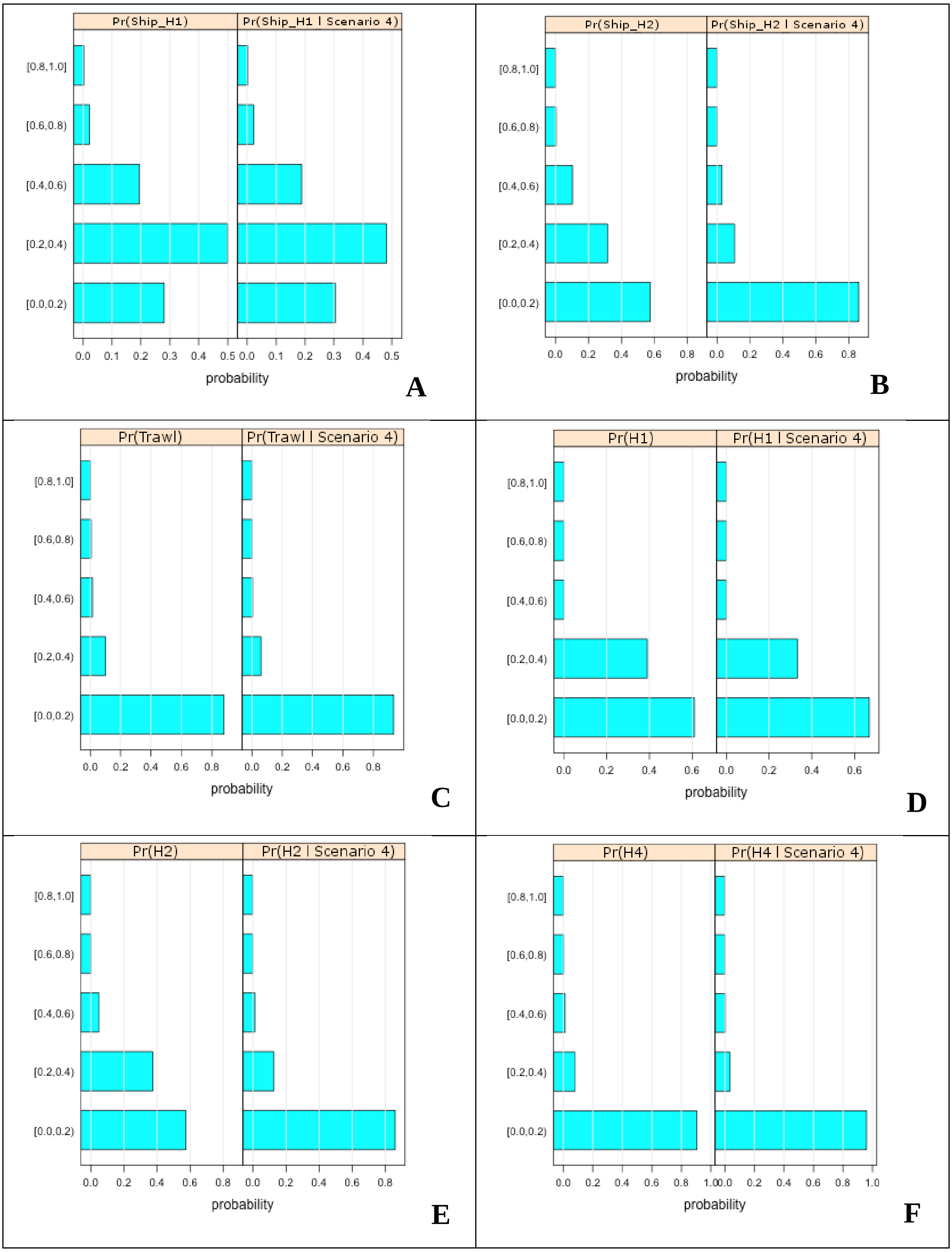


Figure 7.11 Bar charts representing the probability distributions of pressure related to shipping traffic (A, B), trawling fishing activities (C), anthropogenic biological hazard (D) anthropogenic physical hazard by underwater noise (E), and anthropogenic extractive technological hazard (F) under the reference and simulated Scenario 4

Results get from Scenario 4 warn that pressures related to trawling fishing and shipping traffic (i.e. for all the related hazards) need to be better regulated, in order to reduce the overall cumulative impacts in the case study, since they are the two variables with the most significant changes comparing the reference scenario with the simulated one.

CONCLUSIONS

Integrating climate patterns with socio-economic and environmental information of the considered marine area, the proposed cumulative impacts assessment methodology allowed to develop a set of environmental impacts scenarios and related indicators, supporting a semi-quantitative evaluation and relative ranking of areas and targets potentially affected by interactive natural and anthropogenic pressures. This aspect represents a step forward over the traditional methodologies, since it provides a sound procedure to evaluate the overall cumulative impacts induced by the potential interactions among multiple pressures, taking also into account heterogeneous vulnerabilities to different types of hazards as well as alternative climate and management scenarios.

The strength of the proposed approach is represented by the integration of different tools (i.e. environmental indicators, Geographic Information Systems, Multi-Criteria-Decision-Analysis and Bayesian Belief Networks) acting together as a decision support system, able to assimilate different data, information and expertise to effectively aid marine spatial planning and the related decision processes. It is flexible to be applied in different marine regions and for multiple scenarios, supporting to evaluate both the progress toward the achievement of GES and the potential effects of long-term changes. Indeed, the development of cumulative impacts maps, and related scenarios, has to be seen as a part of an iterative process that is expected to progressively improve by considering different hazards (e.g. oceans' acidification, hypoxia), extending the analysis to longer term timeframes, relevant for planning and management purposes (e.g. 2070-2100) and including other and more detailed targets and vulnerability factors as more research on environmental and anthropogenic data is available. Moreover, the developed analysis can be easily up-scaled to evaluate the consequences of interactive pressures at a broader regional scale (e.g. Mediterranean scale) as well as down-scaled by improving the assessment with more detailed dataset (e.g. North Adriatic sea). Finally, the methodology can be enhanced by fine-tuning pressures' spatial modelling, according to metrics and thresholds updated by the EU member states for the step-by-step implementation of the Marine Strategy Framework Directive requirements (EC, 2008; EC, 2010).

Looking at the resulting output at the case study level, a moderate cumulative impact score was detected in the baseline scenario (i.e. 2000-2015), value which tends to increase in the future time window (i.e. 2035-2050), due to the effect of potential rising sea temperature. As a consequence, appropriate actions should be envisaged and implemented (e.g. seagrasses transplantation, enhancement of the MPAs network) in order to anticipate the potential adverse effects of climate change and thus attenuate environmental impacts they can cause receptors and ecosystem services they can provide. However, according to the output of the scenarios' analysis through the BBNs, adaptation strategies should be coupled with more sustainable management options, leading to a more integrated and effective marine management and planning. This approach would allow on one side to increase resilience of natural marine ecosystems to disturbance, and on the other one to reduce the human pressures on these areas, which in turn, would result in an overall decrease of cumulative impacts on the whole basin.

However, the developed multi-risk approach and the related resulting output at the case study level, present some limitations mainly related to the methodological assumptions applied during the assignation of scores in the vulnerability assessment phase, that can be considered too simplistic for potential end-users to trust the reliability of the results of the analysis. For overcoming this limit, different setting of scenarios and scores for the case study, could be compared with reference data (i.e. historical monitoring data, field measurements) or with comparable studies, performed in the same marine region and time slice by applying other impact assessment methods. Moreover, a step forward should be made to develop more accurate spatial models, coupling vulnerability of marine ecosystems to the considered pressures, in order to evaluate their recovery potential and resilience to perturbations (i.e. dynamic vulnerability). Within the multi-hazard assessment, the same issue could be overcome by involving a wide number of marine experts (e.g. physical and biogeochemical modelers, environmental scientists, risk experts, marine planner and managers) in the assignation of the 'interaction weights' to the coalitions of interactive pressures, in order to get a more robust set of scores.

Finally, as far as the application of Bayesian Belief Networks (BBNs) is concerned has to be underlined that the direct acyclic nature of the developed framework sets some critical restrictions, since the directions of arcs cannot loop back, thus neglecting to represent more complex interactions and temporal changes occurring in marine ecosystems. Moreover, variables conversion into equivalent discrete states (for an easier computation) allows to poorly represent dynamic environmental processes acting in a continuous probability distribution in both space and time. Finally, in the proposed application, GIS layers representing pressures, hazards, vulnerabilities, risks and cumulative impacts were explicitly used as direct inputs of all the BNN nodes, thus limiting a more complex integration between these two tools. Drawing on these limitations, a future challenging improvement of the proposed methodology should consider dynamic patterns of marine ecosystems, evaluating the cascading effects on both hazards and vulnerabilities against space and time dimensions through the development of Dynamic Bayesian Networks (DBNs). Such a model should be useful to explore when and how operate to achieve desired management outcomes as well as specific environmental targets (e.g. the GES; EC, 2008). However, understanding where to implement well-targeted measures and management options is often equally critical. A more sophisticated approach integrating DBNs with GIS should be envisaged, allowing to use Bayesian Networks for modelling dynamic spatial processes (i.e. Spatial Bayesian Networks - SBNs), thus becoming a complex decision support system for a more adaptive marine spatial planning.

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ANNEX A: Reviewed methodologies for cumulative impact assessment in marine areas

Application context	**Impact assessment**			**Pressures analysis**			**Vulnerability assessment**			**Reference**
	Considered impacts	**Modelling method**	**Applied assumptions**	**Considered pressures**	**Modelling method**	**Applied assumptions**	**Considered ecosystems**	**Modelling method**	**Applied assumptions**	
Canada's Pacific	Cumulative bottom impacts from individual fisheries.	Additive approach, adapted from Ban et al., (2010). Benthic impact scores were calculated based on fishing intensity and the sensitivity of each benthic class to each fishery. All impact score across all fisheries we summed up.	Cumulative impacts were assumed to be additive. Each incidence of fishing is assumed to have equal impact. This is not ideal as, for example, bottom trawling has been found to have a large initial impact on bottom habitats decreasing with subsequent pass.	12 different bottom and demersal commercial fishing activities (categorized by species harvested/harvest license and gear-type).	Fishing effort was used to represent relative fishing intensity for each fishery (rescaled into a 0-1 range). Then it was assigned to benthic classes where some fishing effort occurred.	Fishing effort was assumed to be equally distributed within the marine areas of each planning unit. The downscaling of fishing effort data from 4X4 km grids to 2X2 km planning units may have assigned fishing effort values to areas where no fishing occurred.	21 broad benthic classes to broadly represent habitat type.	Two different applied approaches: i) expert-derived vulnerability scores based on Teck et al. (2010); ii) fishing gear impact severity scores specific to fisheries in British Columbia were adapted from Fuller et al. (2008) (based on expert input) and multiplied with adjusted benthic sensitivity scores ('habitat factors') to generate new sensitivity scores that provided a regional context.	Benthic classes were assumed to be homogeneous within their spatial boundaries. The analysis was limited by input data with the coarsest scale and thus finer-scale variations and heterogeneity were not detected.	Agbayani et al., 2015
North sea	Cumulative impacts on key marine species and habitats.	Additive approach, expanded from Halpern et al. (2008) to better fit the requirements of the MSFD, including impacts such as	Cumulative impacts were assumed to be additive, summing the products of ecosystem component presence-absence,	33 human activities and types of land and sea-based pollution.	Six distance-based spatial models to describe the spatial ex- tent of the pressures while moving away from locations of the human activities that cause them.	The choice of the spatial models for all activity-pressure combinations was based on expert judgement.	28 "ecosystem components" (key species and habitats).	Sensitivity of key species and habitats to different human activities based on an online survey.	Ecosystem components are mapped as presence-absence. Expert judgement to quantify the sensitivity of	Andersen et al., 2013

Application context	Impact assessment			Pressures analysis			Vulnerability assessment			Reference
	Considered impacts	**Modelling method**	**Applied assumptions**	**Considered pressures**	**Modelling method**	**Applied assumptions**	**Considered ecosystems**	**Modelling method**	**Applied assumptions**	
		the underwater noise and chemical pollution.	stressor intensity, and the sensitivity scores.						the ecosystem components to the stressors.	
EEZ of Canada's Pacific coast	Cumulative impacts on three broad habitat classes (i.e. benthos, shallow pelagic waters, and deep pelagic waters).	Additive approach, based on Halpern et al. (2008).	Cumulative impacts were assumed to be additive, multiplying vulnerability scores to the intensity of activities. Cumulative impact scores represent a relative estimation without the ground-truth the results	38 human activities	Intensity of activities at a location *i*, derived from a linear decay function from all locations of that activity, binned into one of three intensity categories (low=0.5, medium=1, high=1.5) simulating the intensity decay. Land-based activities were buffered from the source.	Linear decay from the origin of activities.	Three broad habitat classes: the benthos, shallow pelagic waters, and deep pelagic waters. The benthos in turn was subdivided into 14 benthic habitats (Fig. 1), whereas both classes of pelagic waters contain no subdivisions.	Vulnerability score of considered habitat to human activities.	Ecosystem components are mapped as presence-absence. Expert judgement was relied upon to provide vulnerability scores.	Ban et al., 2010
Great Barrier Reef	Interactive impacts resulting from interaction between multiple stressors leading to cascading impacts on water quality and coral cover.	Bayesian Belief Network.		Human-made and climate change pressures (e.g. sea surface temperature).	Expert elicitation process for multiple-stressors weighting. Multi-scenarios evaluation combining stressors within and outside management.	Scenarios elicitation approach, constraining the survey length. Probabilities evaluated for a limited number of of levels of each stressor.	Hard coral.			Ban et al., 2014
Territorial sea of mainland	Cumulative human pressures on	Additive approach, adapted from	Cumulative human pressures were	Human-made pressures (e.g.	Human pressure Index (HPI): Relative intensity	Assignation of scores to Human	Marine Protected Areas (MPAs).		Presence-absence of MPAs.	Batista, et

Application context	Impact assessment			Pressures analysis			Vulnerability assessment			Reference
	Considered impacts	Modelling method	Applied assumptions	Considered pressures	Modelling method	Applied assumptions	Considered ecosystems	Modelling method	Applied assumptions	
Portugal	Marine Protected Areas.	Halpern et al. (2008).	assumed to be additive.	commercial fisheries, ship traffic, benthic structures).	among spatial distribution, weight (relative importance of an activity in different locations) and influence distance (one value per layer, equal for all locations) were assigned to each human activity considered. Intensity was calculated based in measurable parameters among different locations in the case study.	pressure Index (HPI) metrics: influence distance: impact frequency. magnitude. Natural pressures (e.g. ocean acidification, increase in sea temperature) not included in the analyses as well as recreational fishing, illegal activities, hand harvesting, dumping and offshore ship traffic due to lack of data.				al., 2014
Western Mediterranean sea	Cumulative impacts on key marine species and habitats.	Additive approach, based on Halpern et al. (2008).	Cumulative impacts were assumed to be additive.	Human-made and climate change pressures (e.g. ocean acidification and warming, increased UV radiation).	Human uses and land-based pollution data are considered as proxies for stressors. Pressure intensity has been then distributed using a decay function inversely proportional to the Euclidian distance	Simple functions to model the spreading of pressures' intensity from the activity. The maximum distance at which a pressure can spread was set using the	22 ecosystem components including seabirds, 4 marine mammal species and 2 turtle specie.	Expert survey for collecting opinion on the vulnerability of Mediterranean coastal and marine ecosystem components to anthropogenic activities.	Expert judgement to quantify the sensitivity of the ecosystem components to the stressors.	Breton et al., 2014

Application context	Impact assessment			Pressures analysis			Vulnerability assessment			Reference
	Considered impacts	**Modelling method**	**Applied assumptions**	**Considered pressures**	**Modelling method**	**Applied assumptions**	**Considered ecosystems**	**Modelling method**	**Applied assumptions**	
					from the activity.	‘impact distance’ defined by experts for each combination activity-stressor.				
Australasia	Interactive impacts resulting from interaction between multiple stressors (i.e. synergistic, antagonistic).	Interactive impacts index applying the additive effects model to incorporate the effects of interactions into an interactive impact map. Three scenarios: no interactions, antagonistic interactions or synergistic interactions.	Additive interactions model.	Local stressor, nutrient inputs, and a global stressor, ocean warming.	Stress mapping approach. Simulation of scenarios with or without management.	Consider only pairs of stressors.	Seagrass meadows.		Focus on only one marine ecosystem.	Brown et al., 2014
South Florida coastal ecosystem	Interactive impacts resulting from interaction between multiple stressors (i.e. synergistic, antagonistic).	Relative interaction strength among pressures, states, and ecosystem services based on experts’ opinion. These data were used to create three interaction matrices: pressure to state, state to state and state to ecosystem		12 human-made and climate pressures (e.g. ocean acidification).			Ecosystem states and services. States are defined by specific attributes or characteristics of an ecosystem, and ecosystem services are defined as the benefits people may derive			Cook et al., 2014

Application context	Impact assessment			Pressures analysis			Vulnerability assessment			Reference
	Considered impacts	Modelling method	Applied assumptions	Considered pressures	Modelling method	Applied assumptions	Considered ecosystems	Modelling method	Applied assumptions	
		service.					from the marine environment.			
German EEZ of the North Sea	Several types of impacts including mortality, competition, and disturbance effects at different spatial scales.	Relative Ecological Risk Assessment Methodology.		Fisheries, gravel extraction.			Benthic communities, harbor porpoise, seabirds.	Sensitivity classes based on Garthe and Huppop (2004). Loss Function.		Fock H., 2011
Marine waters of the UK (England and Wales)	Interactive cumulative impacts on seabed community	4 different simulated cumulative effects scenarios: single greatest, additive, antagonistic, and synergistic, based on different aggregation functions between pressure and vulnerability.	Scenarios investigating cumulative impacts from repeated events of the same activity are missed.	Human activities that lead to 4 direct pressures on the seabed community (i.e. smothering, abrasion, sealing, and extraction).	Different modelling approaches for simulating footprint area.	Use of buffer zone (based on literature review) for defining areas of influence of selected pressures. Comparative in situ observations would improve size estimates of affected areas.	Seabed community based on geological survey sediment types.	Seabed habitat sensitivity to different anthropogenic activities was set, determining recovery rates of the benthic community following cessation of an activity, and based on the activity's distribution and intensity.	It was assumed that recovery of natural benthic communities could not take place where obstructions were present.	Foden et al., 2011
Gulf of Tunis	Cumulative impacts from anthropogenic pressures.	Additive approach, based on Halpern et al. (2008).	Cumulative impacts were assumed to be additive.	Anthropogenic pressures (e.g. rivers discharges, wastewater discharges, maritime traffic, industries and tourism, trawling, dredging and			Seagrasses, coralligenous assemblages and rocky habitats.	Average vulnerability score through an expert survey by considering 5 vulnerability ranks: spatial scale, frequency, functional impacts,	Expert judgement to quantify the vulnerability of the ecosystem components to the anthropogenic pressures. Presence, absence of	Gana S., 2013

Application context	Impact assessment			Pressures analysis			Vulnerability assessment			Reference
	Considered impacts	**Modelling method**	**Applied assumptions**	**Considered pressures**	**Modelling method**	**Applied assumptions**	**Considered ecosystems**	**Modelling method**	**Applied assumptions**	
				disposal of dredge spoil).				resistance and resilience	ecosystems.	
German EEZ of the North Sea	Cumulative impacts due to human- made pressures on plaice nursery grounds.	Additive approach. Assessment under current and future spatial management scenarios for ecologic and economic ecosystem components.	Additive approach calculating the potential level of impact by adding the pressure and sensitivity scores.	Human-made pressures (i.e. abrasion, obstruction, extraction, siltation, contamination, smothering and alteration).	Magnitude and intensity of pressures related to human activities, were generated based on a knowledge base of the benthic ecological footprints for these drivers occurring in the case study. Pressure categories were used to normalize the data to facilitate the assessment of driver intensities and to allow comparison between different spatial locations.	Buffer the geo data representing the spatial distribution of the drivers regarding their footprint.	Economic ecosystem components, i.e. *Pleuronectes platessa* nursery grounds.	Habitat characterization for juvenile plaice based on literature research regarding the local conditions in the case study. Species distribution model using a generalized additive model.	Sensitivity of the plaice nursery grounds were assessed using scores to describe the scale of impact (i.e. low, medium, high).	Gimpel et al., 2013
Great Barrier Reef	Cumulative impacts from human activities.	Additive approach. Cumulative impact as function of the spatial distribution and intensity of pressures, and the degree to which seagrasses respond to threats (i.e.	Cumulative impact of threats was additive	9 human activities threaten the seagrasses, identified using expert opinion (e.g. agricultural runoff, dredging, netting, shipping accidents).	Different modelling approaches based on the investigated pressure.		Seagrasses (seagrass probability maps).	5 vulnerability factor: frequency, functional impact, resistance, recovery time, certainty, scored against expert judgement.	Expert judgement to quantify the vulnerability seagrasses to anthropogenic pressures.	Grech et al., 2011

Application context	**Impact assessment**			**Pressures analysis**			**Vulnerability assessment**			**Reference**
	Considered impacts	**Modelling method**	**Applied assumptions**	**Considered pressures**	**Modelling method**	**Applied assumptions**	**Considered ecosystems**	**Modelling method**	**Applied assumptions**	
		vulnerability). Based on Halpern et al. (2008).								
40 km of coastline in the Ionian Sea, Apulia region	Potential impacts of different combinations of stressors (both land- and marine-based) on vulnerable rocky habitats.			Human-made pressures (e.g. urban pollution, pesticide input, nutrient enrichment through terrestrial run-off).	Data on human pressures were normalized and a Principal Component Analysis (PCA) coupled with a Cluster analysis based on Euclidean distance among sectors were carried out in order to identified groups of sectors exposed to comparable levels and combinations of the different threats. Land-based indicators (i.e. proportion of urbanized, cultivated areas) used as a proxy of coastal modification, demographic pressure, urban pollution and land-based pollution related to pesticide inputs and nutrient enrichment through terrestrial run-off.	Indicators used as proxy of pressure.	Rocky habitats (i.e. lower mid-littoral and shallow infralittoral).	Entire shoreline was digitalized and nine adjacent sectors were identified based on the relative amounts of sandy, rocky, and artificial coast assessed on the basis of orthophotos. In each sector, three sampling sites were randomly selected for the surveys of benthic assemblages on rocky reef. All sites were characterized by similar substrate complexity, slope, and wave exposure.		Guarnieri et al., 2016
Global oceans	Cumulative impacts from natural and	Additive approach.	cumulative impact of threats was	17 human-made pressures	Different modelling approaches based	Spatial data for many anthropogenic	20 marine ecosystems (e.g. hard and	Expert survey for collecting opinion on the	Expert judgement to quantify the	Halpern et al., 2008

Application context	Impact assessment			Pressures analysis			Vulnerability assessment			Reference
	Considered impacts	**Modelling method**	**Applied assumptions**	**Considered pressures**	**Modelling method**	**Applied assumptions**	**Considered ecosystems**	**Modelling method**	**Applied assumptions**	
	anthropogenic pressures.		additive	(e.g. fishing, commercial activity-shipping lanes, oil rigs, ocean pollution) including climate stressors (e.g. sea surface temperature variation, acidification)	on the investigated pressure.	drivers were derived from valid but inexact modeling approaches. Key activities with significant impacts on marine ecosystems such as recreational fishing, aquaculture, disease, coastal engineering, and point-source pollution we excluded since global data were not available.	soft bottom shallow, coral reefs, seagrass beds, mangroves, surface and deep water, nearshore ecosystems).	vulnerability of the considered marine ecosystems to pressures.	vulnerability of the ecosystem components to the considered pressures. Presence, absence of ecosystems. Ecosystem data were highly variable in quality, and in many cases, the full extent of these ecosystems underestimated (with cascading effect of the resulting cumulative impact).	
California Current ecosystems	Cumulative impacts from natural and anthropogenic pressures.	Additive approach.	Cumulative impacts were assumed to be additive.	14 land-based pressures (e.g. nutrient input, coastal engineering, commercial shipping), 7fishing activities (e.g. recreational fishing,	Different modelling approaches based on the investigated pressure.		19 ecosystems classified in intertidal (e.g. beach, salt marshes) and subtidal ecosystems (e.g. rocky reef, seagrasses, seamounts).	Expert survey to quantify vulnerability of ecosystems to human drivers of ecological change.	Expert judgement to quantify the vulnerability of the ecosystem components to the considered pressures. Presence, absence of ecosystems.	Halpern et al., 2009

Application context	Impact assessment			Pressures analysis			Vulnerability assessment			Reference
	Considered impacts	**Modelling method**	**Applied assumptions**	**Considered pressures**	**Modelling method**	**Applied assumptions**	**Considered ecosystems**	**Modelling method**	**Applied assumptions**	
				pelagic high bycatch), including climate stressors (e.g. ocean acidification, UV radiation).						
Massachusetts state waters	Cumulative impacts from climate and anthropogenic pressures.	Additive approach, based on Halpern et al. (2008).	Cumulative impacts were assumed to be additive.	21 human-made pressures including climate stressors (i.e rising ocean temperatures and ocean acidification, increased ultraviolet radiation exposure).	Different modelling approaches based on the investigated pressure.		15 marine ecosystems.	Expert survey to quantify vulnerability of ecosystems to human drivers of ecological change.	Expert judgement to quantify the vulnerability of the ecosystem components to the considered pressures.	Kappel, et al., 2012
Baltic Sea	Cumulative impacts from anthropogenic pressures.	Additive approach adapted from Halpern et al. (2008).	Cumulative impacts were assumed to be additive.	15 pressures types to the marine environment as determined by the MSFD (e.g. smothering and sealing, underwater noise, inputs of organic matter.	Anthropogenic pressure as a human-derived stress factor.	Pressures causing either temporary or permanent disturbance or damage/loss on several components of a marine ecosystem.	Six benthic and two pelagic biotope complexes.	Expert survey to quantify weighting coefficient specific to any combination of pressures and ecosystem components.	Expert judgement to quantify the vulnerability of the ecosystem components to the considered pressures. Presence, absence of ecosystems.	Korpinen et al., 2012
Baltic Sea	Cumulative impacts from anthropogenic pressures.	Additive approach, based on Halpern et al. (2008).	Cumulative impacts were assumed to be	13 human-made pressures posing direct	The intensities of the anthropogenic pressures were estimated based on	Intensities were considered only as	Seabed habitats classified in infralittoral,	Presence, absence of seabed habitats.	Presence, absence of seabed habitats.	Korpinenet al., 2013

Application context	Impact assessment			Pressures analysis			Vulnerability assessment			Reference
	Considered impacts	Modelling method	Applied assumptions	Considered pressures	Modelling method	Applied assumptions	Considered ecosystems	Modelling method	Applied assumptions	
		Pressure layers were multiplied by the weighting factors and then summed up within the grid cells for every benthic habitat type.	additive.	disturbance on the seabed and associated communities.	intensities of the underlying human activities, many of them on a continuous or class scale, while some were limited to the presence-absence scale.	proxies for pressures since there were no or very few data sets available where the actual pressure was measured. Pressure-specific 'buffer zone', ranging from 100 to 1000 m was set to describe the wider affected zone. Weighting factors to translate the 13 pressures to habitat-specific impacts in a standardized way.	circalittoral, deep sea.			
California Current Ecosystem	Cumulative utilization and impact from anthropogenic pressures on marine predator populations.	Additive approach, cumulative impacts based on human stressors weighted by species vulnerability but without species	Cumulative impacts were assumed to be additive.	24 human-made stressors, including change in the sea surface temperature anomalies and ultraviolet radiation.	Different modelling approaches based on the investigated pressure.	The intensity of anthropogenic stressors was estimated using the driver or stressor data, as part of Halpern et al. (2008).	8 marine protected predator species.	Quantitative habitat assessment based on satellite and light-based geolocation tracking data to determine the distribution and key habitats of	The vulnerability weights of each driver or stressor were defined via a literature review to determine expected impacts for each of the	Maxwell et al., 2013

Application context	Impact assessment			Pressures analysis			Vulnerability assessment			Reference
	Considered impacts	Modelling method	Applied assumptions	Considered pressures	Modelling method	Applied assumptions	Considered ecosystems	Modelling method	Applied assumptions	
		distributions incorporated.						the marine protected predators. Species vulnerability (i.e. weight) to human pressures.	eight species.	
Mediterranean and Black seas	Cumulative impacts from climate and anthropogenic pressures.	Additive approach, based on Halpern et al. (2008).	Cumulative impacts were assumed to be additive.	21 human-made and climate pressures (e.g. rising ocean temperature, ocean acidification)	Different modelling approaches based on the investigated pressure.		15 marine ecosystems.	Vulnerability score are based on Halpern et al. (2008).	Vulnerability scores are not specific for the Mediterranean and Black sea.	Micheli et al., 2013
Canada's Pacific marine ecosystems	Potential climate impact.	Sum of the potential climate impacts of an area multiplied by the various climate stressors considered.	Cumulative impacts as an inverse proxy for adaptive capacity.	Climate pressure (i.e. temperature, acidification, and UV radiation).	Data were extracted from global spatial climate estimates that were standardized from 0 to 1 (0 no change, 1 most change). All three climate datasets depicted change in actual or modelled conditions from a previous time period to a more recent time period.	Climate pressures focus on recent climate change, rather than future projections to obtain estimates of future vulnerabilities.	Benthic habitat (e.g. canyon, seagrasses, hard shelf, seamount) classified in bottom habitats, midwater (>200) and surface (<200).	Expert-derived ratings of habitat sensitivity to climate change	Sensitivity scores are based on Halpern et a. (2009), estimated for the California Current ecosystem. Equal weighting of vulnerability components: vulnerability is influenced equally by exposure, sensitivity, and adaptive capacity. This may not apply to ecosystems such as tropical coral reefs	Okey et al., 2015

Application context	Impact assessment			Pressures analysis			Vulnerability assessment			Reference
	Considered impacts	Modelling method	Applied assumptions	Considered pressures	Modelling method	Applied assumptions	Considered ecosystems	Modelling method	Applied assumptions	
									where local stressors appear to have a much stronger effect on coral reef health and resilience than does climate change.	
Papahānaumokuākea Marine National Monument, Hawaii	Cumulative impacts from anthropogenic and climate pressures.	Additive approach, adapted from Halpern et al. (2008).	Cumulative impacts were assumed to be additive.	14 human-made pressures (e.g. alien species, bottom fishing, ship-based pollution, ship strike risks, marine debris, including climate stressors (e.g. UV radiation increase, acidification, sea level rise).	Different modelling approaches based on the investigated pressure.		11 'ecozones', physically classified based on benthic substrates that tend to have distinct community assemblages (e.g. outer coral reef, pelagic habitat, subtidal sand and mud, rocky intertidal).	Vulnerability defined as a combination of exposure and sensitivity and resilience, elicited by expert survey to quantify specific weights describing how each ecosystem is expected to be affected by each stressor.	Expert judgement to quantify the vulnerability of the ecosystem components to the considered pressures.	Selkoe et al., 2009
Waters of UK (England and Wales)	Cumulative impacts from anthropogenic pressures.	Risk of cumulative impacts, under four different scenarios (i.e. a weight was assigned to each pressure-layer reflecting its relative importance), starting from		6 human-made pressures (i.e. abrasion, extraction, localized hydrocarbon contamination, obstruction, siltation and smothering)	Based on the proportion of a grid cell affected by the footprint and/or intensity of all the human activities exerting the same pressure (i.e. proportion of a grid cell impacted by a given pressure).		20 Marine landscapes based on Connor et al. (2006) (e.g. shallow coarse sediment plain, shelf mixed sediment plan, warm deep-water sand	Sensitivity scores derived from an extensive literature review of impact of human activities on UK marine landscapes (Defra 2007).	Literature review to define the vulnerability of the marine landscapes to the considered pressures.	Stelzenmüller et al., 2009

Application context	Impact assessment			Pressures analysis			Vulnerability assessment			Reference
	Considered impacts	Modelling method	Applied assumptions	Considered pressures	Modelling method	Applied assumptions	Considered ecosystems	Modelling method	Applied assumptions	
		the approach developed by Halpern et al., (2008).					plain).	Measure of sensitivity was then converted from an ordinate scale to a numeric scale (no = 0, low = 0.2, medium = 0.6, high = 1.0).		
UK and Welsh waters of the UK continental shelf	Cumulative impacts from anthropogenic pressures.	Additive approach, based on Halpern et al. (2008). Bayesian Belief Network–GIS framework to evaluate cumulative impacts under different management scenarios.	Cumulative impacts were assumed to be additive.	3 human-made pressures (i.e. oil-gas infrastructure aggregate extraction, fishing.	Different modelling approaches based on the investigated pressure. To ensure comparability between the human activity data they were into a qualitative scale of intensity scores from 0 to 9.	Limited number of pressures considered to evaluate cumulative impacts.	19 marine landscapes (e.g. photic rock, shallow coarse sediment plain, warm deep-water sand plain).	Information on the sensitivity of each marine landscape to human activities based on literature review (Defra, 2007).	Literature review to define the vulnerability of the marine landscapes to the considered pressures.	Stelzenmüller et al., 2010

ANNEX B: Concepts and terminologies applied within multi risk methodology

Terminologies	Description
Driver	‘Drivers’ or ‘driving forces’, are the main natural and anthropogenic forces which can cause changes in the state of the environment and/or human systems. Driving forces, in turn, can exert intentionally or unintentionally pressures on the environment (Kristensen, 2004).
Pressure	It represents the physical, chemical or biological mechanism through which an activity can lead to a direct or indirect adverse effect on any part of an ecosystem (e.g. physical disturbance to the seabed due to abrasion, chemical contamination due to shipping traffic) (Robinson et al., 2008).
Hazard	The potential occurrence of a natural or anthropogenic physical event and factors that may cause loss of life, injury, or other health impacts, as well as damage and loss to environmental resources, property, infrastructure, livelihoods and service provision (Elliott 2014; IPCC, 2012).
Exposure	The presence of people, livelihoods, environmental services and resources; infrastructure, economic, social, or cultural assets located in places that could be adversely affected (IPCC, 2012).
Receptor	A physical entity, with a specified geographical extent, which is characterized by particular environmental and socio-economic features (e.g. protected areas, natural ecosystems, infrastructures, etc.) (Balbi S. et al., 2010).
Vulnerability	It represents the degree to which receptors could be adversely affected by the considered hazards, based on site-specific physical and environmental information (Balbi S. et al., 2010).
Risk	Risk is represented as the probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur. It results from the interaction of vulnerability, exposure, and hazard. (IPCC, 2014a).
Impact	It represents changes in the physical, chemical or biological state of the environment defining the quality of ecosystems and the welfare of human beings. Changes in the state of environmental ecosystems, may lead to environmental or economic impacts on the functioning of ecosystems themselves, their life-supporting abilities and, in turn, on human health and on the economic and social performance of society (Kristensen, 2004).
Cumulative impact	Ecosystem components may be affected by a wide range of pressures at the same time, but not necessarily featured by the same effect and extent. These multiple pressures, being frequently overlaid, can lead to cumulative (the sum total of the effects) and interactive effects, resulting in combinations that may be synergistic, when the sum of the effects is increased, or antagonistic in case effects may decrease or cancel each other (Patrício et al., 2014).

ANNEX C: Expert questionnaire for the identification of the interaction weights against the potential coalitions between pressures

A multi-risk model for the assessment of cumulative environmental impacts in marine areas:

Expert questionnaire supporting the aggregation of hazard interactions based on the Choquet integral.

Name	
Surname	
Title	
Affiliation	
Contact	
Competence within marine science or risk assessment	1. General competence: 2. Specific Competence: 3. Years of experience: 4. Familiarity with the case study area (Adriatic sea):

1. Rationale

Marine areas represent complex and dynamic systems facing increasing threats and degradation due to multiple human activities and interactive pressures (e.g. fishing, sands and hydrocarbon extraction, tourism, energy infrastructures). A further complication is determined by climate change which is expected to pose additional pressures on marine ecosystems through rising sea levels, increased sea temperatures and ocean acidification (IPCC, 2014c). The cumulative and synergic impact of these pressures is triggering severe alteration on biological, chemical and physical processes, with negative consequences for the environment and the socio-economic system. In this setting, multi-risk assessment represents an effective approach to address different risks posed by multiple and interactive pressures affecting marine ecosystems and activities (Gallina et al., 2016). Moreover, MCDA has been widely used to aggregate information about environmental risks and vulnerabilities and aid decision-making process (Rizzi et al., 2015; Torresan, et al., 2012; Linkov et al., 2006; Giove et al., 2009).

Here we propose a spatially explicit multi-risk approach to evaluate the cumulative impacts induced by climate drivers in combination with local to regional anthropogenic pressures in marine areas. The case study area selected for the implementation of the developed methodology is represented by the marine sub-region of the Adriatic sea located in the wider Mediterranean sea (Figure 1).

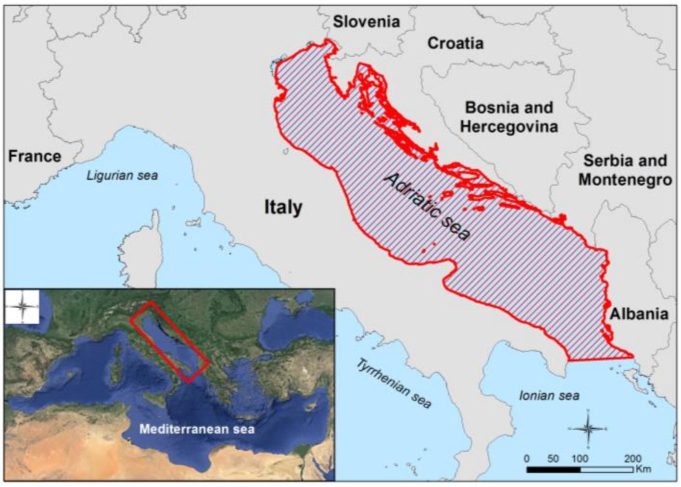


Figure 1: The Adriatic sea case study area

The methodology, as represented in the framework included in Annex A, is based on the consecutive analysis of a wide array of pressures (e.g. temperature variation, bottom stress by abrasion and sealing), hazards (e.g. bio-hazard, anthropogenic acute chemical hazard), exposed targets and vulnerability factors (e.g. sensitive habitat extent and typology, biodiversity indexes). Multi Criteria Decision Analysis (MCDA) is used at each step of the assessment to consecutively aggregate information about multi-hazards, multi-vulnerability and risks. Results of the assessment can be displayed on GIS-based maps useful to define marine areas and targets at higher risk from multiple environmental and anthropogenic pressures and to evaluate the progress toward the achievement of the good environmental status, as required by the Marine Strategy Framework Directive (MSFD; EC, 2008).

This questionnaire is aimed at integrating the expert judgement in the MCDA model developed for the aggregation of multiple natural and anthropogenic hazards and pressures on marine areas. As explained in the following sections it is based on the Choquet Integral (Choquet, 1954), requiring the assignation of scores to scenarios, represented by the combinations of different interacting pressures in the marine environment.

2. Purpose of the questionnaire

This questionnaire aims to involve different experts with relevant expertise in the field of the environmental/marine sciences, risk assessment or ecological and physical modeling, in the calibration of the MCDA model for the aggregation of multi-hazards and pressures based on the application of the Choquet Integral (Choquet, 1954).

Experts are asked to assign a score to multiple scenarios, identified by combinations of interactive pressures for the related hazard to be investigated. The list of hazards considered for the Adriatic sea case study are summarized in the following table (Table 1), providing a list of the main interacting pressures that can cause each hazard (adapted from Patrício et al., 2014).

HAZARD TO BE INVESTIGATED	TYPE	EXAMPLE	MAIN INTERACTIVE PRESSURES
Biological hazard	Anthropogenic but exacerbated by natural pressures (climate).	Non-indigenous, introduced and invasive species.	Sea surface temperature variation. Shipping traffic. Port activity. Aquaculture.
Acute chemical hazard	Anthropogenic but exacerbated by natural pressures (climate).	Pollution from one-off spillages, oil spills by shipping accidents.	Sea surface temperature variation. Oil-spill.
Chronic chemical hazard	Anthropogenic but exacerbated by natural pressures (climate).	Diffuse pollution by nutrients input from land-based run-off and discharges.	Sea surface temperature variation. Nutrient input.

Table 2: Hazards and main interacting pressures considered in the case study

Assigned scores to each combinations of interactive pressures (for the related hazard) will be mathematically implemented and processed by the system in order to produce a final score for every kind of combination among the pressures, as the ones that can occur on the case study area. The advantage of the proposed methodology consists in the possibility to evaluate also conflicting or synergic effects among all the considered parameters thus shaping natural interaction occurring in dynamic ecosystems such as marine areas. As already mentioned, all collected information will be integrated by applying a MCDA model based on the Choquet Integral as aggregation function which allows, by the use of a mapping between criteria values and scores established by environmental experts, to mimic non-linear behaviour and supply a complete ordered ranking of the considered alternatives. The Choquet integral is a discrete fuzzy integral introduced by Choquet (1954), which has found increasing application in the context of environmental assessment and management (Delavar et al., 2015; Zabeo et al. 2010, 2011; Pizzol et al. 2011; Paoli et al., 2007).

It generalizes additive operators, such as the ordered weighted average (OWA) or the weighted mean, and perfectly fit in situations where antagonistic and synergic effects are present between the criteria to be aggregated. In the application of the Choquet integral, the number of combinations to be evaluated depends on the number of the considered parameters (in this case the selected pressures). In every table, expert is called to assign a score from 0 to 100 to a certain combination of parameters values. Each parameter is classified in the range 0 or 1 where 1 stands for the presence of the parameter in its maximum value within its ranging classes and 0 stands instead for the presence of the parameter in its minimum value. For the purpose of this application the 0 and 1 classes for all the considered pressures are summarized in the tables included in the **Annex B** which also provides some specifications about the underlying models and data used for their spatial representation.

More specifically, the question guiding the compilation of this questionnaire is then (in case of four parameters):

"How would I score a possible scenario when the parameter a is at its maximum value (i.e. score equal to 1), parameter b is equally high (i.e. score equal to 1) and parameters c and d are in their minimum (i.e. score equal to 0)?"

The score can be assigned in a 0-100 range, for all the pressures' interaction assessments, identified in the developed multi-risk framework. The assigned score represents the hazard level for each analyzed scenario where 0 stands for the hazard null and 100 to the maximum.

3. How to compile the scoring table?

Following is an example on how to fill in the questionnaire.

Let's take as example the case of the evaluation of biological hazard related to the introduction of non-indigenous species (NIS). This hazard is represented by taking into account four interacting pressures considered as main drivers of NIS spreading in marine areas: sea surface temperature variation (SST), shipping traffic, port activity and aquacultures for which classes (and related 0 and 1 scores) are reported in the suitable tables in Annex B.

Therefore, there are 16 combinations to be compiled for the considered hazard as showed in the following table.

ID	SST variation	Shipping traffic	Port activity	Aquacultures	Score
1	0	0	0	0	
2	1	0	0	0	
3	0	1	0	0	
4	0	0	1	0	
5	0	0	0	1	
6	1	1	0	0	
7	1	0	1	0	
8	1	0	0	1	
9	0	1	1	0	
10	0	1	0	1	
11	0	0	1	1	
12	1	1	1	0	
13	1	1	0	1	
14	1	0	1	1	
15	0	1	1	1	
16	1	1	1	1	

As pointed out in the row corresponding to the ID 12 one of this coalition is 1-1-1-0, which means that the parameter SST, shipping traffic and port activity are in their maximum value (i.e. score equal to 1) and aquaculture is instead at the minimum (i.e. not present in the area, with a related score equal to 0). With this background the question is then:

"How would I score a scenario when, within the marine area, there is the higher number of unusually warm events (due to rising SST variation) and most intense shipping traffic and port activity, but no aquacultures are located in the area of concern?"

The same exercise can be applied to all the other hazard assessments proposed in this questionnaire (Table 1).

In order to better fill in the questionnaire the three following axioms are given to explain the basics of the Choquet integral:

- 0: an empty set has no importance (0).
- 1: the maximum set has a maximal importance (100).
- A new added criterion cannot make the importance of a coalition (a set of criteria) decrease. For instance, if the expert assign a score equal to 20 to the coalition 1-0-0, then the combination 1-1-0 can assume only values higher than 20.

BIOLOGICAL HAZARD ASSESSMENT

Please fill in the Score column, valuing the combination where the selected parameters may be in the highest class (1= maximum value) or in the lowest class (0= minimum value).
The assigned score can varying between 0 and 100.

SST variation	Shipping traffic	Port activity	Aquaculture	Score
0	0	0	0	0
1	0	0	0	
0	1	0	0	
0	0	1	0	
0	0	0	1	
1	1	0	0	
1	0	1	0	
1	0	0	1	
0	1	1	0	
0	1	0	1	
0	0	1	1	
1	1	1	0	
1	1	0	1	
1	0	1	1	
0	1	1	1	
1	1	1	1	100

The 0 and 1 classes for the considered parameters are reported in Annex B.

ANTHROPOGENIC ACUTE CHEMICAL HAZARD ASSESSMENT

Please fill in the Score column, valuing the combination where the parameters may be in the highest class (1= maximum value) or in the lowest class (0= minimum value).

The assigned score can varying between 0 and 100.

SST variation	Oil-spill	Score
0	0	0
1	0	
0	1	
1	1	100

The 0 and 1 classes for the considered parameters are reported in Annex B.

ANTHROPOGENIC CHRONIC CHEMICAL HAZARD ASSESSMENT

Please fill in the Score column, valuing the combination where the parameters may be in the highest class (1= maximum value) or in the lowest class (0= minimum value).

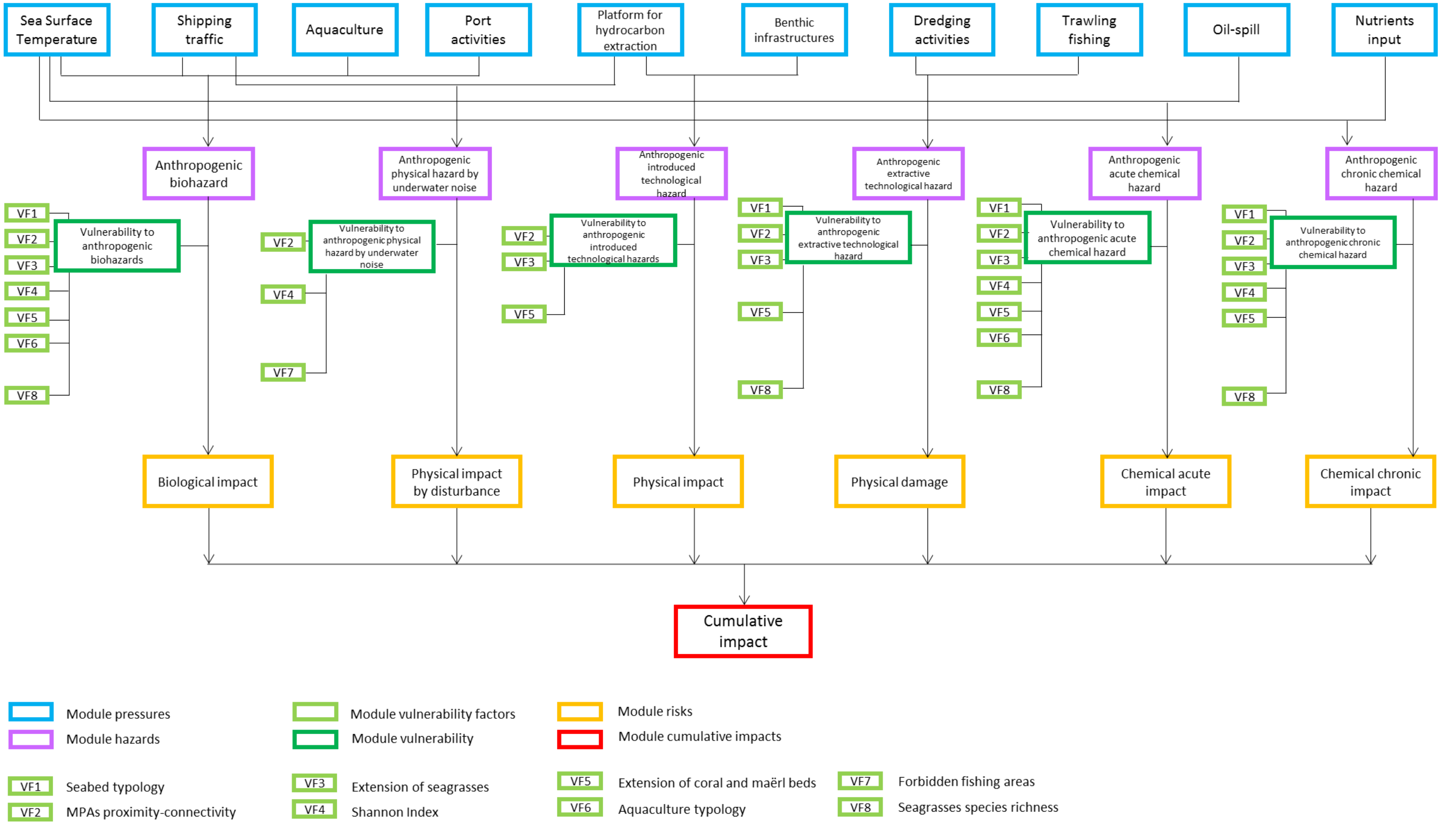
The assigned score can varying between 0 and 100.

SST variation	Nutrient input	Score
0	0	0
1	0	
0	1	
1	1	100

The 0 and 1 classes for the considered parameters are reported in Annex B.

ANNEX A

Multi-risk framework for the assessment of cumulative impacts induced by natural and anthropogenic pressures in the Adriatic sea case study.



ANNEX B

This annex includes the table summarizing classes and scores associated to the selected pressures in the Adriatic sea case study. All pressures were spatially modelled according to the procedures specified in the table below (Description field) as well as the availability of homogenous data for the whole case study. Ranging values of each pressures were classified in 2 to 5 classes by adopting different classification methods based on the applied indicator (i.e. quantitative or boolean). The table below shows only the highest (1= maximum score) and lowest classes (0= minimum score) of the analyzed parameters, useful to fill in the questionnaire.

Pressure	Description	Classes	Proposed scores
SST variation	According to Halpern et al. (2008), pressure related to SST variation was modelled by calculating the total number of positive anomalies of SST in each season and for each cell (pixel) of the case study area, representative of unusually warm events in the considered timeframe window 2000-2015 (Dataset elaborated within the PERSEUS project: http://www.perseus-net.eu).	66 - 162	0
		448 - 544	1
Shipping traffic	Pressure related to shipping traffic was modelled by normalizing in a 0-1 range the shipping traffic intensity in the Adriatic sea as calculated by Halpern et al. (2008) (https://www.nceas.ucsb.edu/globalmarine/data).	0- 0.2	0
		0.8- 1	1
Port activity	Intensity of ports activity was modelled based on the Eurostat data concerning the transport of goods (thousand tonnes) (http://maratlas.discomap.eea.europa.eu).	< 2,000	0
		> 50,000	1
Aquacultures	Pressure related to aquaculture activity was modelled based on the presence/absence of fish and mussels farms located in the Adriatic sea (Dataset acquired by the Adriplan and SHAPE projects: www.shape-ipaproject.eu; http://adriplan.eu).	Absence	0
		Presence	1
Oil-spill accidents	Oil-spill pressure was modelled based on the number of shipping accidents leading to oil-spill, occurred in the Adriatic sea from 1977 to 2014 (Dataset acquired by the REMPEC database, http://accidents.rempec.org).	1	0
		4	1
Nutrient input - Chlorophyll ‘a’ values	Based on the Italian initial assessment report on the ‘*enrichment of nutrients and organic matter*’ (ISPRA, 2012a) to each cell (pixel) of the case study area a value ranging from 0 to 1 was assigned in relation to areas where values of chlorophyll 'a' were greater than 0.2 µg/L, corresponding to the threshold pointed out by ISPRA as the limit below which the impact can be considered negligible. (Dataset elaborated within the PERSEUS project: http://www.perseus-net.eu).	< 0.2 µg/L	0
		> 9 µg/L	1

ANNEX D: BBN model nodes, states and related description

Node	States	Description
Module pressures		
Benthic infrastructures leading to smothering and sealing of seabed	1	Presence
	0	Absence
Trawling fishing activities	0 - 0.2	0 - 235 hours of activity
	0.2 - 0.4	235 - 470 hours of activity
	0.4 - 0.6	470 - 704 hours of activity
	0.6 - 0.8	704 - 939 hours of activity
	0.8 - 1	939 - 1174 hours of activity
Dredging and resources' extraction activities	0 - 0.2	825349 - 2106593 total dredged material (m³)
	0.2 - 0.4	2106593 - 3387837 total dredged material (m³)
	0.4 - 0.6	3387837 - 4669082 total dredged material (m³)
	0.6 - 0.8	4669082 - 5950326 total dredged material (m³)
	0.8 - 1	5950326 - 7231570 total dredged material (m³)
Maritime traffic	0 - 0.2	Normalized intensity of shipping traffic in the Adriatic Sea, based on map developed by Halpern et al. (2008) at the global scale, where 1 stands for the maximum intesity and 0 the minimum
	0.2 - 0.4	
	0.4 - 0.6	
	0.6 - 0.8	
	0.8 - 1	
Platforms hydrocarbons' extraction	0 - 0.2	Normalized intensity of activities related to the hydrocarbons' extraction was featured by applying a simplified spatial model where noise intensity linearly decrease from the maximum score equal to 1 (corresponding to the point where the extraction platform is located) to 0, for those pixels located to a greater distance than 1 Km
	0.2 - 0.4	
	0.4 - 0.6	
	0.6 - 0.8	
	0.8 - 1	
Ports and harbors activities	0 - 0.2	0 - 8401 tons of trasported goods
	0.2 - 0.4	8401 - 16801 tons of trasported goods
	0.4 - 0.6	16801 - 25202 tons of trasported goods
	0.6 - 0.8	25202 - 33602 tons of trasported goods
	0.8 - 1	33602 - 42003 tons of trasported goods

Aquacultures	1	Presence
	0	Absence
Temperature regime variation	0 - 0.2	1028-1138 unsually warm events
	0.2 - 0.4	1138 - 1248 unsually warm events
	0.4 - 0.6	1248-1357 unsually warm events
	0.6 - 0.8	1357-1467 unsually warm events
	0.8 - 1	1467-1577 unsually warm events
Nutrient input	0 - 0.2	0.03 - 0.31 µg/L Chl 'a'
	0.2 - 0.4	0.31 - 0.59 µg/L Chl 'a'
	0.4 - 0.6	0.59 - 0.88 µg/L Chl 'a'
	0.6 - 0.8	0.88 - 1.15 µg/L Chl 'a'
	0.8 - 1	1.15 - 1.44 µg/L Chl 'a'
Oil-spills	0 - 0.2	0 - 1 shipping accidents leading to oil-spill
	0.2 - 0.4	1 - 2 shipping accidents leading to oil-spill
	0.4 - 0.6	2- 4 shipping accidents leading to oil-spill
	0.6 - 0.8	4 - 5 shipping accidents leading to oil-spill
	0.8 - 1	5 - 6 shipping accidents leading to oil-spill
Module hazards		
Anthropogenic introduced technological hazard	0 - 0.2	Very low hazard score
Anthropogenic extractive technological hazard	0.2 - 0.4	Low hazard score
Anthropogenic physical hazard by underwater noise	0.4 - 0.6	Moderate hazard score
Anthropogenic biohazard	0.6 - 0.8	High hazard score
Anthropogenic chronic chemical hazard	0.8 - 1	Very high hazard score
Anthropogenic acute chemical hazard		
Module vulnerabilities		
Vulnerability to the anthropogenic introduced technological hazard	0 - 0.2	Very low vulnerability score
Vulnerability to the anthropogenic extractive technological hazard	0.2 - 0.4	Low vulnerability score
Vulnerability to the anthropogenic physical hazard by	0.4 - 0.6	Moderate vulnerability score

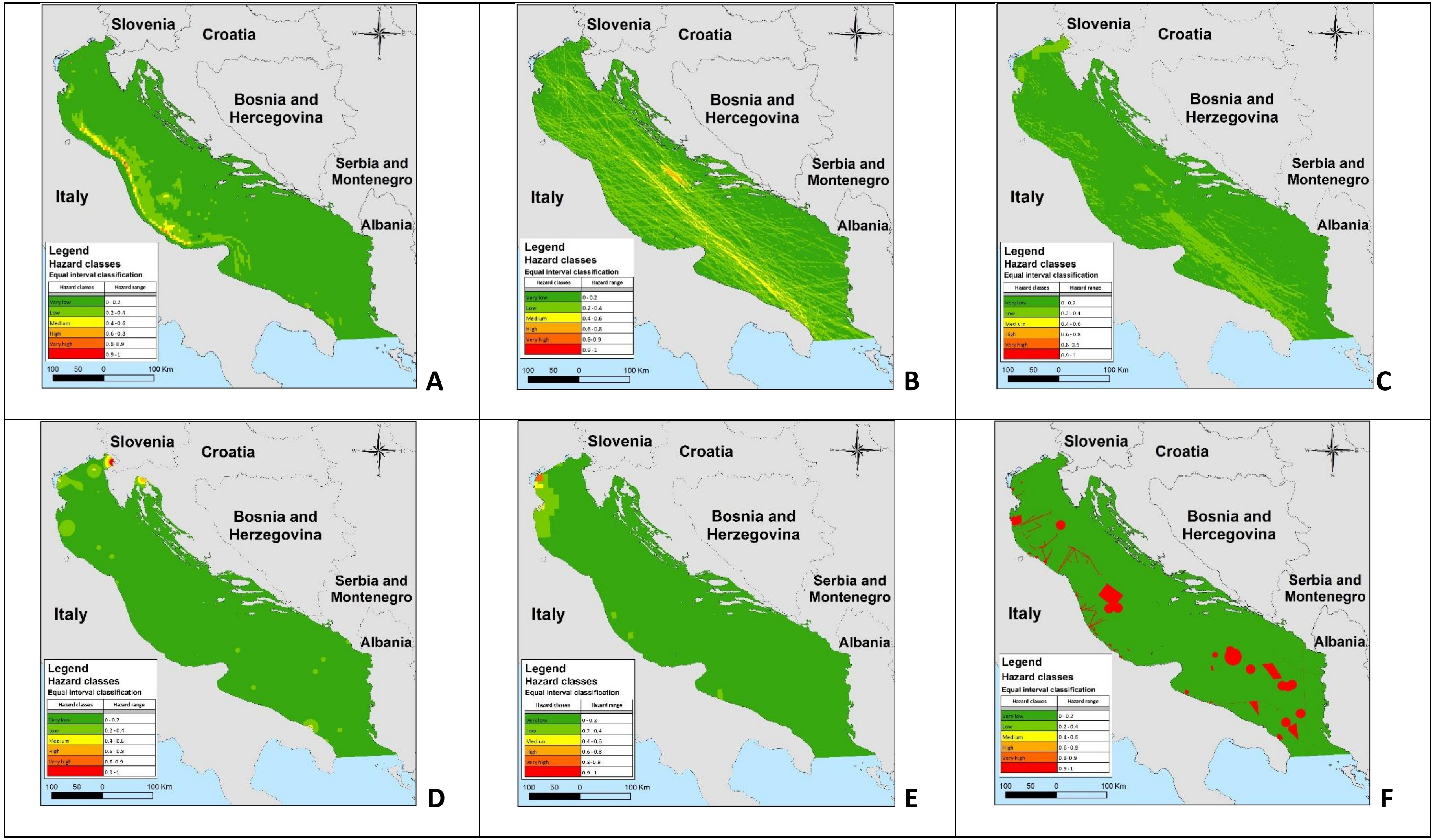
underwater noise		
Vulnerability to the anthropogenic biohazard	0.6 - 0.8	High vulnerability score
Vulnerability to the anthropogenic chronic chemical hazard	0.8 - 1	Very high vulnerability score
Vulnerability to the anthropogenic acute chemical hazard		
Module vulnerability factors		
MPAs proximity-connectivity (km)	0 - 0.2	0 - 25.63 km
	0.2 - 0.4	25.64 - 48.33 km
	0.4 - 0.6	48.34 - 70.58 km
	0.6 - 0.8	70.59 - 95.54 km
	0.8 - 1	95.55 - 137.55 km
Extension of seagrasses (Km²)	0 - 0.2	27.38 - 103.75 Km²
	0.2 - 0.6	6.02 - 27.37 Km²
	0.6- 1	0.02 - 6.01 Km²
Shannon Index	0 - 0.2	4.81 - 5.55 index score
	0.2 - 0.4	4.35 - 4.80 index score
	0.4 - 0.6	3.66 - 4.34 index score
	0.6 - 0.8	2.63 - 3.65 index score
	0.8 - 1	1.39 - 2.62 index score
Extension of coral and maërl beds habitats (Km²)	0 - 0.2	53.46 - 2014.49 Km²
	0.2 - 0.6	17.80 - 53.45 Km²
	0.6- 1	0.07 - 17.79 Km²
Aquaculture typology	0 - 0.6	Fish farms
	0.6 - 1	Mussel farms
Forbidden fishing areas	0 - 0.2	Forbidden areas
	0.2 - 0.5	Not forbidden areas
Seagrasses Species Richness	0 - 0.2	Very high richness (n° 5 of species)
	0.2 - 0.4	High richness (n° 4 of species)

	0.4 - 0.6	Medium richness (n° 3 of species)
	0.6 - 0.8	Low richness (n° 2 of species)
	0.8 - 1	Very low richness (n° 1 of species)
Seabed typology @ anthropogenic extractive technological hazard	0 - 0.2	Shallow sublittoral coarse, sand, mud and mixed sediment
	0.2 - 0.4	Bathyal sediment and abyssal sediment
	0.4 - 0.6	Sublittoral seagrass beds
	0.6 - 0.8	/
	0.8 - 1	Mediterranean coralligenous communities, shallow sublittoral rock and biogenic reef, maërl beds
Seabed typology @ anthropogenic biohazard	0 - 0.2	Bathyal sediment and abyssal sediment
	0.2 - 0.4	/
	0.4 - 0.6	Shallow sublittoral coarse, sand, mud and mixed sediment
	0.6 - 0.8	/
	0.8 - 1	Mediterranean coralligenous communities, shallow sublittoral rock and biogenic reef, maërl beds, sublittoral seagrass beds
Seabed typology @ anthropogenic chronic chemical hazard	0 - 0.2	Bathyal sediment and abyssal sediment
	0.2 - 0.4	/
	0.4 - 0.6	Shallow sublittoral coarse sediment
	0.6 - 0.8	Shallow sublittoral sand, mud and mixed sediment
	0.8 - 1	Mediterranean coralligenous communities, shallow sublittoral rock and biogenic reef, maërl beds, sublittoral seagrass beds
Seabed typology @ anthropogenic chronic chemical hazard	0 - 0.2	Bathyal sediment and abyssal sediment
	0.2 - 0.4	/
	0.4 - 0.6	Shallow sublittoral coarse sediment
	0.6 - 0.8	Shallow sublittoral sand, mud and mixed sediment
	0.8 - 1	Mediterranean coralligenous communities, shallow sublittoral rock and biogenic reef, maërl beds, sublittoral seagrass beds
Module risks		
Risk to the anthropogenic introduced technological hazard	0 - 0.2	Very low risk score
Risk to the anthropogenic extractive technological	0.2 - 0.4	Low risk score

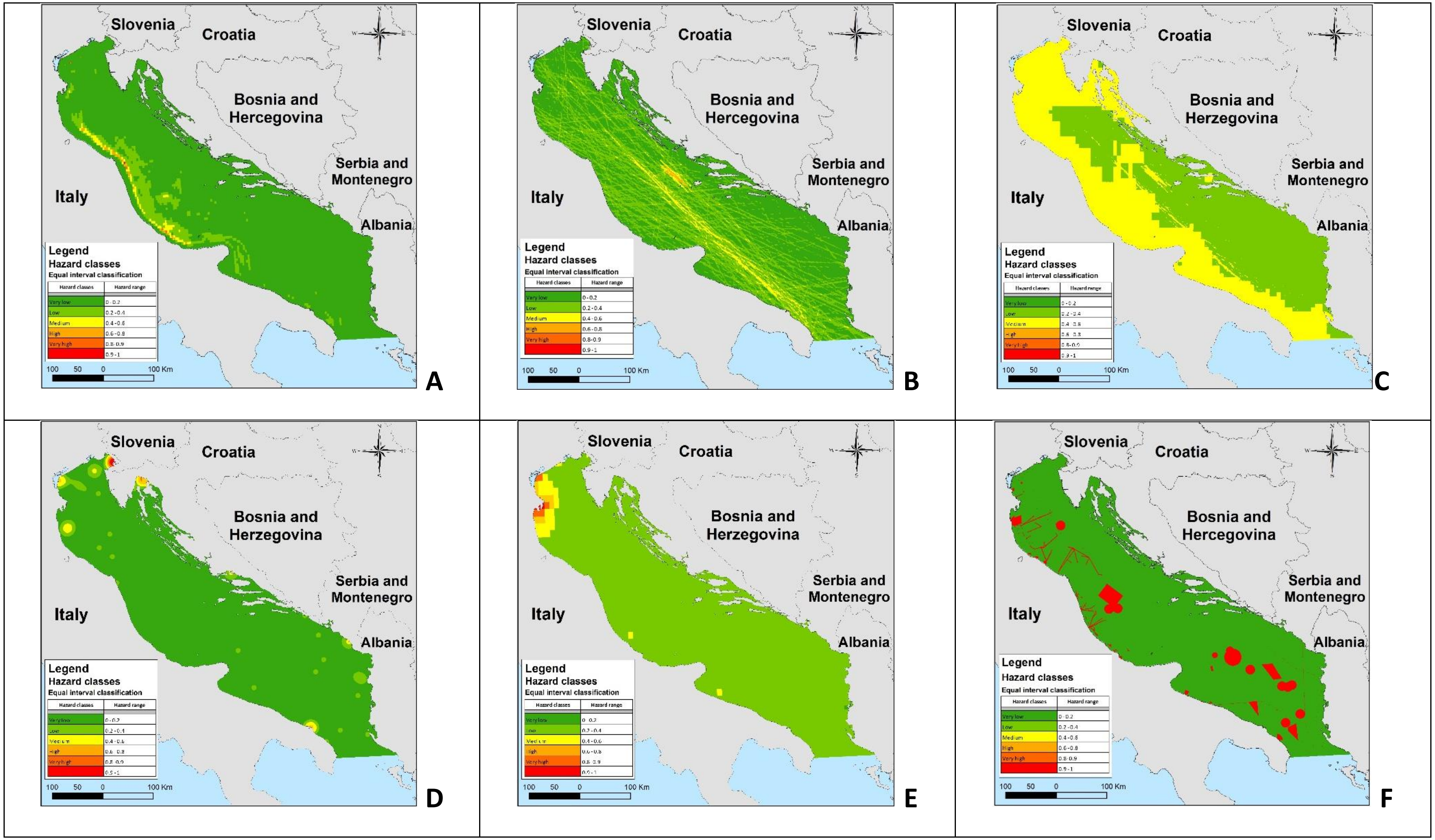
hazard		
Risk to the anthropogenic physical hazard by underwater noise	0.4 - 0.6	Moderate risk score
Risk to the anthropogenic biohazard	0.6 - 0.8	High risk score
Risk to the anthropogenic chronic chemical hazard	0.8 - 1	Very high risk score
Risk to the anthropogenic acute chemical hazard		
Module cumulative impact		
Cumulative impacts	0 - 0.2	Low cumulative impact score
	0.2 - 0.4	
	0.4 - 0.6	
	0.6 - 0.8	
	0.8 - 1	
	1 - 1.5	Moderate cumulative impact score
	1.5 - 2	
	2 - 2.5	
	2.5 - 3	
	3 - 6	High cumulative impact score

ANNEX E: Hazard maps developed for the Adriatic sea

Overall hazards maps produced for the Adriatic sea case study representing the: anthropogenic extractive technological hazard (A), anthropogenic physical hazard by underwater noise (B), anthropogenic biohazard (C) and anthropogenic acute chemical hazard (D), and anthropogenic chronic chemical hazard (E), anthropogenic introduced technological hazard (F), for the baseline scenario 2000- 2015.



Overall hazards maps produced for the Adriatic sea case study representing the: anthropogenic extractive technological hazard (A), anthropogenic physical hazard by underwater noise (B), anthropogenic biohazard (C) and anthropogenic acute chemical hazard (D), and anthropogenic chronic chemical hazard (E), anthropogenic introduced technological hazard (F), for the future scenario 2035-2050



ANNEX F: Vulnerability maps developed for the Adriatic sea

Overall vulnerability maps produced for the Adriatic sea case study representing: vulnerability to the anthropogenic extractive technological hazard (A), anthropogenic physical hazard by underwater noise (B), anthropogenic biohazard (C) and anthropogenic acute chemical hazard (D), and anthropogenic chronic chemical hazard (E), anthropogenic introduced technological hazard (F).