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Research article

Incorporating ecosystem component interactions and indirect effects in cumulative impact assessment models

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ABSTRACT

The cumulative impact of anthropogenic pressures on coastal seas is important to consider for a strategic and sustainable management of marine ecosystems. We aim to demonstrate how, and to what extent, incorporating interactions among ecosystem components (species and habitats) and indirect effects of pressures through other ecosystem components can develop existing cumulative impact assessment (CIA) models. A Swedish case study area was selected to test a simplified version of the extended regional *Symphony* CIA model. Five pollution- and climate-driven pressures acting on three trophically connected ecosystem components, i.e. cod, herring and plankton species/organism groups, were used. In addition, we conducted a systematic review of the scientific literature to determine the impact weight scores for an advancement of the method. The results from the development of CIA models clearly indicate the importance of introducing ecosystem component interactions and indirect effects into CIA models. The total cumulative impact increased by 117 % in the test area, but even more importantly, the development of the model resulted in a spatially more detailed outcome with a greater spatial variability in the magnitude of the total cumulative impact. New areas were highlighted that are under pressure compared to the original model. Thus, the development of the model captures cumulative impacts that would otherwise be overlooked if ecosystem component interactions and indirect effects were ignored. These types of changes to CIA models are required to increase the predictive power and ecological relevance to accommodate solid holistic and ecosystem-based marine management.

1. Introduction

Earth's marine ecosystems are presently experiencing fundamental changes. The ever-increasing pressures from climate change, pollution and overexploitation of natural resources modifies the marine environment in many ways which, for instance, lead to decreased population sizes, loss of biodiversity, habitat degradation and reduced ecological resilience. These changes act to degrade vital ecosystem functions, particularly in coastal areas where the majority of human populations reside and the dependence on sustained ecosystem functions and resources is high. As a consequence, marine conservation managers and policy makers are frequently called upon to create integrated, holistic ecosystem-based spatial management tools to safeguard ecosystem and socio-ecological resilience and ensure sustainable development.

Ideally, concepts to understand the complexity of ecosystem interactions should be incorporated into coherent environmental management strategies. Halpern et al. (2008) introduced a semi-quantitative spatially explicit modelling methodology to map and assess cumulative human-induced impacts in the marine environment from local to global scales; a method that resembled previous work by Landis and Wiegers (1997). Their pioneering studies initiated a new way of quantifying the total impact of different anthropogenic pressures on all components of an ecosystem (species and habitats) in a given area. These multi-pressure models, known as cumulative impact assessment (CIA) models, are now

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well-established and have been used in management and strategic planning in several marine regions, such as the Baltic Sea (Hammar et al., 2020), the North Sea (Depellegrin et al., 2021), the Western Indian Ocean (WIO Symphony, 2023), and within research studies targeting the Arctic Ocean, the Mediterranean Sea and Black Sea (e.g. Andersen et al., 2017; Micheli et al., 2013). In the Baltic Sea region, Sweden utilizes the CIA model for ecosystem-based marine spatial planning. In addition, the Baltic Marine Environment Protection Commission, also known as the Helsinki Commission (HELCOM), uses the method in context of status assessments to illustrate cumulative environmental impacts on the marine environment in the Baltic Sea region (e.g. HELCOM HOLAS, 2023).

However, in order to facilitate the practical application as a management tool, CIA models are often simplified and do not necessarily include natural interactions among ecosystem components or indirect effects of pressures through intermediate ecosystem components. When ecosystem components are included as habitats or ecosystems, the model implicitly accounts for food web interactions and short-range connectivity. This is how the original CIA models are designed. But the problem grows in CIA applications where individual species or taxa are included as ecosystem components, which is often the case in local or regional CIA models to give emphasis to certain valuable species. In these cases, the CIA models do not account for trophic interactions between the different components. Recent studies have shown that overlooking interactions between ecosystem components may lead to underestimation of the cumulative impact of anthropogenic pressures on marine ecosystems (Beauchesne et al., 2021). For example, planktivorous herring are fully dependent on zooplankton for prey and any deleterious effects on the abundance or biochemical quality (due to e.g. climate change or pollution) of zooplankton will induce trickle-down effects on herring. These types of indirect effects have been observed in the Baltic Sea, where increased rainfall and lack of saline water intrusion from the North Sea since the 1980's have indirectly affected herring through direct effects on the reproduction and maturation of a copepod species that constitutes the primary prey for herring. This has forced herring to revert to less favourable prey, with serious implications for their growth and development (Möllmann et al., 2003). Another example concerns the loss of seagrass habitats occurring in coastal areas worldwide (Waycott et al., 2009). In cold-temperate coastal regions, increased eutrophication (due to a surplus of nutrients) and food-web cascades (due to overexploitation of apex predators) are consider major reasons behind an excessive overgrowth by filamentous algae in seagrass meadows (Baden et al., 2012; Moksnes et al., 2008), which has led to widespread seagrass regressions (e.g. Baden et al., 2003; Green et al., 2021; Turschwell et al., 2021). These negative changes have, for instance, made many coastal areas less suitable as nurseries for various fish species (Lefcheck et al., 2019). When individual taxa, such as Atlantic cod and harbor seal, are used as ecosystem components together with habitat-level ecosystem components such as seagrass meadows, the trophic effects are not accounted for and the cumulative impacts will likely be underestimated.

Most coastal ecosystems are complex by nature. Dynamic hydrography drives the temporal and spatial variability of native populations, and topographically complex coastlines form varying dynamics of habitats and links among habitats. Thus, trophic dependencies and interactions are particularly complicated in these environments and simple solutions for management of marine resources often fall short. Therefore, it is especially challenging and urgent in coastal management and conservation planning to understand how to incorporate more detailed information on the influence of climate change in conjunction with other pressures (Santos et al., 2020; Wåhlström et al., 2022). It is important to take into account spatial and temporal shifts in interactions among ecosystem components (hereafter called ecosystem component interactions, ECIs) and any indirect effects of pressures on specific ecosystem components through intermediate ecosystem components (Korpinen and Andersen, 2016). ECIs occur when species interact between trophic levels (trophic interactions) or when species interact with a habitat, such as reef-building organisms creating a new habitat or existing habitats providing organisms with shelter and food (such as seagrass meadows). Indirect effects occur when specific pressures or environmental changes affect organisms or habitats through other organisms or habitats on which they depend. For example, climate change effects on zooplankton can subsequently affect herring populations by altering prey availability. Besides acting as conveyors of indirect effects, ECIs themselves shape ecosystem resilience and should be considered as equally important when deciding on management initiatives (Urban et al., 2017). When ECIs are strong, the risk of indirect effects increases, and effects of pressures may therefore be enhanced or unanticipated.

The main aim of this study was to investigate how and to what extent the incorporation of ECIs and indirect effects on ecosystem components can be incorporated into CIA models. We tested these changes on a subset of the Swedish CIA tool *Symphony* (Hammar et al., 2020), which is based on the previous work by Halpern et al. (2008). *Symphony* calculates the spatial cumulative impact of multiple pressures on multiple ecosystem components through impact weights describing how each ecosystem component responds to a specific pressure.

The *Symphony* tool offers Swedish managers and planners a practical tool to evaluate and compare different options for marine spatial planning according to the EU marine strategy framework directive (MSFD; 2014/89/EU). The directive on Maritime Spatial Planning (MSP) (2014/89/EU) under the European Union's Integrated Maritime Policy (IMP) states the requirement of an integrated planning and management framework to address the combined impact of multiple pressures on coastal resources in regional waters of all member countries. The directive implies that all EU states must develop such a management framework to implement maritime spatial planning. The regional CIA tool used in our study is specifically designed to meet these EU requirements by considering the impact of multiple pressures on many different coastal resources (Hammar et al., 2020). The tool is operationalized and used in Swedish marine spatial planning in offshore areas since 2018 (Hammar et al., 2018), with the code and data publicly available (SWaM, 2022).

2. Methods

In the present study, we chose three climate change pressures, i.e. temperature, ocean acidification (OA) and salinity, and two environmental pollution pressures, i.e. oil from shipping and benthic heavy metals (metal background) from *Symphony*. These pressures were imposed on a simplified food chain of three ecosystem components from *Symphony*: plankton community, herring and cod. Based on our systematic review of the scientific literature, we also propose new impact weight values for ECIs and direct effects of climate change and additional pollutants.

2.1. Basic cumulative impact model

The pre-existing regional-wide spatial cumulative impact assessment (CIA) model, *Symphony* (Hammar et al., 2020), is based on grids with a pixel resolution of 250 × 250 m, and includes 32 ecosystem components (species, communities and habitats), 41 pressures (e.g. fishing, eutrophication, shipping), and impact weight values for all impacts of pressures on all ecosystem components (Fig. 1a; Hammar et al., 2020). In each pixel, the cumulative impact index, I_C, is calculated as the cumulative effect of pressures (or drivers according to Halpern et al., 2008) of stress, D_j, on every ecosystem component, E_i. The strength of the effect of every individual pressure on every individual ecosystem component is indicated by the impact weight, μ_{ij} (Halpern et al., 2008), according to (eq. (1)):

$$I_c = \sum_{i=1}^{n} \sum_{j=1}^{m} E_i D_j \mu_{ij}$$

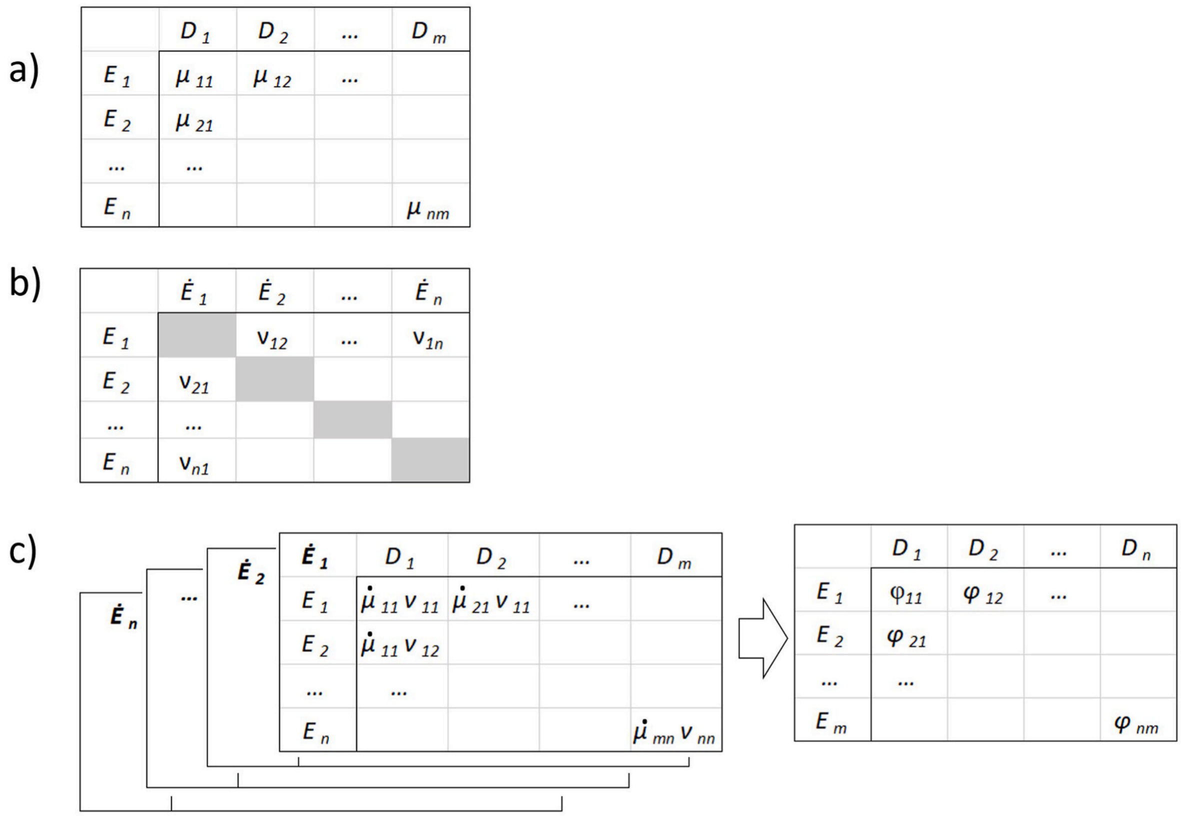

Fig. 1. Sensitivity matrices for total cumulative effects, where E are ecosystem components, D pressures and μ, ν, and φ are impact weights (shaded cells are not used). a) Original sensitivity matrix, b) sensitivity matrix incorporating ECIs, and c) a three-dimensional sensitivity matrix enabling indirect effects through other ecosystem components. The matrices to the left (calculation 1) transform into the matrix on the right (calculation 2) according to equations (4) and (5).

The product, I_c, is the calculated cumulative, or aggregated, environmental impact.

We chose a study area in the central Baltic Sea at the Swedish east coast, Northern Europe (Fig. 2), based on its variability of ecosystem components and pressures. This area is historically important for cod and herring as a nursery ground and there are several busy shipping routes crossing the area, contributing to both oil pollution and increasing metal pollution to the northern and eastern parts of the Baltic Sea.

2.2. Method for calculating ecosystem component interactions and indirect effects

Fig. 1a shows how all ecosystem components are affected by all pressures through the sensitivity matrix of impact weights in the original model developed by Halpern et al. (2008). There are no possibilities to include ECIs or indirect effects of pressures through intermediate ecosystem components in this original sensitivity matrix. However, ECIs can be calculated in a redefined sensitivity matrix (Fig. 1b), where all ecosystem components are grouped together and included in both directions (rows and columns) of the matrix. This allows ecosystem components to interact with other ecosystem components through new impact weights; hence making ECIs possible. In the same way, it would be possible to calculate interactions between pressures, also through new impact weights, e.g. the pressure of climate change's effect on the pressure pollutants. This is summarised as:

$$I_{ECI} = \sum_{i=1}^{n} \sum_{k=1}^{n} E_i \dot{E}_k \nu_{ik}$$

where E is the ecosystem component affected by the ecosystem component $\dot{E}$ through the impact weight ν. The nature of ECIs is both positive and negative. For instance, a predator-prey relationship would be negative for the prey and positive for the predator in terms of predation. However, the model is not intended for ecological modelling and lacks the more realistic representation of interactions among species (such as non-linear functional responses) and the complexity of the food web in models (such as in the EcoPath model; Steenbeek et al., 2016). It is a tool designed to arm decision makers with the best information to decide on e.g. areas to protect or areas to designate for different kinds of exploitation. We therefore assigned the impact weight ν only positive values (as for negative effects) also for ECIs regardless of their direction to avoid negative and positive impacts to counteract each other when trophic interactions are prominent. However, the model is fully capable of handling negative values of ν and it is possible to make full cumulative impact assessments allowing antagonistic behaviour of ECIs, if one wish to do so.

Indirect effects can be handled only using a three-dimensional matrix (Fig. 1c). The resulting relationship is:

$$I_{indirect} = \sum_{i=1}^{n} \sum_{j=1}^{m} \sum_{k=1}^{n} E_i D_j \dot{E}_k \dot{\mu}_{jk} \nu_{ik}$$

where E is the ecosystem component affected indirectly by the pressure D through the ecosystem component $\dot{E}$. Here, $\dot{\mu}_{ij}$ is the impact weight of the effects of D_j on $\dot{E}_k$ and, again, ν_{ik} is the impact weight of the effects of $\dot{E}_k$ on E_i. Thus, $I_{indirect}$ is calculated in a three-dimensional matrix to fit the three parameters, which renders the matrix unfit for use in the cumulative impact model. This problem can be circumvented by introducing a new term:

$$\varphi_{ij} = \sum_{k=1}^{o} \dot{\mu}_{jk} \dot{E}_k \nu_{ik}$$

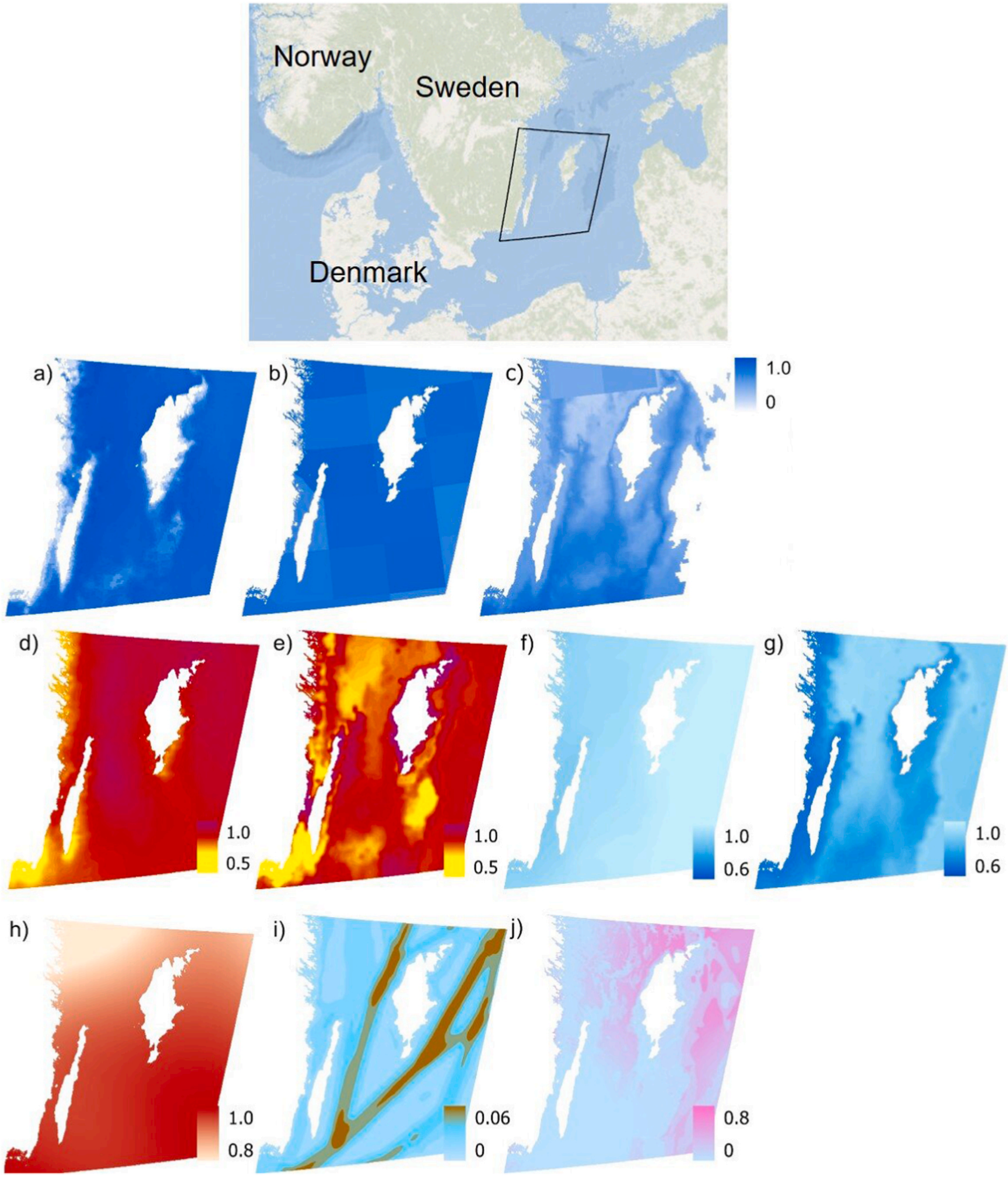

Fig. 2. On top, a map of the chosen study area (black square). Maps of used ecosystem components: a) plankton community, b) herring, and c) cod. Maps of used pressure layers: d) future changes in summer (May–Aug) sea surface temperature and e) bottom temperature, f) future changes in annual sea surface salinity and g) bottom salinity, h) future changes of ocean acidification, i) petroleum oil from shipping, and j) sediment associated heavy metals. Numbers are normalized from 0 (no presence) to 1 (highest value/presence), as derived from original sources. Note the different scales in d-j.

so that

$$I_{indirect}(\varphi) = \sum_{i=1}^{n}\sum_{j=1}^{m} E_i D_j \varphi_{ij}$$

Thus, φ is an expression of the strength of the indirect effect of D_i on E_j through all $\dot{E}_k$. Because $\dot{E}_k$ belongs to the ecosystem component map and is not part of the sensitivity matrix, φ varies geographically among pixels and $I_{indirect}(\varphi)$ can only be solved by first solving φ in each pixel. Consequently, we first ran the model to calculate φ and used these results for the subsequent run to calculate $I_{indirect}(\varphi)$.

2.3. Anthropogenic pressures and ecosystem components

Research shows the importance of the chosen climate pressures (temperature, OA, salinity) for the three species (plankton, herring, cod) in our chosen food chain as these environmental conditions affect e.g. the eggs and larvae's survival ability (Casini et al., 2010; Nissling, 2004; Vallin et al., 1999; Wåhlström et al., 2020). For the pollutant pressures, petroleum oil from shipping and sediment associated heavy metals were included (Fig. 2). Oil-related compounds are among the most important groups of anthropogenic organic pollutants released into the sea today (Sharma et al., 2024). Important pathways for oil pollution to

Scandinavian waters are ship traffic and North Sea oil drilling, however, the latter is not included in the pressures used in the present study. These two activities are already carried out intensively today and predicted to increase sharply in the coming decades despite climate change mitigation actions (UK Government, 2023; Jalkanen et al., 2021; Robbins et al., 2022).

Map layers showing future changes in water temperature and salinity in the study area were calculated from grids retrieved from Wåhlström et al. (2022) and were applied in the model in the same way as in Wåhlström et al. (2022). The grids held the most recent climatological and physical model projections for the region, indicating future changes in temperature and salinity (Gröger et al., 2019, Fig. 2). These climate projections were based on the same assumptions as used in the 2013 Intergovernmental Panel on Climate Change Representative Concentration Pathway (RCP8.5) scenarios for greenhouse gas forcing (IPCC et al., 2013). The applied climate change pressures were changes in summer (May–Aug) surface and bottom water temperature and annual surface and bottom salinity between two 30-year averages, i.e. a historical reference period (1976–2005) and an end-of-century period (2070–2099, Fig. 2). Cod was assumed to be dependent on bottom water changes (T_b and S_b, Fig. 3), while herring and plankton community were assumed to be dependent on surface water changes (T_s and S_s, Fig. 3).

The pH (OA) layer was calculated from global Coupled Model Intercomparison Project Phase 5 (CMIP5) projections of atmospherically driven pH changes obtained from the American National Oceanic and Atmospheric Administration (NOAA). Increasing atmospheric partial pressure of CO_2 is predicted to be the foremost pressure of OA in the Baltic Sea (Gustafsson and Gustafsson, 2020). At present, there are no geographically resolved projections of future OA in the waters surrounding Sweden. For the change in pH, we used the present day mean (2016–2020) and the RCP8.5 end-of-century projection (2096–2100, Fig. 2). The downloaded grid file (50 km × 50 km resolution) was first clipped to a rectangle covering the Baltic Sea and Kattegat/Skagerrak, and then transformed to a geographic raster file, which was in turn transformed to fit the model resolution using spline interpolation in ArcMap 10.8.1, similarly to the methodology used by Perry et al. (2020). The pH values were then transformed to relative values so that the extremes (0 and 1) were set to represent the highest and lowest projected global pH values at the year 2100 (8.06 and 7.55, respectively). All map layers were adjusted to fit the resolution of our model in ArcMap 10.8.1.

Map layers for the three ecosystem components (cod, herring, plankton community) and the two pollution pressures (oil and metals) were retrieved from the Symphony webpage at the Swedish Agency for Marine and Water Management (Hammar et al., 2018). The pressure from oil exposure is represented by the annual probability of ship-related oil spill occurring in Swedish coastal and offshore waters under meteorological conditions equivalent to a drift speed of 0.2 knots (Hammar et al., 2020). Underlying data consist of information on ship traffic and illegal oil discharges, which have been combined and modelled. The pressure from metals was derived from the predicted average concentration of nine heavy metals in coastal Swedish marine sediments (Hammar et al., 2020). Underlying data consist of historical heavy metal concentration data (1984–2014) and modelled benthic substrate data. Finally, all layers were clipped to fit the geographic extent of our study area (Fig. 2), which ultimately consisted of 778,316 pixels (pixel size: 250 m × 250 m).

2.4. Impact weights

The impact weights (μ) define how sensitive each ecosystem component is to each pressure. A systematic review of the scientific literature was performed to determine the impact weights for direct effects as well as ECIs. When empirical data was lacking (i.e. no or few studies found through the literature search), evaluation by researchers with extensive experience in each field was used to provide the different impact weights. In the systematic review, we followed the protocol by Haddaway et al. (2018) for literature selection and data extraction. A total of 24 literature searches were performed in December 2021 combining each of the targeted organism groups and pollutant- or climate pressures, using the Web of Science core collections for the period between 1945 and present.

The amount of available data varied considerably among pressure-ecosystem component pairs and therefore the impacted weight values were divided into three categories: *Sensitivity is based on empirical data*, *Sensitivity is partly based on empirical data* and *Expert assessment* (Table 2). This categorization was made as the review revealed knowledge gaps regarding how and to what extent different pressures affect various ecosystem components. It is therefore difficult to assess impact weights for different ecosystem components and species using empirical data alone. For the presentation of the impact weights, we have indicated the level of judgement by colour in Table 2. Six sensitivity rating categories were explicitly defined, ranging from 0 (No effect/Negligible effect) to 1 (Very strong permanent impact), with definitions slightly modified from those in Hammar et al. (2020) and Wåhlström et al. (2022).

The selected variables for climate pressure were water temperature, OA and salinity, which were used to assess the cumulative impact of climate change on the targeted organisms Atlantic cod (*Gadus morhua*, adults and larvae), herring (*Clupea harengus*, adults and larvae), zooplankton and phytoplankton. In *Symphony*, zooplankton and phytoplankton are grouped together as "plankton community". However, in this study the two groups of organisms are given separate impact weight values but the values for zooplankton are used in the calculations. Phytoplankton form the primary food source for zooplankton, whereas zooplankton form the major food source for fish larvae (Heath et al.,

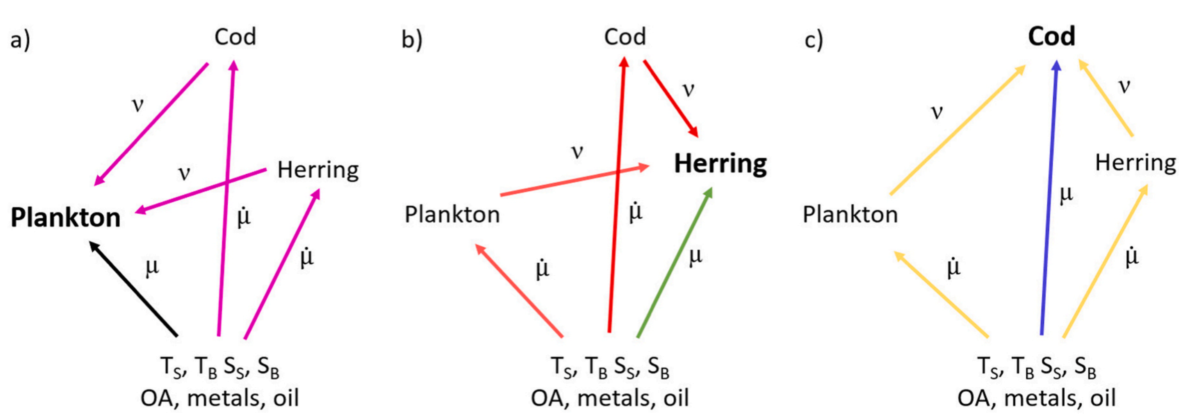

Fig. 3. Directions of effects from pressures to ecosystem components for a) plankton community, b) herring, and c) cod. The pressures are sea surface and bottom water temperature (T_S and T_B), sea surface and bottom water salinity (S_S and S_B), ocean acidification (OA), metals and oil. Black, green and blue arrows are direct effects and pink, red and yellow are indirect effects. Impact weights μ and ν as in equations (3) and (4).

2007), and it is therefore important to distinguish between the two groups of organisms when performing a cumulative impact assessment. The impact levels differ among fish life stages. The fish larval stage is generally the most sensitive of the different life stages to anthropogenic pressures or environmental changes (Foekema et al., 2012), and the preferred prey differs between larvae, juveniles and adults. For the two fish species, we therefore chose the life stage with the highest impact weight to account for the most sensitive or influential part of the life cycle, i.e. the life stage with the highest impact weight score.

The selected pressures in terms of pollutants/groups of pollutants in the systematic review were the heavy metals mercury (Hg) and copper (Cu), and the organic contaminants of petroleum oil with particular attention given to polycyclic aromatic compounds (PAC), a group of many hundreds of individual compounds considered to be the most toxic fraction of oil. Copper was selected as it is commonly used as an anti-fouling agent on ship hulls and on various fixed equipment in the sea (Ytreberg et al., 2022). Mercury is a metal with high toxicity and was selected because concentrations in Swedish coastal waters frequently exceed the Water Framework Directive's environmental quality standard for biota (Dietz et al., 2021; DIRECTIVE2013/39/EU, 2013). In the present study, the *Symphony* layers of oil from shipping and metals background were used. For oil, impact weights from our systematic review were used and for metals the values from *Symphony*, which are 0.2 for plankton community, herring and cod.

2.5. Assumptions used for calculations

For simplicity, we used indirect effects only through two ecosystem components (the directly affected level and the indirectly affected level, Fig. 3). In nature, indirect effects are moving up and down through the

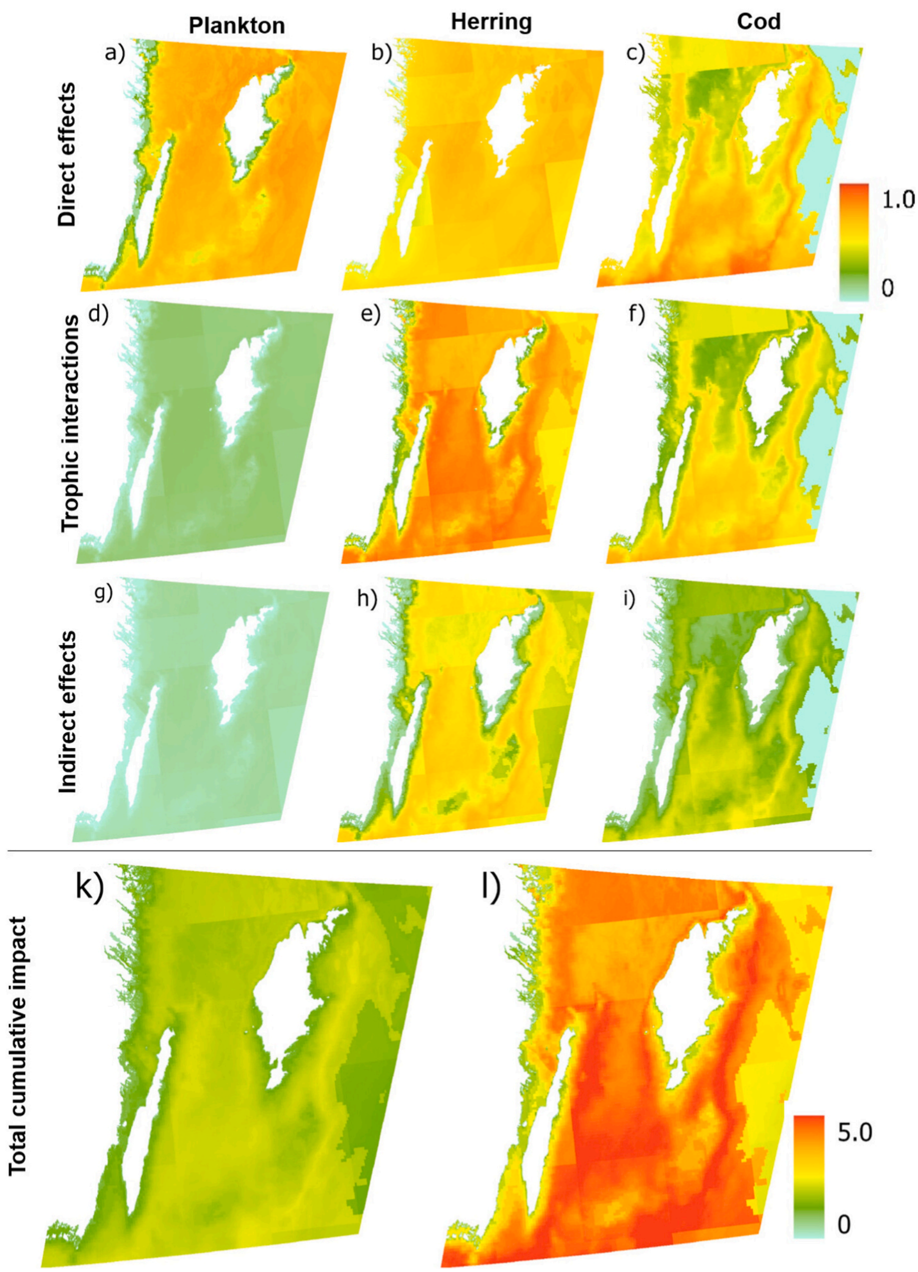

Fig. 4. Values of cumulative impact index of the calculations of direct effects (I_c; a-c), ecosystem component interactions (ECIs) (I_{ECI}; d-f), and indirect effects ($I_{indirect}$; g-i) on plankton community, herring and cod. All ECIs and indirect effects including both top-down and bottom-up indirect effects. Total cumulative impact calculated using only direct effects (I_c; k) (as in *Symphony*, climate change included), and all effects (direct effects, ECIs and indirect effects; $I_c + I_{ECI} + I_{indirect}$; l). The white areas are land. Note the different scales on a-i and k-l.

food chain for all ecosystem components (trophic cascades across trophic levels) and consequently indirect effects on primary producers and top predators may be underestimated. We therefore calculated indirect effects also through three ecosystem components for plankton community and cod to estimate the magnitude of this potential underestimation.

3. Results

3.1. Effects of adding ecosystem component interactions and indirect effects to a CIA model

We have shown that with the proposed methodology it is possible to incorporate ECIs and indirect effects into existing CIA models, which further develops these kinds of models towards sufficient representation of cumulative impacts in the marine environment. The results from our cumulative impact assessment method, which includes both ECIs and indirect effects, show a different and more complex picture (Fig. 4l) compared to the currently applied model, where only the direct effects are included (Fig. 4k). ECIs and indirect effects contribute 54 % to the total cumulative impact (Table 1), of which the impacts from ECIs and indirect effects were 33 % and 21 %, respectively. The average total cumulative impact across the entire study area increased by 117 % ((33 + 21)/46 × 100, Table 1).

Most importantly, adding ECIs and indirect effects increased the variability of the impact across the study area. Across the entire study area, the coefficient of variation (the standard deviation divided by the mean) of the impact values increased from 0.202 when only direct effects were considered to 0.269 when ECIs and indirect effects were included in the model, which corresponds to a 33 % increase in the spatial variability of the impact. Fig. 5 shows the added variability across the study area. While the waters close to the coast and at the far east experienced increases in cumulative impact between 50 % and 90 %, the offshore areas experienced increases between 100 % and 140 %. The total cumulative impact was higher than the average total impact in 57 % of all pixels across the study area and thus lower in the remaining 43 %.

Of the three ecosystem components included in this analysis, the most affected was herring, contributing 46 % to the total cumulative impact, followed by cod and plankton community with 31 % and 22 %, respectively (Table 1, Fig. 4a–i). The analyses of ECIs and indirect effects showed a similar pattern, with herring being strongest affected followed by cod. Plankton community was the ecosystem component most strongly affected by direct effects (Table 1, Fig. 4).

We tested the size of the bias introduced by allowing ECIs and indirect effects to progress only from one ecosystem component to the next, by additionally allowing for indirect effects on cod and plankton community to travel through three ecosystem components (i.e. for cod through plankton community-herring-cod, and for plankton community through cod-herring-plankton community). Integrated over the entire study area, the total indirect effects increased from 6.7 % to 7.4 % for plankton community and from 3.5 % to 7.4 % for cod.

Table 1
Contribution to the total cumulative impact (%) by direct effects, ecosystem component interactions (ECIs) and indirect effects for plankton community, herring and cod as well as summarised for each of species/species groups and pressures across the study area.

	Plankton community	Herring	Cod	Total
Direct effects	17	16	13	46
ECIs	3	18	11	33
Indirect effects	2	12	7	21
Total	22	46	31	

3.2. Impact weights

The results from our systematic review of the scientific literature and the expert assessments of the new impact weights for the ECIs and direct effects from climate change and pollutants on the selected species/groups of species are listed in Table 2. The systematic review revealed large gaps of knowledge regarding the importance of both trophic interactions and how the direct effects of climate change and pollutants affect these three species. For the ECIs, we were able to base the impact weight entirely on literature values for only four of the trophic interactions, and while most interactions were based partly on literature values, we had to revert to pure expert judgement for only two interactions (Table 2). Similarly, for the effects from climate change and pollutants, three impact weights were based on expert judgement and we had to revert to pure expert judgement for four impact weights.

The systematic review assessments showed that the direct effects from climate change induced warming had significant negative effects on adults and larvae of cod and herring, but less so on zooplankton and phytoplankton (Table 2). Future changes in salinity showed negative effects especially on cod larvae and zooplankton, whereas OA impacts were less severe. Pollutants had direct negative effects on all three ecosystem components, but the sensitivity to different pollutants varied among taxonomic groups (Magnusson et al., unpublished results). Most available data indicated that fish (although not specifically cod and herring), and in particular early life stages of fish, were more susceptible to oil and PAHs than zooplankton and phytoplankton. Phytoplankton appeared to be the least sensitive ecosystem component of the included taxonomic groups to oil and PAHs. The assessment showed that the sensitivities to Hg and Cu were generally lower than the sensitivities to oil and PAHs.

4. Discussion

Our study clearly demonstrated the importance and feasibility of incorporating ecosystem component interactions (ECIs) and indirect effects in cumulative impact assessment (CIA) tools, which include individual taxa as ecosystem components. The results showed that with the proposed methodology, the incorporation of ECIs and indirect effects can shift the cumulative impacts among areas. When ECIs and indirect effects were included in the CIA models, the cumulative impact increased from 50 % in some areas to 140 % in others. Thus, the cumulative impact manifested itself in more detail and with higher variance across the tested area. As ECIs and indirect effects are always present, the involved ecosystem components occur, and since the cumulative impact is determined based on a relative and unitless scale, the general increase of the cumulative impact is of less importance than how the relative impact varies across space. For instance, new areas may be highlighted as being under pressure, which might not be found in the more simplistic analysis. What is interesting here for CIA assessors and management interventions is when the cumulative impact increases unevenly across space, so that different patterns of anthropogenic impacts appear.

4.1. Feasibility of the new model

From an ecological perspective, there is a risk that adding both ECIs and indirect effects to the model will inflate the actual effects since indirect effects depend on ECIs. However, the model is not created to mimic the ecology. It is created to arm managers with an appropriate tool to evaluate and compare geographic areas based on their overall environmental conditions (after value judgement) and responses to anthropogenic pressures. This information can then be used to take informed management decisions on selecting areas for intervention such as protection or exploitation. In this perspective, ECIs should be included by its own merits to allow informed selection of areas to protect based on its complexity in terms of trophic interactions or species

Table 2
Impact weight scores based on the results from the systematic review and expert assessment. The impact weights are for the pressures of a) ecosystem component interactions (ECIs), and b) direct effects of climate change (temperature, ocean acidification (OA), and salinity) and pollutants (oil, polycyclic aromatic hydrocarbons (PAH), mercury (Hg) and, copper (Cu)) on ecosystem components (cod, cod larvae, herring, herring larvae, and zoo- and phytoplankton). The level of change is defined for the RCP8.5 and end-of-the-century for each climate change pressure on each ecosystem component. The most sensitive impact weight scores were used to represent the ecosystem component in the calculations (bolded blue numbers).

a)

	ECOSYSTEM COMPONENT INTERACTIONS					
ECOSYSTEM COMPONENTS	Cod	Cod larvae	Herring	Herring larvae/egg	Zooplankton	Phytoplankton
Cod		1	0.3	0	0	0
Cod larvae	1		**0.6**	0.1	**0.4**	0
Herring	**0.4**	0.3		1	0.8	0
Herring larvae/egg	0.4	0.1	1		**0.8**	0.4
Zooplankton	**0**	0.2	**0.2**	0.2		1
Phytoplankton	0	0	0	0.2	1	

b)

	DIRECT EFFECTS FROM PRESSURES						
	Climate change			Pollutants			
ECOSYSTEM COMPONENTS	Temperature	OA	Salinity	Oil	PAHs	Hg	Cu
Cod	**0.6**	0.1	0.3	0.4	0.4	0.2	0.2
Cod larvae	0.6	**0.2**	**0.5**	**0.8**	0.8	0.2	0.2
Herring	**0.6**	0.1	**0**	0.4	0.4	0.2	0.2
Herring larvae/egg	0.6	**0.2**	0	**0.8**	0.8	0.2	0.2
Zooplankton	**0.2**	**0.1**	**0.5**	**0.6**	0.6	0.2	0.2
Phytoplankton	0.2	0.1	0.2	0.2	0.2	0.2	0.2

SENSITIVITY CATEGORIES	
0	No effect / Negligible effect
0.2	Slight effect with consequence only from a cumulative perspective
0.4	Impact with consequence only on survival or reproduction rate
0.6	Impact with strong influence on survival or reproduction rate / Occasional immediate and strong impact
0.8	Frequent immediate and strong impact
1	Very strong permanent impact

COLORS
Sensitivity is based on empirical data (green)
Sensitivity is partly based on empirical data (yellow)
Expert assessment (red)

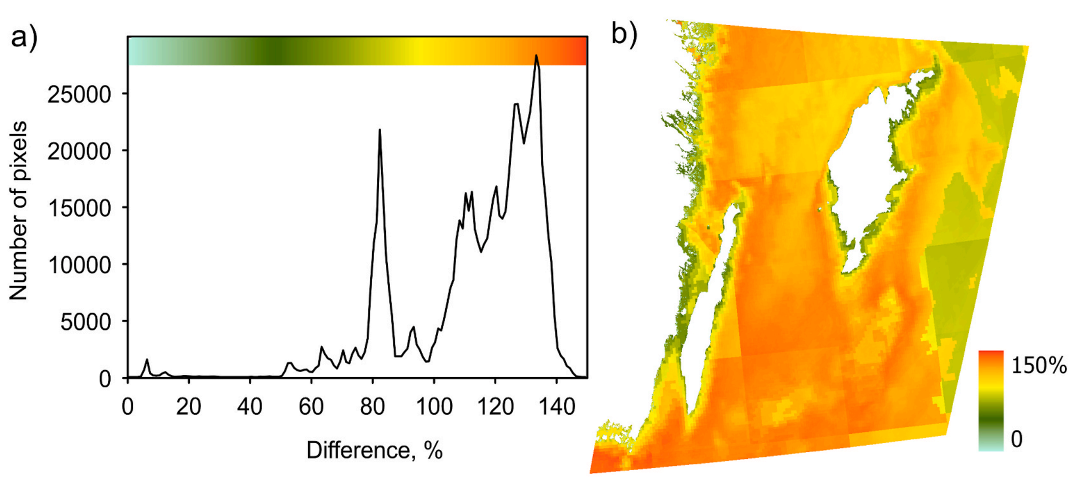

Fig. 5. Increase in cumulative impact. a) distribution among pixels of difference (%) in cumulative impact between the original Symphony model, which includes only direct effects, and the developed model, which includes ECIs and indirect effects. The gradient at the top refers to the colour gradient in the map (b). b) difference in every pixel (%) between the two models.

dependence on important habitats, regardless of anthropogenic pressures. When using the Swedish *Symphony* model, the authorities also use a so-called green map, in addition to the cumulative impact model. The green map shows the combined intensity of ecosystem components (leaving out pressure layers) for an overview of the combined ecological value in each area, i.e. the map pixel. The standalone ECIs should be included also in such green map applications, as this would likely influence the results, based on the findings presented here.

We specifically investigated trophic interactions of three species interdependently through predator-prey interactions, but the method is generally applicable to any interactions among different ecosystem components and pressures as well as for interactions between ecosystem components or interactions between pressures. The model also allows indirect effects of a pressure on an ecosystem component through another pressure, instead of through another ecosystem component (by substituting E with a pressure D as shown in equation (4) and Fig. 1d). This becomes relevant, for instance, when the toxicity of a compound varies with pH, which is true for metals such as copper. A similar model for CIAs has been devised by Beauchesne et al. (2021), who included indirect effects and ECIs in cumulative impact mapping of the St. Lawrence estuary in eastern Canada (Beauchesne et al., 2023). This model makes use of motifs, which comprise subdivisions of the community into trophically connected ecosystem components, to allow indirect effects. To elegantly allow the incorporation into the Halpern model without the problem of generating three-dimensional matrices, the impacts of pressures were averaged over these motifs. Our model comprises a generally applicable version of the same model with the added possibility that all ecosystem components and pressures can affect each other without prior inference of association to motifs.

Due to a general lack of data, the results are demonstrated spatially for a single plankton community layer only, data from shipping represent presence of oil, and a compilation of metals was shown rather than specific compounds separately. Although these simplifications have little bearing on the methodology itself, we caution that any further development of ECIs and indirect effects requires an incorporation of the most accurate and relevant data of ecosystem components and pressures available. In the event more detailed data are available, a specific impact weight score for each interaction effect may be calculated (Halpern et al., 2015, 2019; Hammar et al., 2020; Wåhlström et al., 2022).

The systematic review also revealed a lack of data to determine the impact weight values. However, the values set forth in the current work could serve as an indication of the impact weights relevant for other seas as well. In our study, ECIs were assessed for cod (adults and larvae), herring (adults and larvae), zooplankton and phytoplankton. The current *Symphony* model does not differentiate between these ecosystem components (larvae are grouped into a more generic “fish spawning” ecosystem component and “plankton community” does not separate between phytoplankton and zooplankton). We believe that there would often be merits to separate these components as different organisms and/or life stages of organisms respond differently to potential pressures. Therefore, we suggest using specific impact weights for each one of these ecosystem components, as provided in Table 2. Additionally, we suggest that any future CIA models separate between zooplankton and phytoplankton, with spatially explicit data for each group, because otherwise significant impacts between zooplankton and phytoplankton are likely to be overlooked.

Generalising anthropogenic impacts is difficult. For instance, climate change-induced warming impacts cod and herring negatively, and while some species of zooplankton and phytoplankton will be negatively affected as well, others will benefit from increased water temperatures (Olsen et al., 2011; Sommer et al., 2007; Sswat et al., 2018). Future changes in salinity will also affect ecosystems and the associated species in the brackish Baltic Sea environment; the species originate either from freshwater or a marine environment and do already today live close to the limits of their physiological tolerances (Ojaveer et al., 2010). However, it should be noted that the projected changes in salinity in the study area are uncertain (Meier et al., 2021). Data on copper toxicity on all species of interest are scarce and data on cod and herring is lacking. However, copper toxicity studies on other fish species than in this study indicate that the toxicity is higher in freshwater than in saltwater (Grosell et al., 2007), and therefore can be expected to vary significantly depending on freshwater supply from land.

4.2. Developed versus original model

While the study presented here demonstrates results for a specific geographic region within Swedish coastal waters, the methodological developments can be applied wherever underlying ecosystem and pressure data as well as knowledge about ECIs and impact weights are available. Hereby, previously hidden patterns of environmental impacts may be revealed to users of the *Symphony* tool and other CIA applications, making the proposed method a significant contribution to the field. Additionally, although the results illustrate environmental impacts in a simplified food chain, the ecosystem components selected (cod, herring and plankton community) are critically linked to the marine ecosystem as a whole, and therefore the additions of ECIs and indirect effects are representative of – and generalizable to – a more complex marine ecosystem. Even though the exact degree to which ECIs and indirect effects influence the cumulative impact is area specific and dependent on the ecosystem components and pressures specific to that location, the results from the model clearly illustrate the importance of their incorporation.

CIAs are, by nature, a simplification of the extremely complex natural system and do not consider all aspects of real ecosystems and exposure scenarios such as species interactions, pressure synergies, connectivity, and temporal variability (Halpern and Fujita, 2013). On the other hand, they are easily accessible management tools allowing for the processing and visualisation of interactions between large numbers of ecosystem components and pressure data, increasing the overview of comprehensive systems and overcoming the bias of individual assessors (Fernandes et al., 2017). However, in accordance with Halpern and Fujita (2013), our study raises the concern that given that the quality and reliability of data for each component may vary considerably, managers need to be aware of the limitations behind the data, and thus be critical to the results obtained. Although our model carries most of the shortcomings of all CIAs, specifically the inevitable simplification of complex ecosystems for management purposes, the proposed inclusion of ECIs and indirect effects provides a more finely tuned picture of the sensitivity of marine communities to anthropogenic impacts. This is particularly relevant in areas with a complex food web involving many trophic levels, especially at the lower trophic levels of e.g. phytoplankton and zooplankton. Although our proposed methodology remains a simplification of the natural system as all CIAs are (Halpern et al., 2007), it aids in incorporating some of the necessary complexity to the system, while still benefiting from the simplicity provided by CIAs.

Additive effects are already treated in the original formulation of the CIA model and no rearrangement of the sensitivity matrix has been required. Since the scale of impact weights is in essence of a logarithmic nature with values between zero and one, the sum of two effects is already a very strong additive effect. The original method is therefore sensitive when judging total impact and any adjustment to the interaction of impact weights of the two pressures will achieve little. This also holds for antagonistic effects (negative values of one or more impact weight(s)). *Symphony* allows for positive impacts of pressures to facilitate the inclusion of processes where pressures have any kind of enhancing effect on ecosystem components, and so does our developed model. This would be particularly logical for ECIs. However, we argue that this practice will introduce a risk of underestimation of the total impacts in geographical areas where positive relationships among pressures and ecosystem components become prominent. Positive and negative impacts may simply negate one another and render important impacts undetected when using the tool for environmental management purposes. This is particularly important if ECIs, as discussed above, are added to the green map in the *Symphony* tool to help in designation of marine protected areas. Allowing ECIs to even out each other will introduce a risk that information on the impacts of specific pressures on the involved ecosystem components will disappear. As the output of CIAs is the overall cumulative impact, with no insight into specific ECIs, pressure impacts or the size of their contribution to the cumulative impact, this disappearance will remain unnoticed without any possibility for managers to act upon it.

When marine spatial planners and managers use decision-guiding tools like CIAs, focus is often set on areas with particularly high or low impact (Hammar et al., 2020). In cases where the inclusions of indirect effects or ECIs give a more detailed picture, so that other areas become highlighted, any planning and management guidance will inherently change. We observed not only an overall increase in the cumulative anthropogenic impact in the area but also a diversification of impact levels among areas. Variability among pixels increased and the geographic impact picture became more detailed. We believe that this increased complexity may lead to better understanding of the usefulness and shortcomings of CIAs in ecosystem-based management and spatial planning.

4.3. Uncertainties

A CIA organises data and produces results that can be used to invoke the precautionary principle, which is one of the foundations of the EU legislation (e.g. De Santo, 2010) following the Rio declaration (United Nation, 1992). Because of this, the order of magnitude-level correctness of the outcome is very important. It is particularly important to avoid that the tool generates “false negatives” or type II errors, i.e., give a lower impact result than what will occur in nature (e.g. Fairbrother et al., 2010). Here we investigated the change in outcome of the CIA *Symphony* after making interactions only slightly more complex. The fact that the variability between pixels increased when the more detailed model was used indicates that there is a risk that the original model generates type II errors, assuming that the more complex model is more realistic.

All CIAs involve uncertainties, even when improvements are made, and model restrictions should therefore be made evident to the user so that environmental impacts are not underestimated. The results from the current study demonstrate the challenges of CIA applications based on ecosystem components that represent selected taxa (such as species or groups of species). An alternative is to stay with habitat-based CIA models, such as the original Halpern-based model and some later applications, such as *WIO Symphony*, where ecosystem components represent defined habitats (not individual species) and food web interactions are incorporated in the sensitivity scores. These applications have other restrictions, such as reduced level of detail and the implementing body will have to weigh advantages against restrictions. When species-based CIAs are required, for reasons such as assessing the cumulative impacts on specific taxa, they should preferably be addressed not as full models but as smaller subsets of interconnected ecosystem components (e.g. plankton-herring-cod), and with the inclusion of the functionalities presented in this study. Furthermore, to our knowledge no CIAs have yet been fully validated in the field, and their correctness is therefore not established, but species-based CIA models have been validated (e.g. Rees et al., 2023). However, on strategic – sea basin – level, results from many CIA applications generate similar results to holistic literature-based assessments, which encourages the use of and further development of the principal method. Constant improvements of both models and CIA methodology are of key importance and continuous updates of data should be set as a routine in all CIA applications. Future work includes the important step to try to validate CIA models with empirical data based on contemporary ecosystem conditions.

5. Conclusions

Marine spatial planning is growing in importance across the globe, as an instrument for ecosystem-based management, and tools like *Symphony* and other CIA applications must be continuously developed to answer requests by the users. In this respect, the present study demonstrated a novel approach to incorporate ecosystem component interactions (ECIs) and indirect effects of pressures on ecosystem components through interactions with other ecosystem components into CIAs. The new structure of the model is such that ecosystem components are now allowed to interact with each other. This also allows for practical incorporation of indirect effects. The proposed methodology can be integrated into CIA models in general provided that the underlying maps of geographic distribution of ecosystem components and pressure data, as well as ecosystem component interactions (ECIs) and pressure impact weights, are available.

The most important results of the test of the model became evident in the comparison between the developed and original models. The comparison revealed that if environmental managers would apply the original model with the aspiration to obtain a full picture of the ecosystem and its functions, the cumulative impact would be underestimated in 57 % of the test area (pixels with a difference of more than the average difference, 117 %, between the two models). This discrepancy highlights that constant improvements of the CIA methodology are of key importance and continuous updates of data should be set as a routine in all CIA applications. We believe that the proposed alterations constitute such valuable improvements.

The proposed advancements of the CIA methodology demonstrate not only how to incorporate trophic interactions, ECIs and indirect effects in CIA models but also how important these aspects are in providing a more accurate picture of the true combined impacts within an area. However, the exact degree to which the inclusion of trophic interactions, ECIs and indirect effects influences the spatial variability and the total impact in an area is specific to that location. Clearly, for marine managers using CIA as a tool to help guide in the establishment of regulations, an exclusion of these factors in certain areas would result in a significant underestimation of the total impact in the area of focus. It is therefore of great importance that the proposed methodology will be incorporated in future use of CIAs where feasible.

CRediT authorship contribution statement

Iréne Wåhlström: Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Diana Perry:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Sanne Bergman:** Writing – review & editing, Methodology. **Martin Dahl:** Writing – review & editing, Writing – original draft. **Maria E. Granberg:** Writing – review & editing, Writing – original draft, Funding acquisition, Conceptualization. **Martin Gullström:** Writing – review & editing, Project administration, Funding acquisition, Conceptualization. **Linus Hammar Perry:** Writing – review & editing, Methodology. **Kerstin Magnusson:** Writing – review & editing, Writing – original draft, Funding acquisition, Conceptualization. **Peter Thor:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

There is no conflict of interest between the authors.

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Data availability

All data used are already in databases, and they are listed in the paper.

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