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Cumulative impact assessment for ecosystem-based marine spatial planning

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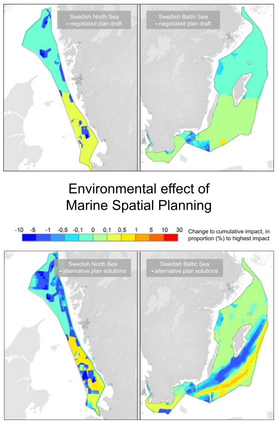
HIGHLIGHTS

- Cumulative impact assessment was integrated with marine spatial planning
- Existing methods were enhanced by developing functions for scenario analyses
- Environmental consequences of different planning options were compared
- Implementing mm marine spatial plans likely to reduce cumulative impact in the Swedish North Sea
- Demonstrated tool supports ecosystem based marine spatial planning in practice

GRAPHICAL ABSTRACT



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ABSTRACT

Claims for ocean space are growing while marine ecosystems suffer from centuries of insufficient care. Human pressures from runoff, atmospheric emissions, marine pollution, fishing, shipping, military operations and other activities wear on habitats and populations. Ecosystem-based marine spatial planning (MSP) has emerged worldwide as a strategic instrument for handling conflicting spatial claims among competing sectors and the environment. The twofold objective of both boosting the blue economy and protecting the environment is challenging in practice and marine planners need decision support. Cumulative Impact Assessment (CIA) was originally developed to provide an overview of the human imprint on the world's ocean ecosystems. We have now added a scenario component to the CIA model and used it within Swedish ecosystem-based MSP. This has allowed us to project environmental impacts for different planning alternatives throughout the planning process, strengthening the integration of environmental considerations into strategic decision-making. Every MSP decision may

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Decision support tool
Symphony-tool

entail a local shift of environmental impact, causing positive or negative consequences for ecosystem components. The results from Swedish MSP in the North Sea and Baltic Sea illustrate that MSP certainly has the potential to lower net cumulative environmental impact, both locally and across sea basins, as long as environmental values are rated high and prevailing pressures derive from activities that are part of MSP. By synthesizing innumerous data into comprehensible decision support that informs marine planners of the likely environmental consequences of different options, CIA enables ecosystem-based MSP in practice.

1. Introduction

Marine Spatial Planning (MSP) is being implemented across the world, with the goal of supporting marine policy through strategic designation of space for various interests (Domínguez-Tejo et al., 2016). MSP encourages integrated marine management and has the potential to reduce investment risks for new industries (PRC, 2011). Guidelines (Ehler et al., 2009) and regulatory instruments emphasize that MSP should be ecosystem-based. Two fundamental aspects of this ecosystem-based approach to MSP are the respect for the structure and function of ecosystems, and strong stakeholder participation. To follow such principles through a long and partially political planning process that is concerned with large areas and various ecological entities, requires sufficient decision support including comprehensive assessment of environmental impact. Marine spatial plans cover vast geographic areas with diverse ecological entities, various human activities, and associated pressures. Through this myriad of information, planners need to envisage how all concurring uses of the sea affect the marine environment, in addition to pressures from land-based sources. At the grand scale of MSP, cumulative effects assessments are key (Hodgson et al., 2019; Willsteed et al., 2018).

A decade ago, Halpern et al. (2008) devised a method for Cumulative Impact Assessment (CIA) based on a geospatial index describing the relative impact of multiple human pressures on the marine environment, resembling previous work by Landis and Wiegers (1997). The CIA index is a function of (i) relevant human pressures expressed by intensity maps, (ii) representative ecosystem components expressed as value maps, and (iii) a sensitivity index defining how sensitive each ecosystem component is to each human pressure. The method has since been applied in many regions (Korpinen and Andersen, 2016) and over time to track changes to environmental impact (Halpern et al., 2019). The transparency and holistic scope of CIA makes it particularly suitable for MSP. However, it may be challenging to incorporate comprehensive data-intensive analyses into the dynamic planning and stakeholder dialogue that is at the heart of MSP. Planning support tools must be scientifically robust to capture ecosystem complexity, but also transparent and simple enough to be understood and accepted by its users, namely planners, stakeholders, and policy makers.

Scholars introduced CIA in support of MSP (Depellegrin et al., 2017; Fernandes et al., 2017), and Sweden is the first country to use CIA integrated with national MSP for marine management. The Swedish Agency for Marine and Water Management (SwAM), the governmental body responsible for drafting the national MSP in Sweden, has developed and used a CIA-based GIS-application for MSP here called the *Symphony*-tool. It has a scenario component that allows adding or adjusting the intensity of human pressures in any delimited area. This functionality has enabled the comparison of expected environmental effects of different plan alternatives.

This example from Swedish ecosystem-based MSP, where CIA has been used directly by marine planners and as a fundamental component of strategic environmental assessment, aims to illustrate the integration of CIA with MSP in practice.

2. Methods

2.1. Legal context and geographical scope

Following the national ordinance under the EU framework for maritime spatial planning (European Commission, 2014), Sweden will be adopting its first national marine spatial plans by March 2021. Three plans are being developed by SwAM: North Sea (NS), Baltic Sea (BS), and Bothnian Bay (not included in this paper). The plan proposals presented in this paper were published in 2019 after four years of development and stakeholder consultations.

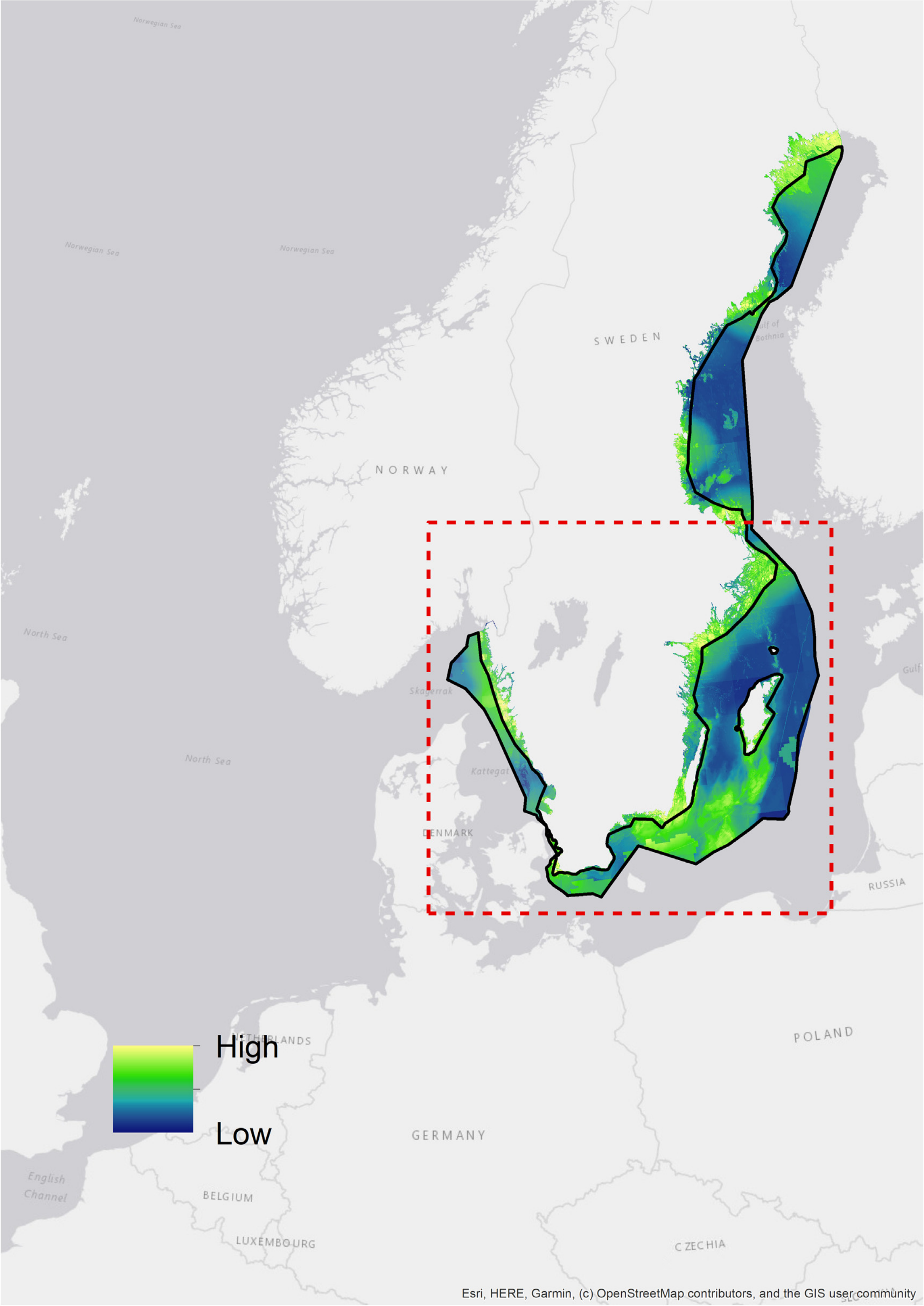
Swedish national MSP covers offshore water (122,095 km^2) beyond 1 nautical mile from the coastal baseline, including territorial water and the Exclusive Economic Zone (Fig. 1), while coastal waters are under the responsibility of local municipalities. Swedish marine spatial plans are guiding but not legally binding. However, the MSP ordinance designates the plans to be the principal decision support for future marine policy, consenting procedures, and local development plans.

The MSP proposals indicate the “most appropriate use of space” among shipping, fishing, energy, mineral mining (sand), defense, recreation, cultural values, and nature protection (Appendix A). Overlapping priorities indicate coexistence. In addition to priorities, the plan proposals also indicate “precaution areas” where other uses should be planned with particular caution and regard for sensitive environments.

2.2. Basic model and included components

The *Symphony* GIS-model is based on generic CIA principles (Halpern et al., 2008) where cumulative environmental impact is calculated as the sum of all impacts of all identified pressures on all selected ecosystem components in each pixel of the map. Human pressures are changes to the marine environment (physical, chemical, biological) caused by human activities, directly or indirectly. Ecosystem components are made up of habitats or populations based on distribution maps where the ecological value of each component is evaluated. The number and type of human pressures ($N = 37$; Table 1) and ecosystem components ($N = 33$; Table 2) were adapted to regional conditions in a selection process where lists based on previous work were reviewed and adjusted. First, a gross list of human pressures and ecosystem components was gathered from publications covering the North Sea and the Baltic Sea (Andersen et al., 2020; Korpinen et al., 2012). This list was then scrutinized with respect to ecological relevance and human activities, respectively, in Swedish waters, and with respect to Swedish political commitments, resulting in adjusted, regionally relevant lists. The marine pollution (plastic debris and microplastics) and invasive species pressures were later removed because of insufficient data access and difficulties with spatial representation, respectively. Ecosystem component lists differ slightly between NS and BS due to species distributions. See Appendix B for metadata.

The datasets underpinning each map represent data from 1989 to 2016, with most data from the last decade. Seasonal variations were not included. Only persistent or recurring pressures were included. The resulting *baseline* analyses therefore represent the current cumulative impact status in NS and BS, respectively.



Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community

Fig. 1. Geographical scope of this study. Solid lines frame the total Swedish national MSP area while the dotted red box indicates the parts of the area included in this study. The color legend shows the level of aggregation of ecosystem components, indicating where ecological values accumulate (yellow and green fields).

2.3. Data collection and assumptions

The collection of spatial data took place between 2016 and 2018. Preexisting and openly available data were gathered from a wide range of sources by multiple partners including academia, governmental agencies and consultancies. Data were reanalyzed through spatial modelling to produce individual maps for each human pressure and ecosystem component (Appendix B). The spatial resolution of the map grid was 250 × 250 m, although most input data were of lower resolution.

Table 1
Included pressures and their proportional contribution to cumulative environmental impact under current conditions (baseline), given for all waters and the parts covered by the MSP, in Swedish North Sea (NS) and Baltic Sea (BS).

Baseline results		Pressure	Contribution to cumulative impact (%)			
			Offshore waters (MSP-area)		All waters (coast included)	
Type	Category / sector		NS	BS	NS	BS
Pressures	Eutrophication	Phosphorous background	1.78	19.20	2.56	19.89
		Anoxia background	3.28	33.14	6.71	30.76
		Nitrogen background	10.29	10.62	11.72	10.86
	General pollution	Heavy metals background	3.01	9.43	2.60	8.64
		Oilspill wreck	0.70	<0.00	0.92	0.01
		Synthetic toxins background	12.21	14.74	10.55	13.98
		Toxic munition dump	1.57	0.78	1.08	0.67
		Heavy metals mine dump	0.28	0.36	0.28	0.31
	Shipping	Turbidity shipping	0.02	0.03	0.10	0.05
		Noise 2000 Hz shipping	0.04	0.04	0.05	0.04
		Oilspill shipping	2.16	1.51	1.98	1.55
		Noise 125 Hz shipping	10.46	6.43	10.33	7.00
	Coastal development	Synthetic toxins treatment plant	0.00	0.00	0.12	0.05
		Habitat loss dumping	0.00	0.00	0.06	0.01
		Habitat loss infrastructure	0.00	0.04	0.02	0.05
		Habitat loss coastal exploitation	0.00	0.00	0.95	0.47
	Recreation	Pollution boating	0.06	0.02	1.70	0.38
		Noise boating	0.03	0.01	1.09	0.26
		Bird hunt	0.05	0.04	0.73	0.17
	Fisheries	Abrasion bottom trawl	26.01	0.97	19.59	0.86
		Catch gillnet	0.58	0.41	0.71	0.50
		Turbidity bottom trawl	12.80	0.39	9.64	0.35
		Catch bottom trawl	13.60	0.60	10.16	0.53
		Catch pelagic trawl	0.24	0.26	0.26	0.23
	Industry	Synthetic toxins industry	0.00	0.00	0.35	0.07
		Synthetic toxins harbor	0.00	0.00	4.52	1.17
	Sand extraction	Turbidity sand extraction	0.00	0.01	0.00	0.01
		Habitat loss sand extraction	0.00	0.01	0.00	0.01
	Defense	Heavy metals military area	0.03	0.25	0.06	0.30
		Explosions Sound Exposure Level (SEL)	0.79	0.64	1.12	0.78
		Explosions peak	<0.00	0.04	<0.00	0.04
	Aquaculture	Habitat loss mussel farm	0.00	0.00	0.01	0.00
		Habitat loss fish farm	–	0.00	–	< 0.00
		Nutrients fish farm	–	0.00	–	< 0.00
	Energy	Disturbance wind power	0.00	0.01	0.00	0.01
		Noise 125 Hz wind power	0.00	<0.00	0.00	< 0.00
		Electromagnetic field	0.01	0.01	0.02	0.01
	TOTAL	**Sum of pressure contributions**	**100**	**100**	**100**	**100**
	Impact score	Average impact (score per pixel*)	2.13	2.09	2.08	1.98
Statistics		S.D.	0.76	0.70	0.99	0.79
		Minimum	0.2	0.38	0.09	0.05
		Maximum	5.51	7.11	17.90	15.22
	Area	km^2	9564	74,834	14,203	91,805
		* 1 pixel = 0.0625 km^2				

Resulting maps of human pressures and ecosystem components were normalized to a scale from 0 (no exposure/no value) to 100 (upper threshold representing highest exposure disregarding outliers). Human pressures data were not transformed prior to normalization, with the exception of data describing habitat loss from bottom trawling, which were log-transformed in accordance with the non-linear relationship between trawling intensity and effect on benthos (Lambert et al., 2014). This approach differs from other CIA studies where log-transformations were applied on human pressure data (Halpern et al., 2008). We believe that a general log-transformation of pressure data is not suitable within the context of MSP because it may enhance the relative impact from low-intensity pressures.

Ecosystem components representing habitat coverage and ecological functions were not transformed prior to normalization (0—100). In contrast, ecosystem components representing species abundance (*e.g.* cod and herring) were first transformed linearly from 0 to 100 to standardize the logarithmic effect, and then log-transformed. This method was considered necessary because abundance data of heavily fished species are patchy with outliers that otherwise diminish the value of areas utilized by more healthy populations. Porpoise, a species with spatially distinct populations of very different numbers, was normalized on population level in order to account for population-specific impacts.

The aggregation of ecosystem components across space, calculated as the mean value of all components per pixel, are shown in Fig. 1. This representation reflects areas of higher and lower ecological value, according to this analysis.

2.4. Spatial representation of data uncertainty

It is important for planners and other users to have an idea of the confidence in the underlying data. Marine data is sparse, particularly for ecosystem components, and all maps included in *Symphony* or any other CIA tool involve some level of modelling or interpolation to fill areas where field sampled data are missing. A multitude of different ecosystem components may enhance uncertainty and thus the confidence of the results. There are several ways to describe the uncertainty of CIA models (Halpern and Fujita, 2013; Stock and Micheli, 2016) from an analytical standpoint. To assist practitioners with an immediate overview of the confidence in ecological input-data in different areas we collated a raster of average confidence and a raster of data availability. This

Table 2
Included ecosystem components and how affected they are in terms of their proportional contribution to cumulative environmental impact under current conditions (baseline), given for all waters and the parts covered by the MSP, in Swedish North Sea (NS) and Baltic Sea (BS).

Baseline results		Ecosystem component	Contribution to cumulative impact (%)			
			Offshore water (MSP-area)		All water (coast included)	
Type	Category		NS	BS	NS	BS
Ecosystem components	Birds	Coastal birds	0.06	0.09	1.14	0.55
		Seabird coastal wintering	0.01	0.04	1.20	0.35
		Seabird offshore wintering	0.49	1.11	0.69	1.50
	Fish	Cod	12.22	12.11	11.84	11.69
		Herring	8.90	11.13	8.59	11.16
		Sprat	6.29	5.40	6.59	5.50
		Rivermouth fish	–	–	0.02	<0.00
	Fish functions	Fish spawning	13.25	4.98	11.14	5.10
		Eel migration	0.63	0.08	1.19	0.16
	Habitats	Plankton pelagic community	8.01	12.66	7.13	11.69
		Hard bottom photic	0.20	0.39	1.62	1.07
		Hard bottom aphotic	0.27	1.23	0.25	1.07
		Hard bottom deep	0.38	0.89	0.55	1.19
		Transport bottom photic	0.73	0.92	2.04	1.99
		Transport bottom aphotic	1.49	4.77	1.22	4.80
		Transport bottom deep	0.47	4.92	0.35	4.26
		Rough bottom photic	0.06	0.01	0.36	0.19
		Rough bottom aphotic	0.20	0.24	0.19	0.30
		Rough bottom deep	1.35	2.12	1.02	1.84
		Soft bottom photic	2.25	0.23	5.34	1.08
		Soft bottom aphotic	11.11	3.39	8.87	3.55
		Soft bottom deep	16.62	29.17	11.89	25.29
		Shoreline shallows	–	–	1.24	0.68
	Mammals	Porpoise North Sea population	8.16	–	7.73	–
		Porpoise Baltic population	–	2.40	–	2.31
		Porpoise Belt Sea population	1.76	0.18	1.61	0.21
		Harbor seal	4.95	0.12	5.58	0.21
		Grey seal	–	1.25	–	1.71
	Plants	Angiosperms (seagrass)	0.00	0.01	0.19	0.29
	Reef habitats	Deep reef	0.09	0.00	0.13	<0.00
		Artificial reef	0.02	0.13	0.04	0.12
		Mussel reef	0.02	0.02	0.25	0.15
		Haploops reef	<0,00	–	<0.00	<0.00
	TOTAL	**Sum of contributions**	**100**	**100**	**100**	**100**

was accomplished by producing individual confidence-maps for each ecosystem component, prior to use in the CIA. Predefined numerical data quality categories were used: 0 = no data value; 0.25 = interpolation; 0.5 = distribution model; 0.75 = accurate validated model; 1 = field measurement. These categories were assigned to every data pixel for every ecosystem component, based on assessment by the data provider for each specific ecosystem component. An index (0–1) of average confidence was then calculated for each pixel and represented to planners as a raster, superimposed on the results maps. Additionally, a raster with frequency of "no data" were provided. By this method, areas with high and low input-data uncertainty are easily distinguished, as well as areas with low data availability. Although the index only involves a small part of the combined model uncertainty, it provides a valuable spatial representation for the user.

2.5. Sensitivity matrix

We used expert judgement to develop a matrix representing ecosystem component sensitivity to each pressure (Appendix C). For two main reasons, preexisting sensitivity matrices (Korpinen et al., 2012; Andersen et al., 2017; HELCOM, 2018a) were not used. Firstly, the pressures and ecosystem components in Sweden did not fully match any previous CIA. Secondly, the question posed when collecting the sensitivity score must refer to a specified level of pressure intensity. For instance, high levels in the noise pressure data corresponds to a recurring sound exposure level of 150 dB re 1 μPa. This noise level intensity was thus communicated to the experts while assessing its effect on different ecosystem components, rather than simply asking how noise in general affects ecosystem components.

Carefully designed questionnaires with defined categories and assessment criteria (Table C3) were distributed to and answered by experts ($N = 34$); ecologists and managers with expertise on specific ecosystem components. Answers where the respondent acknowledged a low level of confidence were disregarded, and the mode value of the remaining responses was used to set the sensitivity scores. Where applicable, we compared these scores to published sensitivity scores (Andersen et al., 2017) for adjustments where deviations were substantial (>30%).

2.6. Analyzing future MSP scenarios

Two different MSP scenarios were evaluated with respect to environmental impact: *negotiated* plans and *eco-alternative* plans. *Negotiated* plans are the marine spatial plan proposals developed after extensive stakeholder dialogue (Fig. 2). *Eco-alternative* plans are closely related versions of the negotiated plans, but with more priority given to the safeguarding of ecological functions and the ambition for achieving good environmental status in accordance with the Marine Strategy Framework Directive 2008/56/EC (European Commission, 2008) of the European Union (Carneiro et al., 2019). The *negotiated* plans were further developed and proposed as main alternatives in the Swedish MSP process while the *eco-alternative* plans were only presented in the strategic environmental assessment of the MSP (Carneiro et al., 2019; SwAM, 2020). Because planning is prospective, each of the two MSP scenarios were compared to a *Business As Usual (BAU) scenario* for the year 2030. The *BAU scenario* represents a future situation with no implemented MSP, based on a simple projection from current industry trends (Table D.1).

MSP scenarios were analyzed through the following procedure: each plan was incorporated as a group of polygons, overlaying the human pressure maps (Appendix A). Each polygon represents a planning area where one or several uses, such as fishing or wind energy, have priority over the others (see Fig. 2). Additional pressures associated to new activities were added where MSP polygons indicated their priority. The amount of added pressure in each such polygon was based on the average pressure intensity of pre-existing areas with the same use (*e.g.*

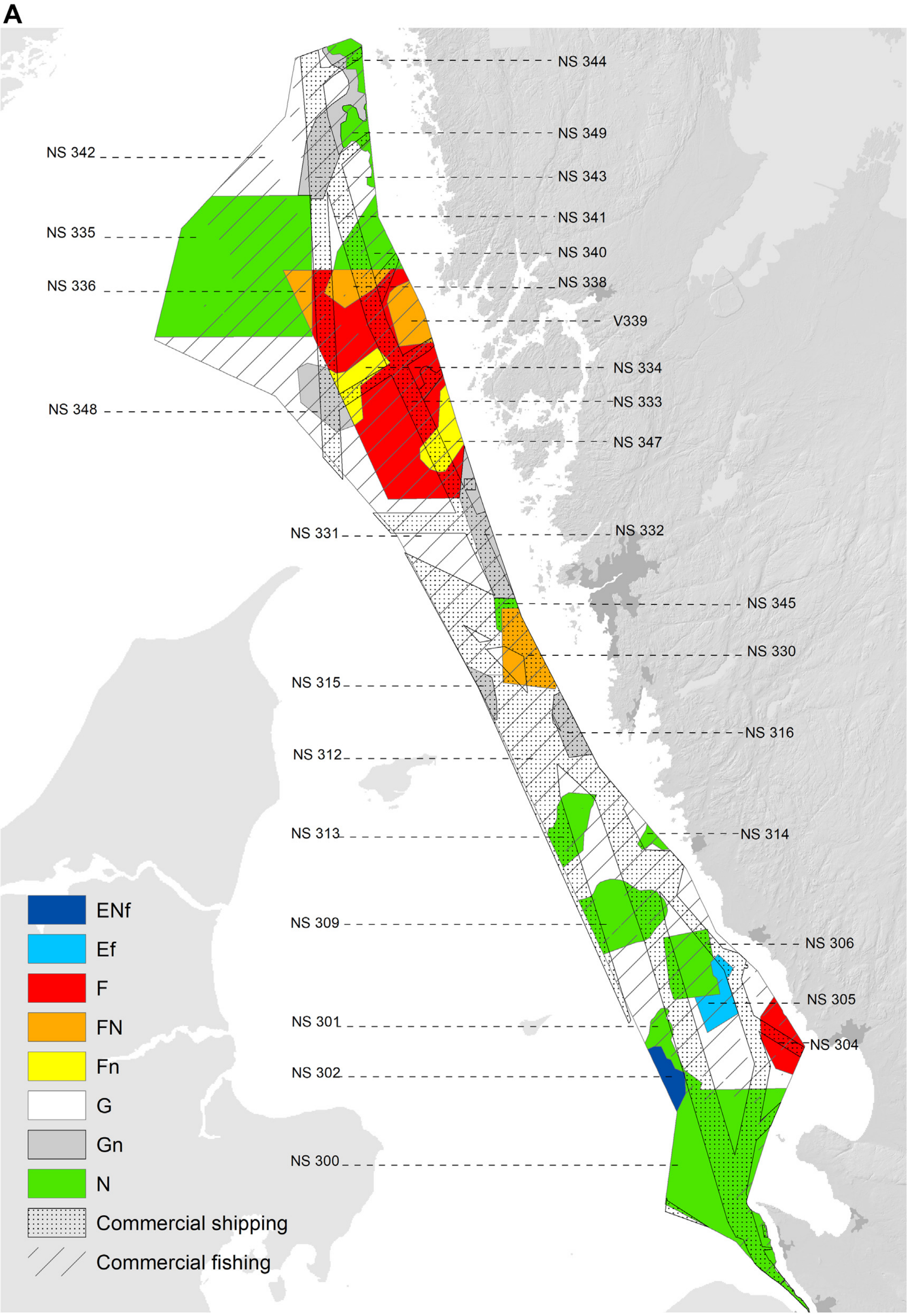


Fig. 2. MSP for *negotiated* plans as of March 2019 for Swedish (a) North Sea (NS) and (b) Baltic Sea (BS) with inlet showing Öresund. Legends indicate priorities in terms of "most appropriate use of space". E = Energy, N=Conservation/marine protection, F = Military defense, G = Multi-use/no priority, f = precaution (military defense), n = precaution (sensitive environment). Information on individual polygons and reference to *eco-alternative* plans are provided in Appendix A.

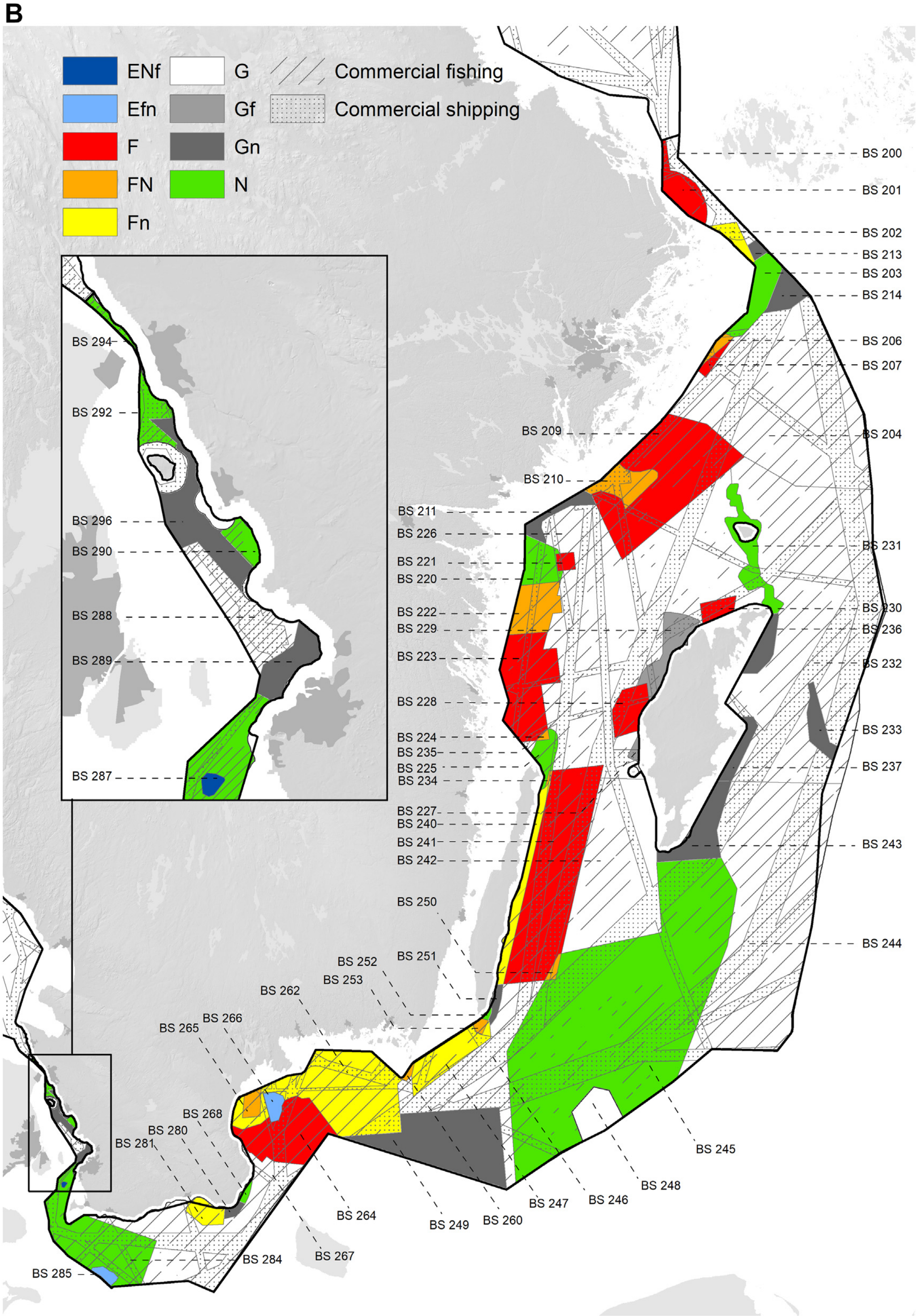


Fig. 2 (*continued*).

existing wind farms). The resulting increase of cumulative impact varies because different areas have different ecosystem components. Likewise, pressure scores were removed or lowered within polygons where MSP polygons indicated priority for uses incompatible with current activities. In the case of displacement of activities, such as trawl fishing in wind farms, these were rectified by removing pressure from the incompatible polygon and redistributing the same amount in neighboring polygons (see Table D.2).

Precaution areas, where the MSP indicated that human activities should adopt precautionary measures to safeguard sensitive environments, were simulated through altering the sensitivity matrix. In the resulting "precaution matrix", the sensitivity of particular ecosystem components to particular pressures were reduced in accordance with expected mitigation effects (Table D.3). For example, if the MSP provided guidance relative to the use of bycatch-reducing fishing gear within a precaution area, then the sensitivity of birds and mammals to gill net fishing was reduced in the precaution matrix, while the sensitivity for targeted fish was unchanged. This way, pressure-specific mitigation measures with effect only on selected ecosystem components could be evaluated. MSP guidance also includes specific precaution areas with respect to military defense. In such areas human activities should seek to avoid interference with military interests. Since these guidelines have no direct bearing on the environment it was not included as part of the analysis.

With the MSP scenarios incorporated as described, cumulative impact scores were calculated using the same model as for the *baseline* analysis (current status of cumulative impact). The evaluation of the *negotiated* and *eco-alternative* plans involved subtracting the results of the *BAU scenario* (2030) from each of the two MSP scenarios. The applied analytic framework is depicted in Fig. 3.

For the *Symphony*-tool or any other CIA tool to be valuable over time it is necessary for the tool, as well as the analytic framework, to be flexible. Pressures and even ecosystem components may need to be introduced, exchanged, or removed. New scientific findings will also require updates and sometimes even immediate adjustments. This is no problem if assessors keep track of changes when comparisons are done. The scenario component presented here also facilitates the quick introductions of new pressures, such as a new oil spill or the introduction of invasive species. Details on the geographical extent, dispersal, and sensitivity scores are obviously needed. The simplicity of the CIA method makes most updates and developments manageable.

3. Results

3.1. Baseline results

The resulting heat-map of *baseline* cumulative impact (Fig. 4) indicates high spatial variation, with patches of both high and low impact across the Swedish waters. These pre-planning baseline results can be valuable for planners, indicating where high pressure currently overlaps with ecologically valuable and sensitive areas. In the Swedish MSP, environmental precaution areas were designated using criteria including both heavy cumulative impact and vulnerable marine ecosystems (*i.e.* low impact and high or susceptible natural values).

When aggregating results, fisheries (53%), pollution (18%), eutrophication (15%), and shipping (13%) clearly dominate the current impact in the NS. In the BS, the pressures contributing the most to cummulative environmental impact are eutrophication (63%), pollution (25%), and shipping (8%) (Table 1).

Even if impacts from coastal activities are only evident close to shore, it should be noted that several of these sources also contribute to the general pollution and eutrophication levels in offshore waters over time. Some of the hypoxic areas in the BS are actually naturally occurring, though there has also been a large degree of expansion of hypoxic bottoms from eutrophication-related pollution in the past decades (Diaz and Rosenberg, 2008).

3.2. Comparison of future scenarios

Considering the modelled changes in human uses, caused by the MSP in each basin, the *negotiated* plans would reduce cumulative environmental impact by 3% in the NS, compared to *BAU*, but have no net effect (< 1%) in the BS. The *eco-alternative* plans would generate a much greater (6%) impact reduction in the NS while only a 1% reduction in the BS (in terms of impact scores the net reductions are rather similar between NS (26900) and BS (21200), but the total number of impact scores are higher in the BS (2908600) than the NS (467700) mainly because of its greater size). These results may give planners a rough overview of the environmental performance of each MSP alternative, at the sea basin level.

The simulations also demonstrate changes and redistributions of cumulative environmental impact across space. These differences between *BAU* and the two MSP scenarios, as shown in Fig. 5, provide planners with a valuable overview of where MSP may relieve or intensify environmental impacts. For example, Fig. 5 clearly shows how the *negotiated* plan for NS can drastically reduce impact in certain areas (designated for wind power and marine conservation) while surrounding areas may experience little change and even increases (due to relocation of fishing pressures). Figs. 6 and 7 further exemplify how CIA analyses can support planners by illustrating the details of MSP-related change for any given area. In NS, the *negotiated* plan reduces environmental impact from trawl fishing, to the benefit of soft bottom

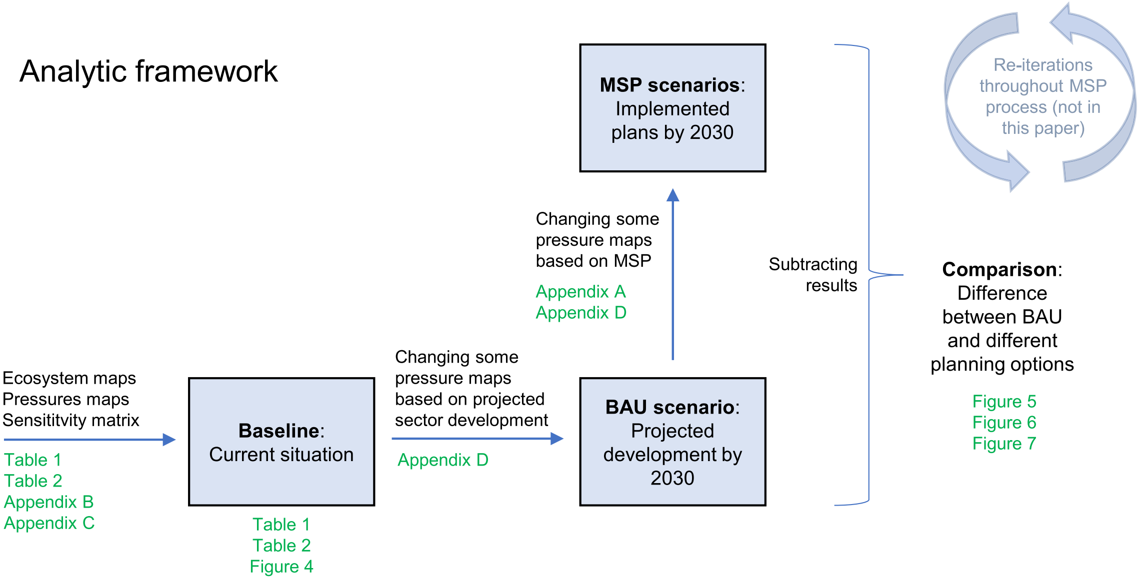


Fig. 3. Analytic framework where boxes indicate CIA analyses and arrows denote key assumptions and procedures for each analysis. Reference to tables, figures and appendices in this paper are provided for orientation.

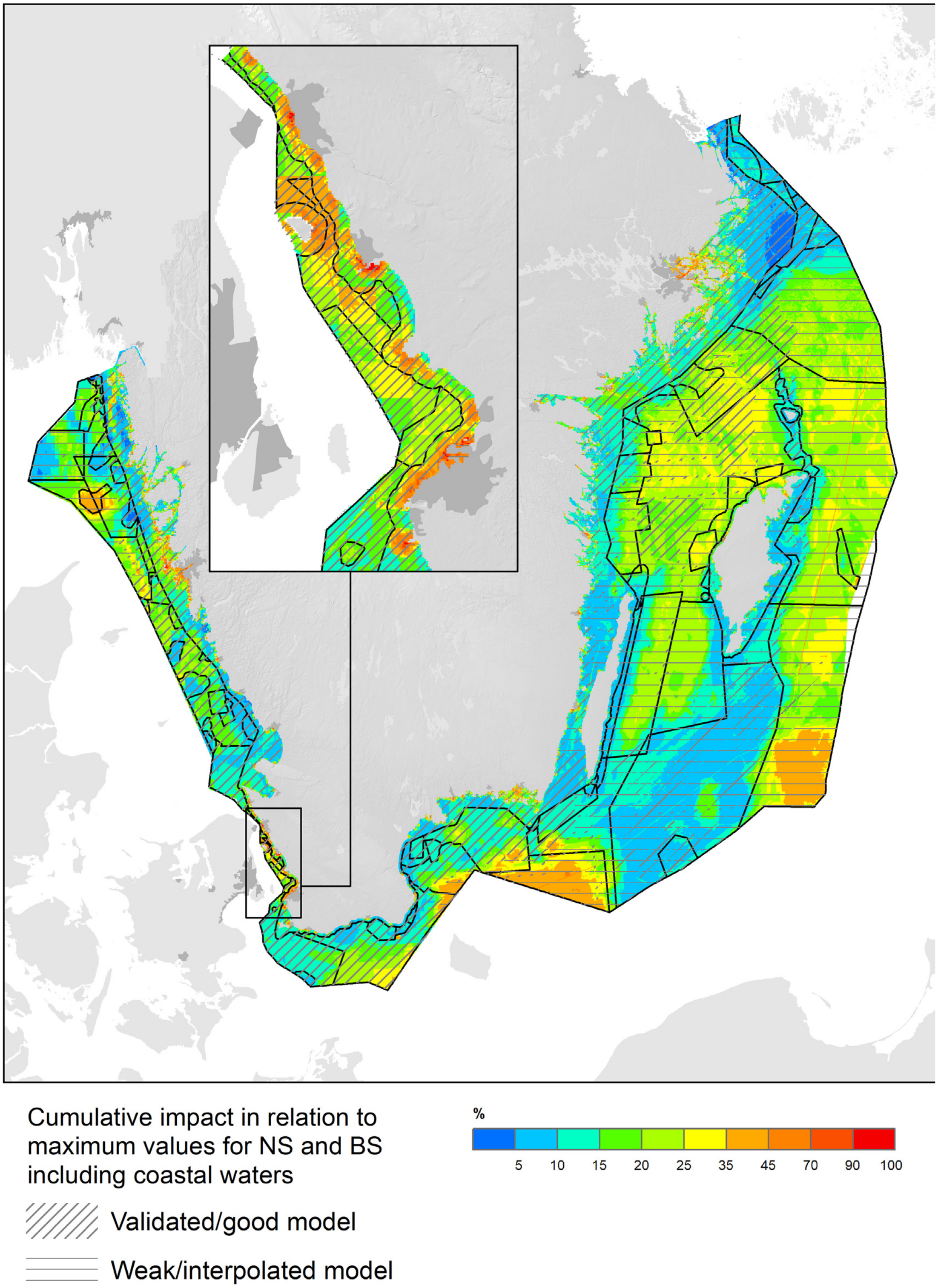


Fig. 4. Baseline cumulative impact across parts of Swedish North Sea (NS) and Baltic Sea (BS). The heat map shows the spatial variation of impact scores, at a resolution of 250 m, before MSP is implemented. The color ramp is scaled by percentiles from the lowest to the highest impact score for each sea basin (NS and BS), including coastal waters. Overlay polygons represent MSP zonation (Fig. 2). The overlay pattern indicates the average confidence level of the ecosystem component data layers.

habitats and fish spawning (Fig. 6B). The corresponding additional impacts from offshore wind power (Fig. 6A), caused by the same MSP scenario, is 60 times smaller than the decreases of trawl fishing impacts and thus insignificant on a sea basin level. Locally, at specific wind power areas, the small impact increase may be more relevant, namely because of effects on seabirds (Fig. 6A).

For the BS, the *negotiated* plan implies a shift of impact from pressures of bottom trawling and military exercises to sand extraction and wind power, to the benefit of fish and soft bottom habitats and at the expense of seabirds and transport (sand) bottom habitats (Fig. 6 C-D). Impact reductions are approximately twice as high as the increases.

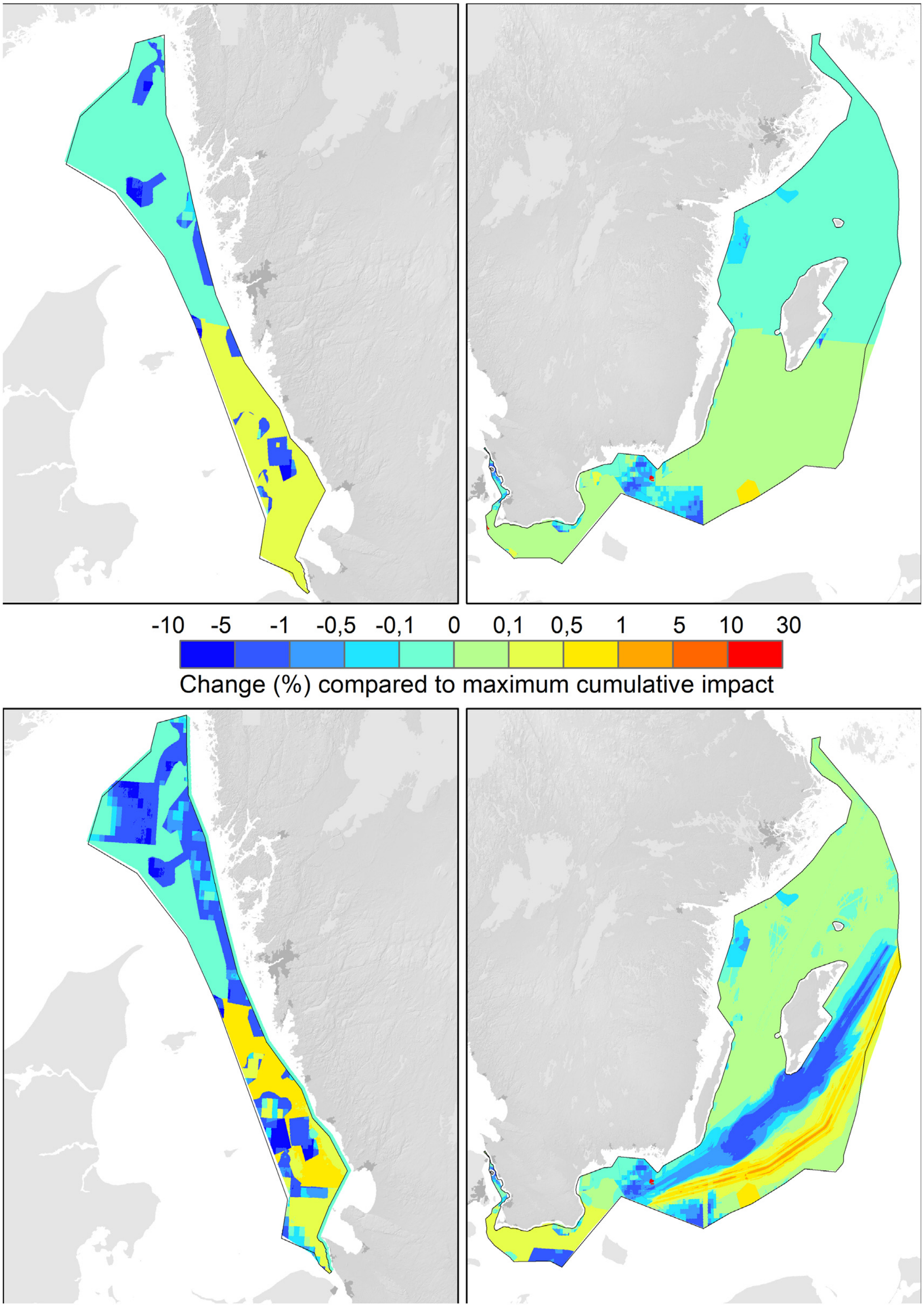


Fig. 5. The change in cumulative impact after implemented MSP for scenarios *negotiated* plans (upper panel) and *eco-alternative* plans (lower panel) in comparison with *BAU scenario* (2030). Colors indicate the level of change (decrease/increase) in cumulative impact as the percentage of the maximum impact in each sea basin (left: NS; right: BS).

The corresponding MSP induced changes for the *eco-alternative* plans, which include more wind power and environmental precaution in the NS, and a major relocation of shipping through the BS, are shown in Fig. 7. As an illustrative example, by studying impact increases and reductions from shipping in Fig. 7C and D, respectively, it is clear that the net effect of relocating the ship route (see Fig. 5) would mean reduced impact (*i.e.* by 15,500 impact scores). At sea basin level this reduction corresponds to about 6% of the total calculated impact contribution from shipping. Locally, the change could be important, in particular for those ecosystem components most sensitive to shipping-related pressures.

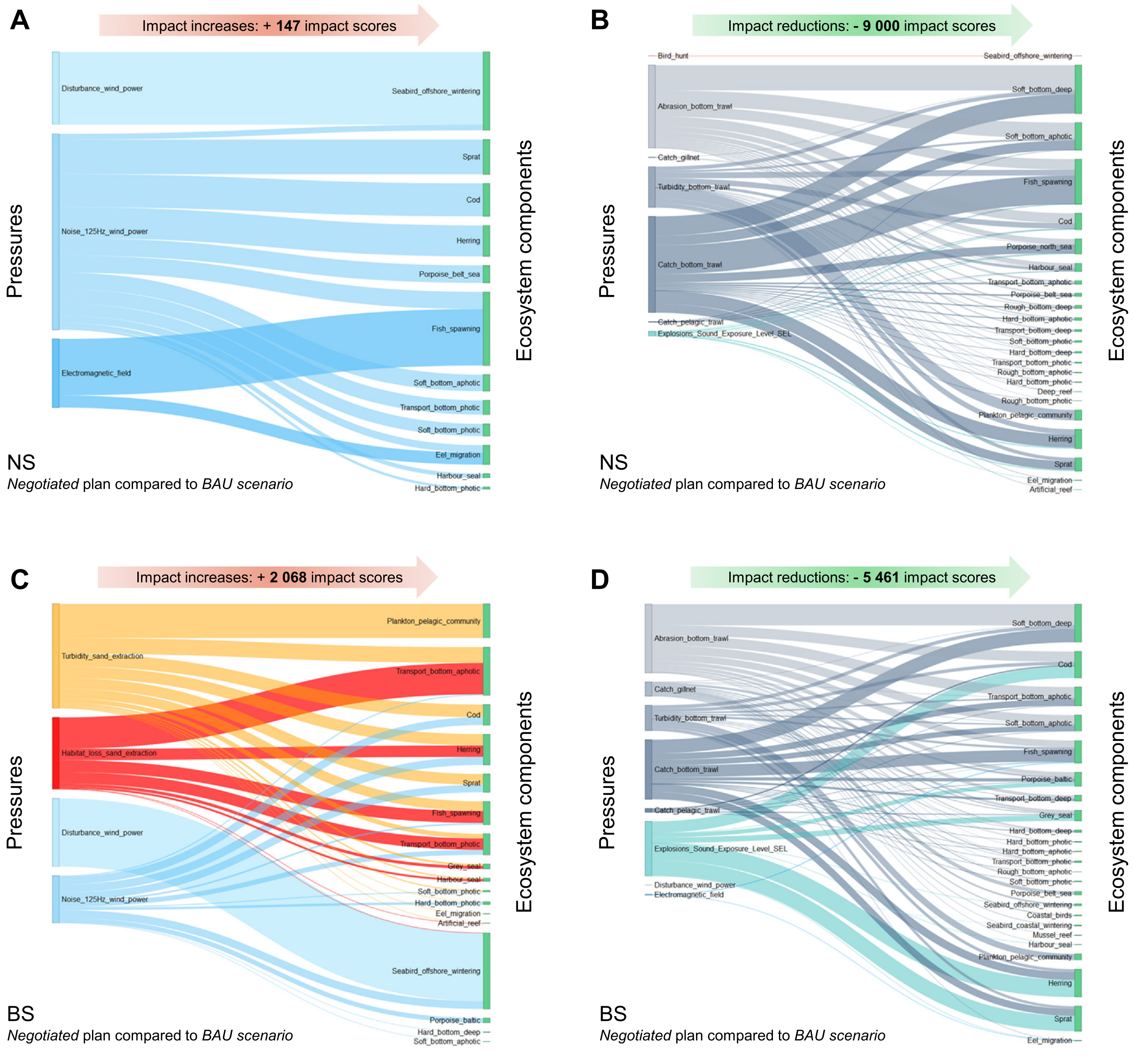


Fig. 6. MSP-related change in environmental impact for the *negotiated* plan scenarios compared to *BAU scenario* (2030), for the Swedish North Sea (NS, A-B) and Baltic Sea (BS, C-D). The diagrams illustrate how implemented MSP can be expected to *increase* (A, C) and *reduce* (B, D) environmental impact. The width of each flow between pressures (left) and ecosystem components (right) indicates the relative magnitude of change, calculated as the proportion of the total increase/reduction of impact scores (total number of increased or reduced scores are given at top of each diagram). The following observations can be made relative to the changes in impact scores between the two diagrams: for NS, impact reductions (B) are 60 times greater than the increases (A); for BS, impact reductions (D) are about twice as great as the increases (C). This means that, for both NS and BS, the net effect of MSP is a reduced environmental impact. The full model total impact scores for the *BAU scenarios* are 467,700 for NS and 2,908,600 for BS (note that BS has a much larger geographical area).

4. Discussion

In essence, the application of CIA in MSP visualizes the complexities of how multiple pressures from different activities affect marine ecosystems and how this impact can be altered by different planning solutions. Moreover, the compilation and standardization of open source marine data is an asset for both planners and stakeholders (Hodgson et al., 2019). These benefits are however accompanied by a range of challenges associated with the model's shortcomings, assumptions, and uncertainties.

4.1. Cumulative impact as a baseline for ecosystem-based MSP

The baseline results provide holistic views of the current state of environmental impacts in the two sea basins. Results indicate that the dominating impact-driver in the NS is trawl fishing, followed by pollution, eutrophication, and shipping. In the BS, the main drivers are eutrophication, pollution, and to a lesser degree shipping. This conforms with previous pressure-specific studies (Fleming-Lehtinen et al., 2015; Gascuel et al., 2016; Pommer et al., 2016). Previous attempts to validate the CIA method show a significant correlation between high impact and low environmental status (Andersen et al., 2015). It is, however, noted that baseline results from the *Symphony*-tool (this study) only partially concur with the parallel CIA for the whole Baltic Sea region published by the Helsinki Commission (HELCOM, 2018b). Differences are due to the HELCOM study having a different selection of source data, which do not cover the entirety of Swedish waters. Major differences are easily identified: for example, there is a lower level of detail where pressures are grouped; HELCOM includes a proxy for invasive species (not included in the *Symphony*-tool);

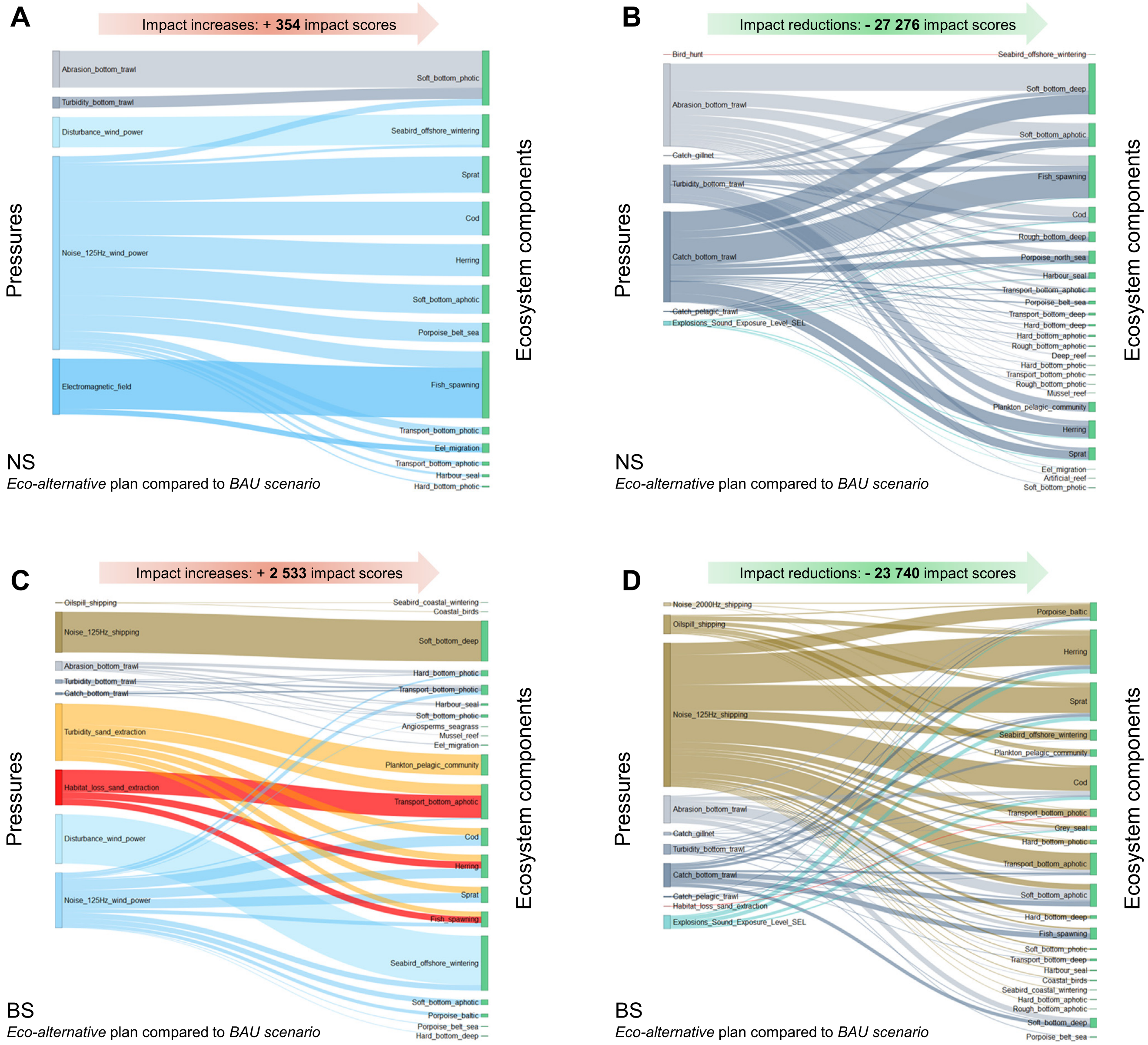


Fig. 7. MSP-related changes in environmental impact for the *eco-alternative* plan scenarios compared to *BAU scenario*, for the Swedish North Sea NS (A-B) and Baltic Sea BS (C-D). The diagrams illustrate how implemented MSP can be expected to *increase* (A, C) and *reduce* (B, D) environmental impact. The width of each flow between pressures (left) and ecosystem components (right) indicates the relative magnitude of change, calculated as the proportion of the total increase/reduction of impact scores (the total number of increased or reduced scores are given at top of each diagram). Considering the total changes of impact scores, the reductions are far greater than increases, indicating that *eco-alternative* plans would mean lower environmental impact in both NS and BS.

and considers hypoxic areas as an ecosystem component (while hypoxia is considered a human pressure in the *Symphony*-tool). While these differences can be identified and explained, too large deviations between different CIAs in the same region may be problematic for the general acceptance of CIA-based tools. It is therefore important to strive towards methodological conformity (Judd et al., 2015; Korpinen and Andersen, 2016; Willsteed et al., 2018). As highlighted by Stelzenmüller et al. (2020), it is also important to allow for methodological differences related to the purpose of the chosen method, where CIA tools for marine spatial planning serve different purposes than cumulative assessments for regional policy advice, which may require bespoke source data.

In the Swedish example provided here, marine planners used the baseline results to early identify areas where MSP guidance for environmental precaution were particularly important and to understand which human activities were already contributing to a greater impact in any given area.

4.2. CIA scenarios for ecosystem-based MSP

Scenario-based CIA enables planners and stakeholders to transparently compare different MSP options with respect to environmental impact. In the Swedish case, this was used both for evaluating expected effectiveness of precautionary measures in the planning and for comparing different locations of new activities. Scenario analyses were also a fundamental pillar of the Strategic Environmental Assessment of the MSP proposals. At the local (polygon) level, such comparisons sometimes revealed significant differences between alternatives, as demonstrated in Fig. 5.

Another insight was that even a more stringent ecosystem-based MSP would probably do little to relieve impact of the dominating pressures on the BS, as they relate to emissions from land (runoff, point source pollution and atmospheric emissions). However, MSP may still make an important contribution to improving the environmental condition by limiting the cumulative impact from additional pressures on sensitive species and habitats in particular areas. It should also be noted that neither the effects of historical pressure from fishing in the Baltic Sea, nor food web interactions are covered by the analysis.

The results provided here for NS, where trawl fishing and (to a lesser degree) shipping are major contributors to environmental degradation, indicate that the *negotiated* plan provides a slight improvement, while the *eco-alternative* plan allows for substantial impact reductions. The Swedish marine plan proposals submitted in December, 2019, which are more similar to the *negotiated* plans (SwAM, 2020), show that MSP implies a compromise among many interests: the ambition of ecosystem-based MSP may, in practice, stop at the level of avoiding additional environmental impact. Whether or not such a level of ambition fulfills the requirements of the ecosystem-based approach to MSP depends on the status and the functioning of the ecosystems in each area (Douvere, 2008).

MSP is a political process and decision-makers often require that complex scientific information be synthesized and presented in ways that are easy to grasp for non-specialists. CIA tools such as the *Symphony*-tool fulfil such requirement, in particular with respect to how different policy scenarios and planning decisions affect ecosystems. In doing so, they play a central role in the practical application of ecosystem-based MSP, by enabling a broader group of practitioners and decision-makers to engage with often very disparate and complex information. The transition to ecosystem-based management across all maritime sectors remains, despite MSP and the novel approaches accompanying it, a lengthy process, though. MSP is but one among many different legal and policy instruments, and is often implemented through those other, sector-specific, instruments. It is mostly through gradual shifts in practice and cross-sectorial negotiations, involving in particular fishing and shipping, that MSP will operate that transition.

4.3. Transboundary CIA

Despite the holistic aspiration of CIA, each application of the method is delimited by its geographical scope. Sovereign nations plan their own waters, even when instructed by a common legal or policy framework, such as the EU maritime spatial planning directive (European Commission, 2014). This is the reason that the application of the *Symphony* tool presented here has been confined to the Swedish MSP area, even though marine ecosystems have no such borders. But transboundary dialogues are important components of any MSP process and environmental impacts are typically core issues for consultation, not least because of the Espoo convention on environmental impact assessment in a transboundary context, with its general obligation of states to notify and consult each other on projects and plans that may cause significant environmental impact across borders (United Nations, 1991). Multiple CIA have been conducted in the North Sea and Baltic Sea region (Andersen et al., 2020; Korpinen and Andersen, 2016) and several tools or studies have recently been developed for explicit support to MSP. This includes transboundary CIA work within the Pan Baltic Scope (Bergström et al., 2019), founded on both the Swedish *Symphony*-tool and the Baltic Sea Impact Index by the Helsinki Commission (HELCOM, 2018b). Future MSP processes, in this part of the world and elsewhere, will have opportunities to co-develop and use transboundary CIA tools, even if the planning remains under national jurisdiction.

4.4. Limitations of the applied method

While CIA facilitates for planners and assessors to conduct ecosystem-based MSP, it also implies a range of challenges. The apparent power of the method calls for careful consideration and communication of its limitations and underlying assumptions.

The basic CIA model involves uncertainties at multiple levels (Halpern and Fujita, 2013; Stock and Micheli, 2016). First and foremost, marine environmental data are sparse and maps representing ecosystem components are based on models with a varying, but always significant, degree of uncertainty. Here, the way of illustrating average in-data confidence in a spatial dimension has added value for planners who can get a visual representation of the areas with less reliable input data (Fig. 4). The CIA model also has ecological limitations (namely food-web interactions and connectivity) and the selection of pressures and ecosystem components implicate bias. Moreover, ecosystem components are typically based on the current or recent state of the environment and CIA therefore fails to account for historical losses, for example already reduced fish abundances lead to lower impact scores of fisheries in certain areas. In the examples described in this paper, that is particularly explicit for the BS, where impact contributions from current fisheries are minuscule compared to the previous very large stock declines (Gascuel et al., 2016). Other issues concern temporal mismatches by not accounting for seasonality, as well as the assumption of simply additive effects despite that response to multiple pressures may also be synergistic or even antagonistic, and dose-response relationships are often not linear (Cabral et al., 2019; Hodgson et al., 2019).

The scenario analyses demonstrated in this paper are new features to the CIA methodology. Scenarios imply a full range of new assumptions and uncertainties. For instance, it is uncertain how the MSP guidelines will be implemented in practice. The assumptions in Table D2-D3 are approximations, but can have a strong influence on results. Assumptions related to future sector developments, used for setting the *BAU scenario* (2030), are even more uncertain, but also have less influence on the results, since all scenarios that are compared are based on the same projections. This all means that results presented in this paper must be interpreted with emphasis on relative measures and orders of magnitude rather than on absolute values.

As shown by Hodgson and Halpern (2019), no single tool can resolve all questions by itself and therefore combinations are needed. CIA applications such as the *Symphony*-tool should preferably be used for decision support at a strategic level, not replacing mechanisms for local impact assessment and conservation measures.

4.5. Methodological contributions

The main methodological contributions from this paper may be listed as:

- Incorporation of scenario analyses in CIA enables transparent comparison of expected environmental performance between different planning options and management measures (Fig. 3 and Figs. 5-7).
- By adjusting scores in the sensitivity matrix CIA can simulate the tentative effects of specific mitigation measures that target only certain ecosystem components, such as selective fishing gear that keeps affecting target species but reduces the effect on by-catch (Table D3).
- Superimposed maps of average input-data confidence, based on spatially represented confidence levels for each ecosystem component, provide a simple but comprehensible way of presenting data uncertainty to CIA practitioners (Fig. 4).

5. Conclusions

This paper exemplifies how CIA can support ecosystem-based MSP in practice, and it provides methodological advancements to traditional CIA.

Swedish MSP has utilized the *Symphony*-tool in support of the MSP process. Among planners and stakeholders, the greatest benefits from the use of the *Symphony*-tool were in terms of a better understanding of (i) how cumulative impact varies across space; (ii) how environmental impact from different sectors and activities differs by orders of magnitude; and (iii) how environmental impact of different planning solutions can be evaluated throughout the planning process.

The use of CIA in MSP may improve the capacity of planners to address environmental impacts from a spatial perspective and may increase the transparency of planning decisions during stakeholder consultations.

This works in favor of the ecosystem approach, which should underpin MSP, and enables policymakers to better balance the benefits and consequences of plans and policies prior to implementation.

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CRediT authorship contribution statement

Linus Hammar: Conceptualization, Funding acquisition, Methodology, Data curation, Formal analysis, Validation, Project administration, Writing - original draft, Writing - review & editing. **Sverker Molander:** Conceptualization, Supervision, Writing - original draft, Writing - review & editing. **Jonas Pålsson:** Formal analysis, Validation, Project administration, Writing - original draft. **Jan Schmidtbauer Crona:** Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing. **Gonçalo Carneiro:** Formal analysis, Writing - original draft. **Thomas Johansson:** Conceptualization, Funding acquisition, Supervision, Project administration. **Duncan Hume:** Methodology, Data curation, Formal analysis, Validation, Writing - original draft, Writing - review & editing. **Gustav Kågesten:** Conceptualization, Methodology, Data curation, Formal analysis, Writing - original draft, Writing - review & editing. **Daniel Mattsson:** Data curation, Visualization. **Oscar Törnqvist:** Data curation, Visualization. **Lovisa Zillén:** Conceptualization, Funding acquisition, Supervision, Project administration. **Martin Mattsson:** Data curation, Software, Formal analysis, Visualization, Validation. **Ulf Bergström:** Methodology, Data curation, Writing - original draft, Writing - review & editing. **Diana Perry:** Methodology, Writing - original draft, Writing - review & editing. **Chris Caldow:** Conceptualization, Methodology, Writing - original draft. **Jesper H. Andersen:** Supervision, Writing - original draft, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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