# A modelling framework for MSP-oriented cumulative effects assessment

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## Abstract

This research presents a comprehensive Cumulative Effects Assessment (CEA) based on the Tools4MSP modelling framework tested for the Italian Adriatic Sea. The CEA incorporates five methodological advancements: (1) linear and non-linear ecosystem response to anthropogenic pressures/effects, (2) modelling of additive, dominant and antagonist stressor effects, (3) implementation of a convolution distance model for stressor dispersion modelling, (4) application of a CEA backsourcing (CEA-B) model to identify and quantify sources of anthropogenic pressures affecting environmental components, based on the convolution distance model and (5) a novel CEA impact chain visualization tool based on Sankey diagrams. Results from CEA in the Italian Adriatic Sea show that highest CEA scores are located in the Northern Adriatic Sea (Port of Trieste and Venice Lagoon inlets) while abrasion, marine litter and selective extraction are the most pronounced pressures within the 12 nm. Results from CEA-B application for two case studies evidence a clear distinction among local human impacts (trawling, small scale fishery) versus long-range diffusive human impacts (underwater noise and marine litter). Results were discussed for their geospatial outcomes, importance for transboundary effects assessment, conservation planning and future application potentials.

*Keywords:* Cumulative Effects Assessment, Cumulative Impacts, CEA backsourcing, Maritime Spatial Planning, Italy, Adriatic Sea

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## 1. Introduction

Cumulative effects assessment (CEA) have received increasing attention to aid the identification of marine conservation priorities and management actions

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(Halpern et al., 2008, 2015; Micheli et al., 2013; Tulloch et al., 2015). Their application has been exemplified in many different geographical domains ranging from global (Halpern et al., 2015) or sea basin (Korpinen et al., 2012; Micheli et al., 2013) level to regional level (Menegon et al., 2017; Holon et al., 2015; Murray et al., 2015) assessments. Moreover, the need to address anthropogenic impacts on marine ecosystems is widely expressed through environmental legislations (MSFD), requiring coordinated management programs to reach the good environmental status (GES) and the marine spatial planning (MSP) directive, requiring an ecosystem-based approach aiming at ensuring that collective pressures from human activities are kept at levels compatible with the GES and contribute to the sustainable use of marine goods and services and their preservation for future generation.

Despite the methodological advancements, assessment methodologies still rely on major assumptions leading to potential bias of results (Gissi et al., 2017; Stock and Micheli, 2016): spatial accuracy of input dataset (Ban et al., 2010), assumptions on the additivity of impact, while synergistic and antagonistic effects are neglected (Crain et al., 2008), linear response versus more common non-linear response to pressures (Halpern and Fujita, 2013) are still unsolved bottlenecks within the scientific community dealing with cumulative impact assessment. In addition, another critical aspect is the inconsistency and poor specificity in the principles, definitions and approaches adopted in the CEA applications (Judd et al., 2015; Jones, 2016; Stelzenmüller et al., 2018) leading to large variation of CEA research agendas, creating difficulties in the comparing methods and outcomes and posing barriers to proper interpretation and communication of outputs (Stelzenmüller et al., 2018; Foley et al., 2017; Stock and Micheli, 2016). In order to address these issues, the improvement of a CEA framework within the principles of the ecosystem-based management and environmental risk assessment is a promising approach (Judd et al., 2015; Stelzenmüller et al., 2018). A key aspect of the risk assessment is the identification and understanding of the relationships between the source of a pressure, the pathways by which exposure might occur, and the environmental receptors that could be harmed (source–pressure–pathway–receptor linkages) (Judd et al., 2015). Similarly to other sea areas around the globe, also in the Adriatic-Ionian Region (AIR) cumulative impact assessment techniques have been implemented on macro-regional level (Barbanti et al., 2015; Gissi et al., 2017), including regional case studies on high resolved geospatial datasets in Emilia-Romagna region (Barbanti et al., 2017). The CEA in the AIR was performed through the ADRIPLAN Portal (CNR-ISMAR, Tools4MSP group, 2014–2017), an MSP-oriented and community-based web-platform for publishing, sharing and processing multidisciplinary geospatial data. The portal supports the Spatial Data Infrastructure (SDI) capabilities and interoperable standard services enabling the data-sharing with external infrastructures and portals (e.g. EMODnet Data Portals, European Atlas of the Seas, EEA map services, SHAPE Adriatic Atlas). Based on Free and Open Source Software (FOSS) components, the ADRIPLAN Portal integrates and implements the Tools4MSP modelling framework allowing the user communities to perform shared analysis of Cumulative Effect Assess-

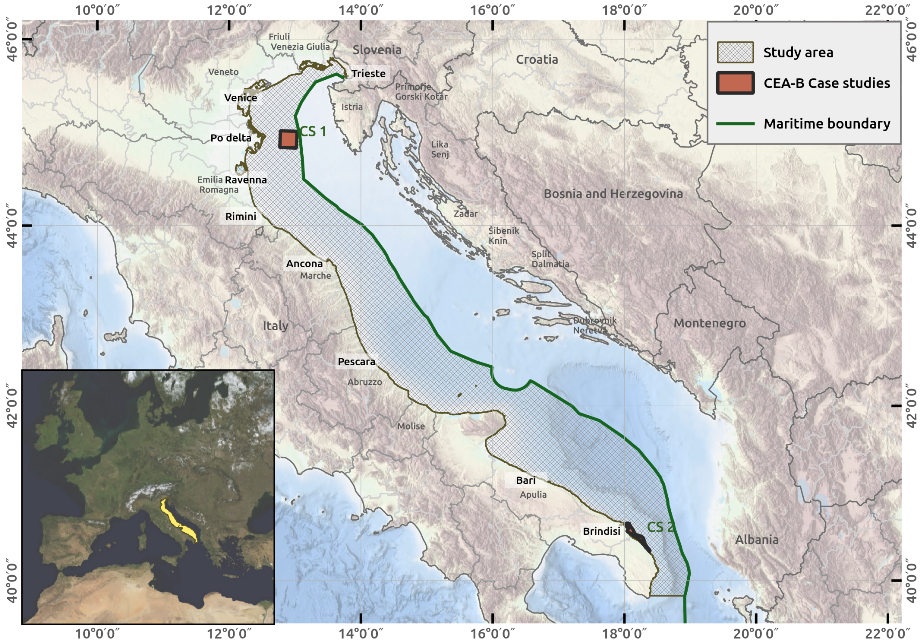


Figure 1: CEA The study area and CEA-B case studies (CS-1: Nortehrn Adriatic Sea; CS-2: Southern Adriatic Sea, Apulia Region).

ment (CEA), Sea Use Conflict (SUC) and Marine Ecosystem Services (MES) (Depellegrin et al., 2017; Menegon et al., 2016; Barbanti et al., 2015).

This research presents a comprehensive Cumulative Effects Assessment (CEA) methodology based on the Tools4MSP modelling framework applied to the Italian Adriatic Sea. The CEA approach adopts a new CEA model that better formalizes the source–receptor conceptual linkage, combines linear and non-linear ecosystem response, additive, dominant and antagonist effect models and presents a convolution distance model for flexible stressor dispersion modeling. A CEA impact chain visualization is proposed using Sankey diagrams. Based on the convolution distance model we propose a novel method to identify and quantify sources of anthropogenic pressures affecting specific environmental components, named CEA backsourcing (CEA-B). The CEA-B is a reverse CEA application demonstrated for two case studies: effects of underwater noise on hotspots of Loggerhead Turtles (*Caretta caretta*) in the Northern Adriatic Sea and multiple effects on environmental components of coastal Natura 2000 sites in Apulia Region in the Southern Adriatic Sea. Modeling results are discussed for their geospatial outcome, importance for transboundary impact assessment and future application potentialities.

## 2. Material and methods

### 2.1. CEA definition

The comprehensive CEA modelling approach builds on the definition of CEA provided by Judd et al. (2015). In particular, we consider "*CEA as a systematic procedure for identifying and evaluating the significance of effects from multiple pressures and/or activities on single or multiple receptors. CEA provides management options, by quantifying the overall expected effect caused by multiple pressures and by identifying critical pressures or pressure combinations and vulnerable receptors. The analysis of the causes (source of pressures), pathways, interactions and consequences of these effects on receptors is an essential and integral part of the process*". Moreover, we use the terms "*human activity*", "*uses*" and "*source*" as synonyms and define "*pressure*" (Judd et al. (2015)) as "*an event or agent (biological, chemical, or physical) exerted by the source to elicit an effect*". In appendix A we also report the definitions for the terms "*effect, sensitivity, vulnerability, pathway receptor, and impact*" (Stelzenmüller et al., 2018) adopted for CEA in the Tools4MSP modelling framework.

The following sections present the CEA approach adopted in the Italian Adriatic Sea including a CEA backsourcing (CEA-B) model.

### 2.2. Study area

The Italian Adriatic Sea covers about 143000 $km^2$ and ranges from coastal waters to the maritime boundary delimiting the italian part of the continental shelf (Figure 1). Its coastline spans from Friuli-Venezia-Giulia Region to Apulia southern coast. The area falls within the "Adriatic Sea" subregion according to the Marine Strategy Framework Directive (2008/56/EC). Its maritime boundaries are shared with Slovenia, Croatia, Montenegro and Albania. The Adriatic Sea is a semi-enclosed basin that communicates with the Ionian Sea through the Otranto Strait. The Northern Adriatic Sea is the most extended shelf area of the entire Mediterranean, with a very smooth coastal area and a softly sloping bottom. The Southern Adriatic Sea is characterized by the presence of a circular pit (South Adriatic Pit), bordering the Apulian continental shelf with a maximum depth of 1200 m. The Adriatic Sea features extremely diverse coastal and seabed landscapes with a wide heterogeneity of geomorphological features and bottom sediments (UNEP/MAP-RAC/SPA, 2015a). The Northern and Central Adriatic seabed sediments are predominantly composed by sandymudds, influenced by fluvial supply, while in the Southern Adriatic sea coarser sediments of rocky bottoms featuring bio-constructions (e.g. coralligenous assemblages) and *Posidonia oceanica* meadows are more frequent. The Adriatic Sea is a recognized hotspot of biodiversity within the Mediterranean Sea, hosting invertebrate species, fish species, resident marine mammals, turtles and seabirds (Coll et al., 2010). Its relatively small sea space is subjected to intense anthropogenic activities such as shipping, commercial fishery, oil and gas extraction, coastal tourism, aquaculture or cabling that can exert multiple pressures on its valuable ecological resources.

### *2.3. CEA dataset*

The geospatial dataset implemented for the study features 41 layers: 28 environmental components (E) and 13 human uses (U). Appendexes B and C present a detailed overview of the geospatial dataset implemented. The units of the spatial indicators U and E are presence/absence, weighted dummy and intensity indicators. For intensity indicators a log[x + 1] transformation and a rescaling from 0 to 1 was applied. Land-based activities (LBA) were modelled for nutrient distribution for Nitrogen (N) and Phosphorus (P) exerted by 80 rivers in the sea basin and 40 coastal urban areas using SHYFEM (Shallow Water Finite Element Model; Umgiesser et al. (2004). Full E, U and P geospatial datasets and relative metadata references can be downloaded under Menegon (2017).

### *2.4. CEA processing: Tools4MSP Modelling Framework*

The Tools4MSP Modelling Framework is a regularly updated open source software suite (Menegon et al., 2016) providing multi-objective toolsets for maritime spatial planning (Depellegrin et al., 2017). The framework supports the development of spatially explicit results, graphics, tables and multi-dimensional grid dataset that can be utilized for more detailed spatial investigations. Currently, the framework implements a Cumulative Effect Assessment (CEA), sea use conflict (SUC) analysis model and a marine ecosystem services (MES) capacity model. Tools4MSP can be flexibly deployed to different geospatial contexts ranging from macro-regional (Menegon et al., 2017; Gissi et al., 2017) to local/ regional level assessments (Barbanti et al., 2017). There are two modes of access of the framework: (1) The ADRIPLAN Portal (data.adriplan.eu) provides a user-friendly interface enabling users to run customized scenarios of CEA by choosing the area of analysis, the data layers and the resolution of the model outputs (Menegon et al., 2016). Modelling results were automatically published on the portal and shared among the user community. (2) Another option to use Tools4MSP model functions is via a stand-alone open source geopython library available in its latest version on GitHub (Menegon, 2015–2017).

#### *2.4.1. CEA model*

Originally, the presented CEA model is based on the methodology developed by Halpern et al. (2008) and later modified by Andersen et al. (2013). In Figure 2 the CEA impact chain is presented defining the relationship of multiple human uses (U) generating single or multiple pressures/effects (P/Eff) causing impacts on single or multiple environmental components (E) (e.g. habitats, marine mammals). The CEA model considers the 15 pressures identify by the Marine Strategy Framework Directive (MSFD, 2008/56/EC, Annex III) (European Union, 2008).

Compared to archetypical CEA implementations, the presented CEA incorporates a set of methodological advancements:

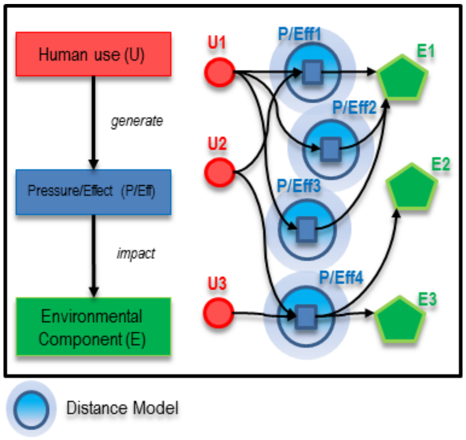


Figure 2: CEA impact chain: human uses (U) generate single or multiple pressures/effects (P/Eff) which may cause impacts on a single or multiple environmental component (E).

1. Implementation of a non-linear response function ranging from linear to S-shaped to represent the response of an ecosystem to anthropogenic pressures. However, assessing non-linear response to a pressure exerted by multiple uses is challenging (Korpinen and Andersen, 2016). The original sensitivity scores are divided into two parts: a proper sensitivity value (to estimate the impact elicited by certain pressure and related effects) and the use-pressure relative weights, as a measure of the relative importance of different uses contributing to a certain pressure.
2. Implementation of a flexible distance model, based on a 2D spatial convolution with a Gaussian kernel function to assess the propagation of the pressure (P) generated by anthropogenic uses impacting an environmental component (E).
3. Extension of the traditional additive effects with a flexible approach that models dominant effects (where the CEA score of a cell depended only on the effects having the highest impact on each environmental component) and mitigative/antagonistic effects on environmental components (where the combined effect produced by the action of two or more pressures, being less than the sum of their separate effects; Appendix A).
4. Implementation of a CEA backsourcing (CEA-B) model that spatially identifies sources of pressures generated by anthropogenic uses on environmental components and quantifies the relative contribution of each cell to the CEA score within an area of influence.
5. Visualization of the CEA impact chain through a Sankey diagram, representing complex human use-pressure/effects-environmental component flows.

CEA model application in this study was divided in a regular square grid of 1 $km^2$ (approximately 143,000 cells) using the EEA's reference grid for Europe

(Peifer, 2011) extracted for marine areas only. The CEA for a single grid cell (x, y) was calculated as follows:

$$CEA = \sum_{k=1}^{n} d(E_k)\Big(\overbrace{\sum_{j=1}^{m} s_{j,k}\,(1-mecf_k)\,eff\big(P_j,E_k\big)}^{Additive\ model} + \overbrace{\max_{j=1}^{m} s_{j,k}\,mecf_k\,eff\big(P_j,E_k\big)}^{Dominant\ model}\Big) \tag{1}$$

where

$$eff\big(P_j,E_k\big) = rfunc_{j,k}\Big(\big(\sum_{i=1}^{l} w_{i,j,k}\; i(U_i, M_{i,j,k})\big)'\Big) \tag{2}$$

whereas,

$U$ = i-th human use
$P$ = j-th pressures derived from the MSFD (2008/56/EC)
$E$ = k-th environmental components
$mecf$ = multi-effects combination factor, defining the type of impact combinations ranging from 0 (fully additive) to 1 (fully dominant), intermediate values identify antagonist effects.
$eff(Pj, Ek)$ = effect exerted by the pressure Pj over the k-th environmental component.
$s(Pj; Ek)$ = sensitivity of the k-th environmental component to the j-th pressure
$wi, j, k$ = weighted effect coefficient to properly combine the effects
$rfunc$ = response function.
$d(Ek)$ = Intensity/probability of the k-th environmental component on the cell (x, y) describing the presence/absence of Ek, which is 1 for fixed E (seabed habitats), and varies from 0 to 1 for mobile special features (turtles, marine mammals and seabirds).
' = operator to rescale from 0 to 1

In more detail, the distance model (i) is defined as follows:

$$i\big(U_i, M_{i,j,k}\big) = \big(D(U_i) * M_{i,j,k}\big)' \tag{3}$$

$i(U, M(Ui, Pj, Ek))$ = distance model propagating j-th pressure caused by i-th activity over the k-th environmental component
$M(Ui, Pj, Ek, )$ = 2D gaussian kernel function used for convolution considers buffer distances at 1 km, 5 km, 10 km, 20 km and 50 km.
$D(Ui)$ = intensity of i-th activity over the region of analysis

In addition to the geospatial input dataset of human uses and environmental components, the CEA model requires four groups of input parameters: sensitivity scores (s), buffers for the distance model (M), multi-effect combination factor (*mecf*) and response function (*rfunc*). The s and M parameters were defined through desk research and expert elicitation process. For each of these first parameters the experts have also associate a confidence value (c) that characterizes the level of reliability of their judgments. For a detailed description of the process we refer to Gissi et al. (2017).

The knowledge gaps related to *mecf*, *rfunc*, the uncertainty in expert based sensitivity scores and buffer distance implied the application of a quasi-Monte Carlo Method based on 1000 model runs (N) (Lilburne and Tarantola, 2009): The *mecf* parameter was randomly varied within a range from 0 (additive) to

1 (dominant). The *rfunc* parameter has been parameterized by two variables: the shape of the function that was randomly varied from 0 (linear) to 1 (S-shaped) and the function mid-point that was randomly varied between 0.3 to 0.7. Finally, to take into account the expert confidence, the sensitivity scores and buffer distances varied following a triangular distribution, assuming the modal values from expert judgment on sensitivities (s) and the variance from the confidence (c).

The CEA model outputs were modelled using three algorithms: The mean CEA ($\overline{CEA}$) is the expected value of CEA score within a grid cell. It is defined by the CEA score of the i-th run divided by N = 1000, corresponding to the number of model runs. The CEA mode ($CEA_m$) defines the most probable CEA score per cell (Appendix D). It is evaluated through a Gaussian Kernel Density estimation (KDE) of bandwidth 0.22. The bandwidth was selected to minimize the mean integrated squared error. The CEA coefficient of variation ($CEA_{cv}$) was calculated as measure of uncertainty of the CEA model. The advantage of the coefficient of variation is to compare the grid cells having widely different means and spatially represent the CEAs relative uncertainties in additive-dominant behaviour, the linearity of the effects on environmental components and in sensitivities confidence. This is estimated as the ratio between the standard deviation and the CEA. Appendix E reports the formulas applied for CEA model outputs ($\overline{CEA}$; $CEA_m$; $CEA_{cv}$)

### 2.4.2. CEA backsourcing (CEA-B) model

The CEA-B is a reverse CEA modelling approach. The CEA backsourcing model is defined as the spatially explicit identification and quantification of the single and/or multiple pressures (P) affecting one or several environmental components (E). Environmental components can refer to ecological features, such as marine habitats, hotspots of marine mammals distribution, fish nursery areas or spawning ground, nature conservation areas or any other user defined management area. In detail, the model is initiated from the CEA score on a specific environmental component, identifies the affecting single or multiple pressures and, based on a distance model (M), localizes and quantifies the human uses determining the CEA score 3).

The CEA-B model spatially integrates the additive and dominant CEA model (eq. 1 and 2) through the distance convolution model M. The CEA-B model is defined as follows:

$$\begin{aligned} CEA\text{-}B = \sum_{k=1}^{n} \Bigg( & \sum_{j=1}^{m} \sum_{i=1}^{l} \big(w_{i,j,k}\ (s_{j,k}\ (1 - mecf_k)\ eff(P_j, E_k)) \\ & * M(U_i, P_j, E_k)\big) \\ & + \max_{j=1}^{m} \sum_{i=1}^{l} \big(w_{i,j,k}\ (s_{jmax_k,k}\ mecf_k\ eff(P_{jmax_k}, E_k)) \\ & * M(U_i, P_{jmax_k}, E_k)\big) \Bigg) \end{aligned} \tag{4}$$

Where $P_{jmax_k}$ is the pressure that has maximum contribution on the k-th

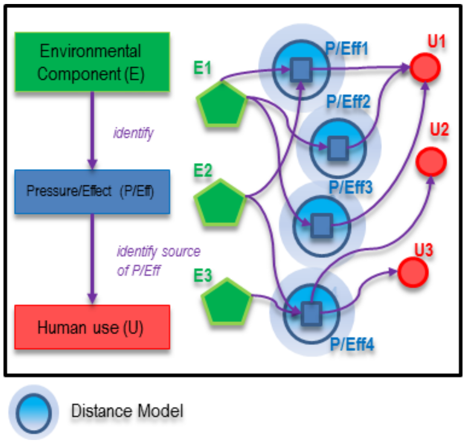


Figure 3: CEA-B impact chain: identification of pressures/effects (P/Eff) on the environmental component (E) and identification and quantification of single or multiple human uses (U) generating the pressure/effects.

environmental component. For other parameters see definitions eq. 1 and 3.

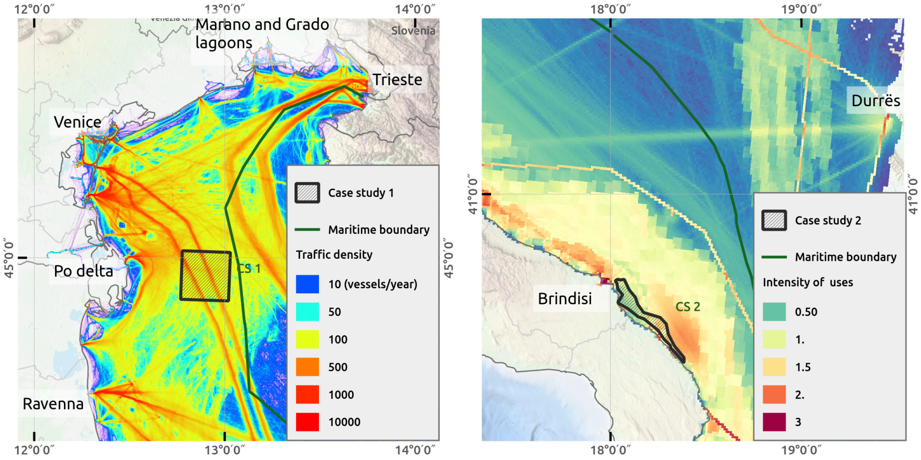
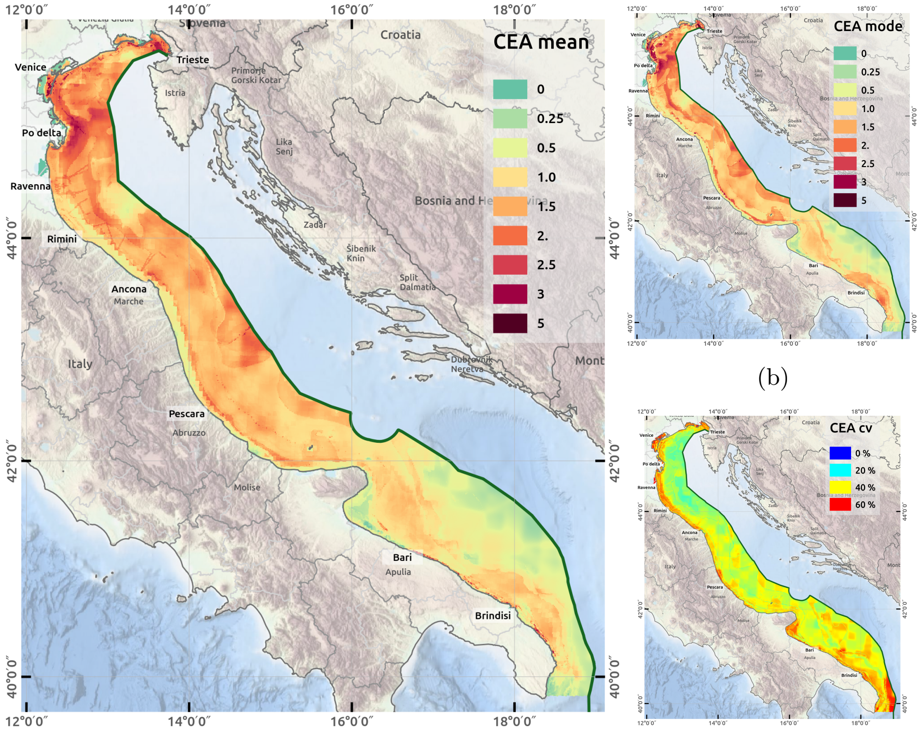


Figure 4: Case study 1 (CS 1; left): Northern Adriatic Sea, Loggerhead Turtle hotspot and traffic density. Case study 2 (CS 2; right): Coastal NATURA 2000 sites along Apulia Region in the Southern Adriatic Sea and intensity os sea uses.

### *2.4.3. CEA-B case study setup*

The CEA-B, based on additive impact model, was tested for two case studies (Figure 1, 4). Case study 1 refers to a Loggerhead turtles (*Caretta caretta*) hotspot area of 20 km x 20 km located at 13 nm from the Po river outlet in the Northern Adriatic Sea. The hotspot refers to the number of sightings (n =

13) entirely located in the Italian Adriatic Sea, based on a survey from 2010-2013 (UNEP/MAP-RAC/SPA, 2015b). The CEA-B model was tested for a single anthropogenic pressure, namely underwater noise generated by multiple human uses such as maritime traffic, coastal tourism and commercial fishing. Case study 2 refers to 6 contiguous NATURA 2000 Sites of Community Importance (SCIs; area = 176 $km^2$; IT9140001, IT9140003, IT9150003, IT9150003, IT9150025, IT50032) along the southern coasts of Apulian Region. The SCIs feature extensive coverages of highly sensitive habitats such as *P. oceanica* meadows and coralligenous assemblages and are entirely located within Italian Territorial Waters. The CEA-B model was tested for multiple anthropogenic pressures generated by multiple human uses on the SCIs.



(a)

(b)

(c)

Figure 5: CEA model results for a) mean; b) mode and c) coefficient of variation (CV).

## 3. Results

### 3.1. CEA modelling

In Figure 5 geospatial results from CEA modelling are presented: Figure 5a presents the mean CEA model as the expected value of the cumulative effect for each cell. Very high CEA scores >= 3 (46 $km^2$ – 0.1% of the study area) are located in proximity of the Gulf of Trieste and in front of the Venice Lagoon inlets (Malamocco and Lido). In total 65 grid cells were affected. High CEA scores from 2.5 to 3.0 (419 $km^2$ – 0.65%) are also located in the Gulf of Trieste (coastal areas of Grado Marano Lagoon and the northern coastal areas of the Venice Lagoon), Po Delta and Chioggia. In southern Italy, coastal areas of Apulia Region close to coastal urban areas and ports of Bari and Brindisi register high CEA scores as well. Medium-high CEA scores from 2.0 to 2.5 (1765 $km^2$ – 2.74%) include recreational areas of the Northern Adriatic Sea from Veneto Region, Emilia Romagna Region (Ravenna, Rimini and Riccione), in central Italy Marche (Ancona port) and Abruzzo (Pescara) Region and in southern Italy Apulia Region. Medium CEA scores range from 1.5 to 2.0 (11088 $km^2$ – 17.2%) and are distributed in offshore area of the Northern Adriatic Sea, Emilia-Romagna and Marche Region. Medium–Low CEA scores ranging from 1.0 to 1.5 (25702 $km^2$ – 40%) are distributed in coastal and offshore areas of the entire study area. Low CEA score corresponding to lower 1 (25377 $km^2$ – 39.4% ) cover residual coastal areas of the Emilia-Romagna, Marche, Abruzzo Region and offshore areas in Southern Italy.

Figure 5b represents the most probable value (mode) of the CEA for each cell. In terms of spatial distribution the mode is comparable with the mean while, globally, it tends to identify higher values (see Appendix F).

Figure 5c represents the coefficient of variation in percentage (CV) of the CEA scores as measure of uncertainty of model results. In this sense, CV is a measure of relative variability over the 1000 runs. Low values of the CV identify low uncertainty, instead high values of CV identify high value of uncertainty. The 95% of the study area has a CV variation ranging from 28.1 % to 54.2% with a mean CV of 38.9% (Appendix G).

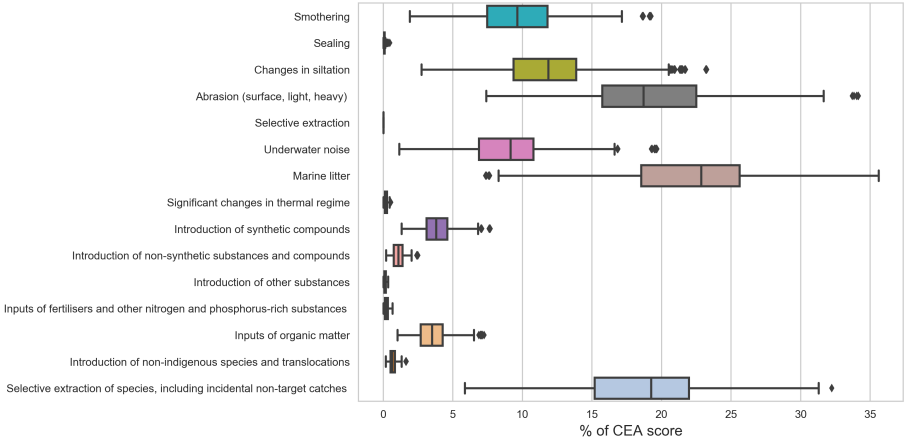


Figure 6: Boxplot illustrating the percentage contribution of pressures to the CEA score. Boxplots show maximum/minimum outliers, boxes enclose first and third quartiles and box centres define median.

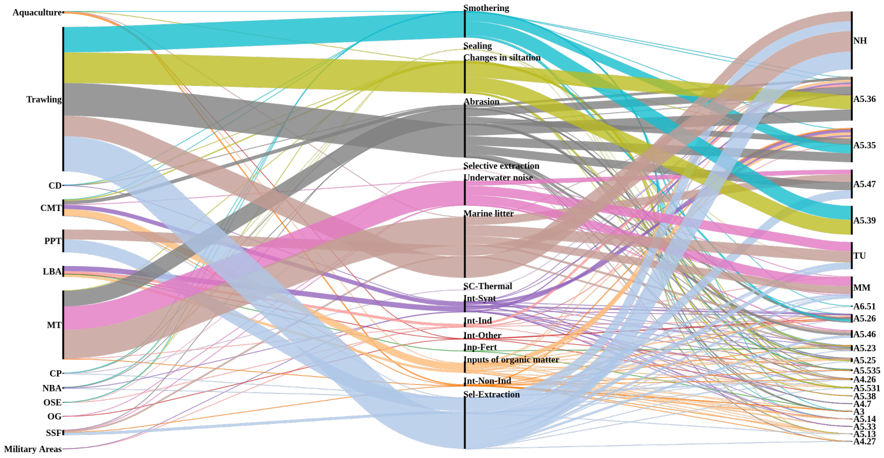


Figure 7: CEA impact chain visualization. Sankey diagrams that identifies the interactions and the flow of impacts generated by the Human uses (left axes) through the Pressures (mid-axes) on the Environmental Components (right axes). The width of the bands are directly proportional to CEA score and each color identifies a specific Human use. Human uses: CD - Coastal Defence Work; CMT - Coastal and Maritime Tourism; CP - Cables and Pipelines; LBA - Land based activities; MT - Maritime Transport; NBA - Naval base activities; OG - Oil & Gas extraction; OSE - Offshore sand deposits; PPT - Flying; SSF - Small scale fishery. Pressures: Inp-Fert - Inputs of fertilisers and other nitrogen and phosphorus-rich substances; Int-Ind - Introduction of non-synthetic substances and compounds; Int-Non-Ind - Introduction of non-indigenous species and translocations; Int-Other - Introduction of other substances; Int-Synt - Introduction of synthetic compounds; SC-Thermal - Significant changes in thermal regime; Sel-Extraction - Selective extraction of species, including incidental non-target catches Environmental components: A3 - Infralittoral rock and other hard substrata; A4.26 - Mediterranean coralligenous communities; A4.27 - Fauna communities on deep moderate energy; A4.7 - Circalittoral rock and other hard substrata; A5.13 - Infralittoral coarse sediment; A5.14 - Circalittoral coarse sediment; A5.23 - Infralittoral fine sands; A5.25 - Circalittoral fine sands; A5.26 - Circalittoral muddy sand; A5.33 - Infralittoral sandy mud; A5.34 - Infralittoral fine mud; A5.35 - Circalittoral sandy mud; A5.36 - Circalittoral fine mud; A5.38 - Mediterranean biocenosis of muddy detritic bottoms; A5.39 - Mediterranean biocenosis of coastal terrigenous muds; A5.46 - Mediterranean biocenosis of coastal detritic bottoms; A5.47 - Mediterranean biocenosis of shelf; A5.531 - Cymodocea beds; A5.535 - Posidonia beds; A6.4 - Deep; A6.51 - Meditteranean communities of bathyal muds; A6.511 - Facies of sandy muds with Thenea muricata; GDR - Giant devil ray; MM - Marine mammals; NH - Nursery habitats; SB - Seabirds; TU - Turtles.

Figure 6 represents the contribution (in percentage) of the single anthropogenic pressures to the CEA score: Marine litter has the highest contribution ($\overline{x} = 22.1\%$; $\sigma = 5.3$) to the CEA score, followed by abrasion ($\overline{x} = 19.2\%$; $\sigma = 4.9$), extraction of species ($\overline{x} = 18.4\%$; $\sigma = 4.9$), changes in siltation ($\overline{x} = 11.8$; $\sigma = 4.0$), smothering ($\overline{x} = 9.7\%$, $\sigma = 3.3$), underwater noise ($\overline{x} = 9.0\%$, $\sigma = 3.0$). The mean contribution of remaining pressures ranges from 3.9% to 0%.

Figures 7 illustrates a Sankey diagram to represent the CEA impact chain. The chain represents the flow of impact, with the band width directly propor-

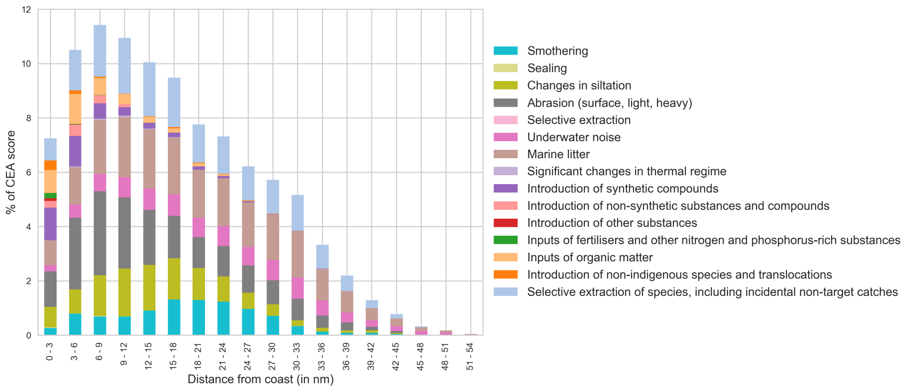
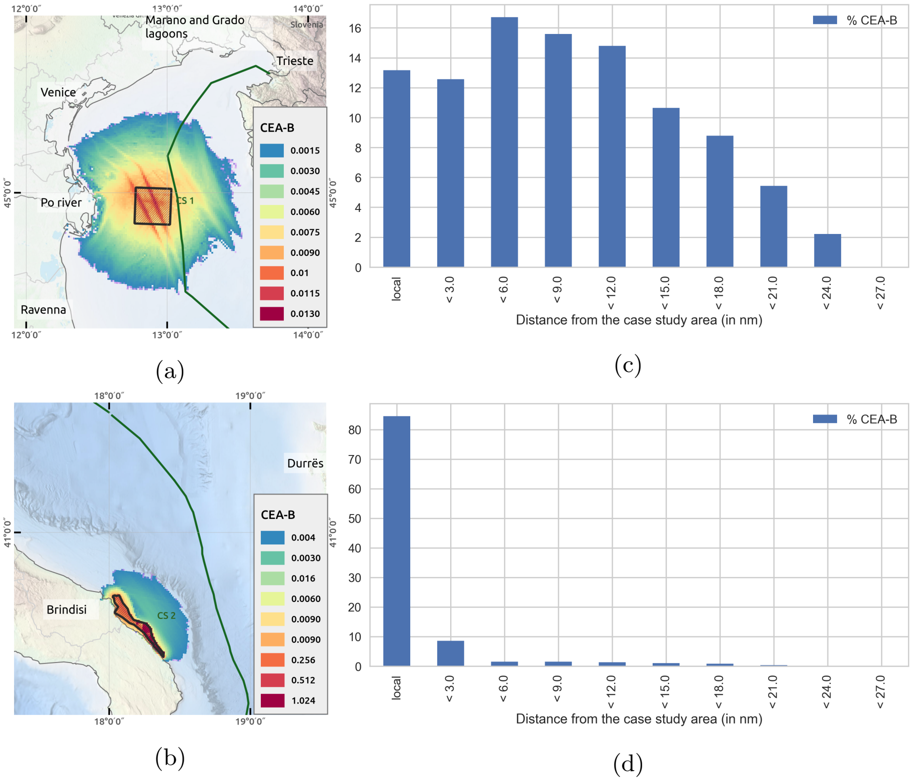


Figure 8: Percentage contribution of CEA scores by pressure over a distance gradient of intervals at 3 nautical miles (nm). Pressure are listed from highest to lowest impacting, from bottom to top.

tional to the total CEA score. Results show that the maritime uses with highest contribution to CEA score were were trawling (52.8 %), maritime transport (25.1%), pair pelagic trawling (8.3 %), coastal and maritime tourism (6 %) and land based activities (4%). The most impacted environmental components were nursery habitats (21%), circalittoral fine mud (16 %), circalittoral sandy mud (12.5 %), mediterranean biocenosis of shelf-edge detritic bottoms (10.5 %) and mediterranean biocenosis of coastal terrigenous muds (10.5 %). Other relevant environmental components are turtles (9.9 %) and marine mammals (7.9 %). The diagram also illustrates how a single use impacts an environmental component through its pressures: for instance the 30% of the impacts on nursery habitats is generated by selective extraction of species caused by trawling.

Figure 8 shows the percentage contribution of mean CEA score (in %) over a distance gradient in intervals of 3 nautical miles. On overall, there is an increase of CEA scores from 0 (the coastline) to 9 nm. Coastal areas ranging from 0 to about 12 nm contribute to 40.1 % of the overall CEA scores. The pressures with highest contribution within the 12 nm refer to abrasion (24.1 %), marine litter (16.2 %), selective extraction (15.6 %), changes in siltation (12.2 %). Pressures deriving from land-based activities refering to introduction of synthetic compounds and organic matter contribute to 8.0 % and 7.3 % of CEA score respectively. Coastal areas with highest mean CEA scores are defined at 6-9 nm (11.4 %). The most contributing pressures include abrasion (27.0 %), marine litter (17.5 %) selective extraction (16.7 %) from fishing activities and changes in siltation (13.1 %). Beyond the 12 nm the pressures with highest contribution to total CEA score include marine litter (26.3 %), selective extraction (20.1 %), abrasion (15.9 %), smothering (11.9 %), changes in siltation (11.5 %) and underwater noise (11.4 %). In general pressures related to land-based activities such as introduction of synthetic compounds and organic matter contribute decrease drastically.



(a) (c)

(b) (d)

Figure 9: CEA-B application results: Case study 1: a) CEA-B visualization for underwater noise and c) CEA-B score contribution for a distance gradient at 3 nm intervals. Case study 2: b) CEA-B visualization for multiple pressures and d) CEA-B score percentage contribution for a distance gradient at 3 nm intervals. Note: the term local refers to impact exerted by in-situ human uses.

### *3.2. CEA-backsourcing model*

Results from case study 1 application for the Northern Adriatic Sea present the contribution of anthropogenic uses generating underwater noise having a potential effect on Loggerhead turtles hot spot areas of 20 km x 20 km. Underwater noise impacting the turtles hot spot has an area of influence of about 6200 $km^2$ (Figure 9a). The Figure defines three main sources of underwater noise impacting the hot spot: Shipping routes (including motorways of the sea, ferry routes) intersecting the hotspots connecting Venice port to the Mediterranean Sea; significant motorways of the sea located easterly from the hotspot connecting Trieste port to the Mediterranean Sea and diffusive maritime traffic composed by commercial fishery, local ferry traffic, offshore supply ships and tugs. The most significant impacts to the hotspot are within a radius of approximately 24 nautical miles (Figure 9c). The sources of highest contribution to the impact on the hotspots are located at 2 to 4 nautical miles and refer to the commercial shipping routes from Venice and Trieste port. To notice is that about 86.8 % of CEA score derives from long range distance effects, located outside the turtle hotspot. Transboundary effects from Croatian and Slovenian sea areas contribute to 27.9 % of the overall CEA score.

Results from case study 2 application are presented in Figure 9 (bottom 9b and 9d) for Natura 2000 sites located along Apulia (Southern Italy). The area of influence covers 7851 $km^2$. In contrast to case study 1, the majority of pressure is generated from in-situ anthropogenic uses (0 nautical miles) contributing to 84.6% of the CEA score. The most important contributing pressures (Appendix H) refer to abrasion (38.0%), selective extraction of species (23.4%) and changes in siltation (16.9%). At distance from 0 to 3 nautical miles the contribution to CEA is 9%. The most relevant pressures are introduction of non-indigenous species (41.1%), changes in siltation (24.8 %), selective extraction of species (10.7%) and marine litter (8.6%). Beyond 3 nautical miles, the contribution to CEA gradually decreases from 1.5% to 0, due to introduction of non-indigenous species, introduction of synthetic compounds and marine litter. The anthropogenic activities with the highest contribution to multiple stressors (Appendix I) derive from in loco exploitation activities, such as trawling (33.3%), followed by small scale fishery (20.5%) and naval based activities (11.8%). Maritime transport and coastal and maritime tourism were the anthropogenic uses causing the highest long range distance cumulative effects, respectively 21.5% and 9.4%. About 15.4% of cumulative effects derive from transboundary sea areas.

## 4. Discussion

### *4.1. CEA overall results*

The results of CEA analysis show that Adriatic waters appear to be strongly influenced by human activities generating a complex set of pressures on habitats and ecosystems. In our analysis, distinct patterns of impact scores were detected at regional scale, with trawling fisheries, maritime transport and riverine runoffs as the most pervasive threats across the region. CEA outputs show the highest values in areas featured by the whole set of activities considered, mainly close to densely populated coastal areas (e.g. close to the cities of Trieste, Venice, Ancona, Bari and Brindisi), in presence of intense naval activities (due to the shipping and cruise traffic), medium–high trawling pressure and strong riverine inputs (e.g. Po river Delta). Areas showing medium–high scores are largely represented along the region. Other areas, mainly offshore (30 nm from the coast to the midline) are exposed to less and moderate pressures and, consequently, feature lower scores, except for the presence of highly valuable pelagic species (e.g. marine turtles, mammals and seabirds). Results evidence that the highest contribution to the cumulative effects scores is given by activities producing marine litter, selective or accidental extraction of species, seabed abrasion , changes in siltation and smothering. These pressures affect several ecologically relevant environmental components. Essential fish nursery habitats and soft-bottom benthic communities are the most affected by activities (in particular trawling fisheries) generating mechanical damage to the sea bed, extracting species and introducing marine litter. The prominent role of trawling fisheries in the overall analysis is evident from the spatial distribution of CEA scores over a distance gradient (Figure 8), showing lower scores in areas where trawlers are excluded (from 0 to 3 nm from the coasts). These outputs may represent a key knowledge for a proper determination of planning needs to reach the Good Environmental Status (MSFD, 2008/56/EC).

Our CEA approach incorporates linear, non-linear, additive, dominant and antagonist effects of pressures on environmental components. The multi-effects combination factor allows to define pressure interactions, on a range from 0 (fully additive) to 1 (fully dominant), with intermediate values identifying antagonistic effects. This conceptual model integration allows to take into account dominant effects obtained summing the contributions exerted by each activity through a single pressures (e.g. abrasion from different trawling activities) and is an improvement of existing additive-dominant cumulative assessments, which take into account only the dominant activity (aka stressor, sensu Halpern et al. (2008) to Stock and Micheli (2016)) and therefore potentially underestimating other sources of the same pressure. Currenlty, the multi-effects combination factor does not include synergistic interaction due to the lack of information regarding real multiple synergies in multiple stressors in similar environments (Côté et al., 2016). Moreover, the model includes a convolution distance model for flexible stressor dispersion modelling. The convolution distance model can be applied to any human use independently from its spatial structure (point, polygon or line feature) and therefore provide an advancement of CEA approaches compared to more archetypical applications. In case the propagation of pressures is too simplified such as non-isotropic, the methodology allows to integrate pressure indicators generated by external models, such as hydrodynamic model applications (e.g. SHYFEM) for land-based activities (Menegon et al., 2017; Depellegrin et al., 2017). The modelling of environmental and socio-economic dynamics in the land-sea interface is essential for the analysis of land-sea interactions and to support coherent planning as required by the MSP Directive (2014/89/EU). Moreover hydrodynamic models can support the analysis and prediction of MSFD descriptors (e.g. eutrophication, contaminants, marine litter) that are not place specific (Gilbert et al., 2015).

The CEA coefficient of variation is a measure of uncertainty of the CEA model that can be compared on grid cell level. Highest variations (up to 55%) are evident in crowded coastal areas featuring several intense activities (e.g. coastal areas of Veneto and Emilia-Romagna region and highly urbanized and port areas) exerting various important pressures to many environmental components. In those areas, randomized model runs considering factors ranging from a fully additive to a fully dominant combination of the effects, from linear to S-shaped response functions of environmental components and varying according a triangular distribution for the sensitivity scores and buffer distances can give significant differences in CEA values. Otherwise, offshore areas show more homogeneous scores, with the exception of pelagic areas where sensitivities confidence is lower due to knowledge gaps (e.g. close to the South Adriatic Pit).

### *4.2. CEA backsourcing application*

Based on two case studies, the CEA-B model supported the spatial identification and quantification of sources of pressures and the use-specific contribution to the CEA score in given grid cell (Figure 9a and b). The case studies for the Northern and Southern Adriatic Sea demonstrated the flexibility of the approach and its applicability beyond the case study area context. The application opportunities are manifold and can support planners and decision-makers in addressing different sustainability challenges in MSP: CEA-B can be used as analytical tool to support the design of marine conservation areas and specify protection measures aiming at maximizing conservation values and reducing localized and long range distance pressures. It can support environmental risk and impact assessment at level of individual project by comparing ecosystem effects through different planning scenarios. Moreover the CEA-B has transboundary applicability as it can highlight potential transboundary effects of existing or proposed activities with potential adverse environmental effects. Also, the CEA-B can contribute to the development of alternative planning objectives in transboundary sea areas, and possibly stimulate bi- or multi-lateral consultations among relevant parties and support the analysis and monitoring of implemented decisions on proposed activities oriented to minimze and prevent impacts.

The first case study addressed the potential sources of underwater noise on Loggerhead Turtles (*C. caretta*), listed by IUCN as a globally vulnerable species and by the Habitat Directive (92/43/CEE – Annex II) as Species of Community Interest, requiring the designation of Special Areas of Conservation (SACs) for its conservation. Descriptor 11 of the MSFD directive requires that the introduction of energy, including underwater noise, should not adversely affect the ecosystems (2008/56/EC). Despite complex set of activities generating noise (e.g. seismic surveys, drilling operations, coastal engineering, and military activities), particular attention should be given to continuous noise disturbances from different shipping activities (commercial shipping, fishing activities and recreational shipping), accounting for more than 90% of the anthropogenic contribution to ocean ambient soundscapes (Green et al., 1994; Hildebrand, 2009). In this sense, the loggerhead turtle hotspots is in proximity of the most trafficked highway of the sea, with an annual traffic density of about 2400 vessels/$km^2$ for the years 2014–2015. The main threats affecting turtles in the Adriatic Sea refer to fisheries, marine litter, chemical and biological pollution, collisions with ships and habitat degradation (Fortuna et al., 2015). Although several national and international management measures have been taken to reduce risks for local population, their effectiveness may be reduced in sea areas with intenisve human activities responsible sea noise pollution (Hildebrand, 2009; Ross, 2005; Andrew et al., 2002), that can cause communication masking, stress, hearing loss or habitat abandonment (Nowacek et al., 2007; Clark et al., 2009; Lavender et al., 2014; Nelms et al., 2016). In this context underwater noise pollution mapping (Tasker et al., 2010), has been identified as a major research priority (Maccarrone et al., 2015). Our effort to map the potential noise sources on a *C. caretta* hotspot in the Northern Adriatic confirms the pervasive/diffusive effect of noise, potentially impacting turtles from a distance to 24 nm from the considered area. Case study 1 results evidences the transboundary nature of underwater noise, determining long range distance effects especially in a narrow, enclosed sea region, such as the Adriatic Sea. The contribution to CEA scores from underwater noise on loggerhead hotspots derive by 27.9% from sources located in transboundary sea areas.

To better support decision makers and planners in the setup of noise mitigation measures for MSFD, there is the need for modelling procedures that take into account the severity of impacts at species or habitat level according to the origin, frequency, intensity and duration of the anthropogenic phenomena (Williams et al., 2015). A future development of the CEA-B will support a selective extraction of AIS data by typology of vessel and seasonal traffic density (especially seasonal fishing activities), which can effectively support monitoring of continuous noise effects towards activity and seasonal specifics. This information can result crucial to implement management measures, hypothesizing mitigation measures involving technological solution to reduce noises and dynamic shipping routes considering turtles' seasonal migration patterns.

Case study 2 features a higher level of modelling complexity, assessing multiple effect sources on different environmental components of coastal SCIs. According to the SCIs European regulation (92/43/CEE), in order to protect the natural habitats and establish the necessary conservation measures, the sites management has to involve appropriate plans specifically designed for the sites or integrated into other development plans. Since the determination of the sources of pressures is the baseline knowledge for environmental protection, management and planning and can determine the achievement of conservation targets, our tool can offer decisive knowledge to planners and managers in order to increase the effectiveness of measures. For instance, the CEA-B model identified 16 local pressures and 3 long-range distance pressures within 6 to 27 nm (Appendix H). Results shows that the most important pressures to high value habitats (Posidonia beds and biogenic reefs) protected by the SCIs derive from anthropogenic activities localized within the site. Still, activities conducted outside the SCIs borders potentially impact protected habitats causing introduction of non-indigenous species, pollution and litter, changes in siltation, and directly extracting species. As a consequence, measures may result impaired by these pressures, indicating the needs of a management approach wider than the mere sites borders and a proper precautionary planning along the whole region. In this context the CEA-B can be re-run by dislocating and or removing specific uses exerting significant pressures and therefore support the identification of alternative management scenarios.

As performed in case study 2, based on the ecological structure, integrity, requirements and ecosystem functioning of any SCI and protected areas, the CEA-B can be re-run by determining, dislocating or removing specific uses exerting significant pressures.

### *4.3. Dataset*

The CEA model is supported by a geospatial datasets of 41 layers retrieved from a variety of data providers with limitations in spatial and temporal data availability, richness of data attributes and variable data resolution. Seasonality of human use datasets, such as maritime traffic were represented with annual traffic density (July 2014 - June 2015), similarly nutrient discharge from land-based activities is based on annual mean discharge rates and does not take into account seasonal river runoffs Depellegrin et al. (2017). Seasonality can underestimate, overestimate or neglect impacts generated by extreme events or, in contrast, can evidence artificial impacts, where the interactions between human use and environmental component do not persist. Similarly, seasonality of highly dynamic environmental components such as marine mammals is based on sighting datasets of monthly resolution, and therefore not providing any information on the spatio-temporal behaviour of the target species. Additional data gaps occur for datasets derived from regional authorities, such as coastal defence or extraction work (available for Emilia-Romagna and Apulia Region) and military areas, which have higher resolution compared to national or EU level datasets. The datasets evidence a high variability of resolution that can cause alteration of CEA score, especially for datasets of resolution higher than the proposed 1 km EEA grid resolution. For other datasets, such as coastal and maritime tourism and naval based activities, a proxy of distance buffer was implemented. In order to overcome some data gaps, the application of proxy datasets was required based on a distance buffer applied for marinas and ports respectively.

### *4.4. CEA model shortcomings*

Major shortcomings of the CEA model can be defined as follows: the presented CEA model implements expert-based sensitivity scores derived from stakeholder engagement process developed within Gissi et al. (2017). Similarly to other studies around the globe, sensitivities are one of the major sources of model uncertainty. In parallel, the CEA model proposed in this paper introduces input parameters, such as the multi-effects combination (*mecf*) and the response function (*rfunc*), which are an additional source of uncertainty with very little knowledge availability (Halpern and Fujita, 2013). The statistical approach based on quasi-Monte Carlo Method allows to deal with the missing input informations obtaining a Cumulative Effect Assessment for the study area in term of expected value (mean) and most probable value (mode). CEA mean analysis can over - and or underestimate the impacts, therefore an uncertainty analysis was applied. In addition, the definition of the range of variability and the estimate of uncertainty (spatial distribution of CEA coefficient of variation) is needed to properly interpret the results especially within a decision making process.

### *4.5. Future implementation*

In future, the Tools4MSP modelling framework will be further aligned and advanced with geospatial datasets and models implemented in other sea areas

(North Sea and Baltic Sea) such as additional human uses will be implemented including oil spills, coastal population, coastal wastewater treatment plants, atmospheric deposition of nutrients, atmospheric deposition of heavy metals, changed siltation due to land use (e.g. river dams, deforestation) and global change effects (acidification, ocean warming, increased UV radiation).

In parallel, also datasets referring to environmental components will be further implemented by integrating novel information concerning species biomass or probability of presence. Sensitivity scores of habitats will be fine-tuned using species and community specific sensitivity scores, ideally, in local levels validation of CEA should be performed using field data (Clark et al., 2016).

The presented CEA-B model is currently based on the pollution propagation using convolution distance models. Further augmentation of the Tools4MSP modelling framework will require the implementation of pollutant specific dispersions models, such as marine litter, oil spills and waterborne pathogens.

### *4.6. CEA Impact chain visualization*

The increasing complexity of CEA modelling driven by methodological advancements, novel datasets and improved modelling capabilities requires additional visualization tools to represent the impact chain. In this context, the implemented Sankey diagram (Figure 7) was a useful visualization instrument in support of the geospatial results (Figure 5) enabling decision-makers to understand the underlying linkages and magnitude of flow among human use-pressure/effect-environmental component.

## 5. Conclusions

Based on a case study for the Italian Adriatic Sea, the Tools4MSP modelling framework demonstrated to be a versatile tool for the assessment of cumulative effects, uncertainties and identification and quantification of anthropogenic sources of pressure. The framework can be applied to any study area around the globe and its functionalities can support decision-makers and planners in the development of conservation and planning strategies. The novel CEA back-sourcing module provides planners with an additional instrument for the setup and monitoring of conservation strategies supporting the ecosystem-based approach, that can localize type of pressures and most impacting maritime uses also in transboundary context, and therefore define sea use specific management strategies for target ecosystem components.

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